# Expected Performance of Cosmic Muon Veto Detector at IICHEP, Madurai, India.

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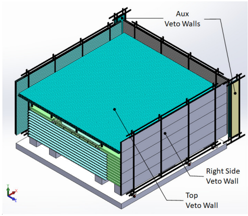
# Motivation

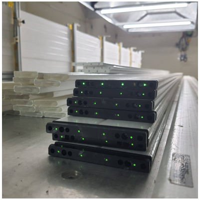
- The motivation of the **C**osmic **M**uon **V**eto **D**etector (CMVD) is to explore the feasibility of building a large-scale neutrino experiment at shallow depths.
- Earlier investigations utilizing a compact experimental setup have yielded promising outcomes, achieving a cosmic muon veto efficiency of 99.98 %.
- However, a much larger scale experiment is required to establish and improve this result.
- With an aim to achieve 99.99% veto efficiency, simultaneously maintaining the false-positive rate of less than $10^{-5}$, an extruded plastic scintillator-based cosmic muon veto is being built around the existing miniICAL detector at the transit campus of India based Neutrino Observatory, Madurai.

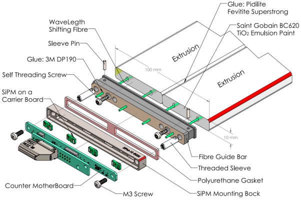
# mini-ICAL detector

- Currently operational at IICHEP, Madurai, the miniICAL stands as an 85-ton prototype detector of the larger ICAL (Iron Calorimeter) experiment.
- The mini-ICAL consists of ten layers, each comprising two 2 m $\times$ 2 m glass Resistive Plate Chambers (RPCs), sandwiched between 11 layers of 5.6 cm thick iron plates.
- The detector involves two coils comprised of copper conductors, capable of generating a maximum magnetic field strength of 1.5 T.
- A gas mixture of R134a, iso-butane, and $SF_6$ in a proportion of 95.2 %, 4.5 % and 0.3 % respectively are used to operate these RPCs in avalanche mode configuration.
- Using the orthogonal readout strips and the layer number, precise coordinates of particle trajectories can be determined.

# Cosmic Muon Veto Detector

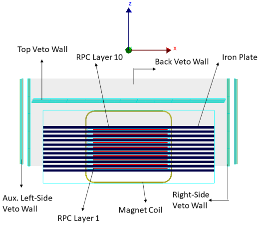


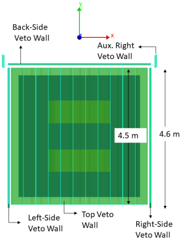



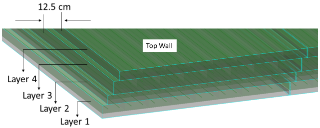



- **Detector Design:** Veto walls around 3 sides & top using Extruded Plastic Scintillator (EPS) strips
- **Technical Details:** EPS Strips: 4.5-4.7 m length, 5 cm width, 0.9/1.8 cm thickness
- **Photon Capture:** Two 1.4mm double-clad WLS fibers for efficient scintillation light collection
- **Photon Detection:** 2 mm $\times$ 2 mm Hamamatsu SiPMs (model S13360-2050VE) with both-side detection.
- **Integration:** More than 700 EPS strips & $\approx$3000 SiPMs.

# Detector Geometry in GEANT4 toolkit



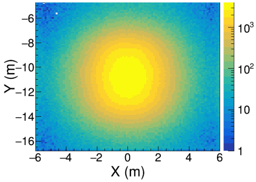



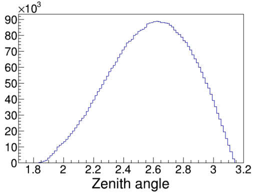

| Veto Wall | # of Layers | Layer staggering | # of Scintillator strips | Strip dimensions | distance from miniICAL |
|---|---|---|---|---|---|
| Top | 4 | $\frac{1}{4}$ width | 88/Layer | $4.5\ m \times 5\ cm \times 1$ - $1.8\ cm$ | $52\ cm$ |
| Side | 3 | $\frac{1}{3}$ width | 40/Layer | $4.5 — 4.6\ m \times 5\ cm \times 1\ cm$ | $30 — 33\ cm$ |
| Auxiliary | 3 | $\frac{1}{3}$ width | 8/Layer | $4.7\ m \times 5\ cm \times 1.8\ cm$ | $33\ cm$ |

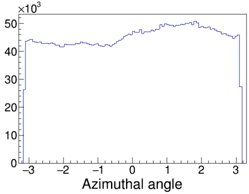
* Each Tiles has 8 EPS in the form of 4 Di-counters. Gap Between two EPS is ≈1 mm. Spacing Between two tiles is ≈2 mm. Extra Side Walls for filling dead spaces between the edges of side & back walls.

# Event Generation

- The event generation process integrates CORSIKA and the detector geometry.
- Trigger acceptance is established by extrapolating particle positions from the topmost RPC layer (layer 10) to the layer below (layer 7).
- This approach defines the Mini-ICAL trigger efficiently, with event vertex calculation based on interpolated positions on the rooftop.
- Improved computational time by rejecting muon trajectories that do not intersect the top and bottom trigger layers.



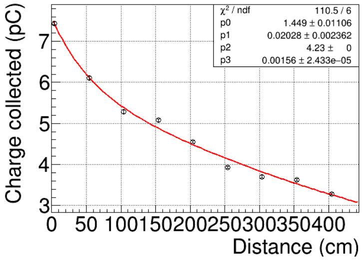



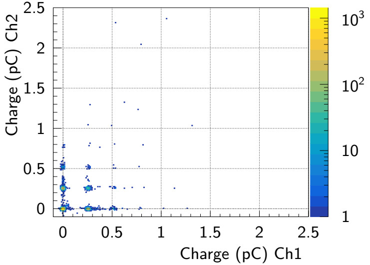
# Digitization

- Instrumental effects like energy loss along WLS fiber, noise in SiPM, threshold etc are added.

Charge Collected




Noise in SiPM's

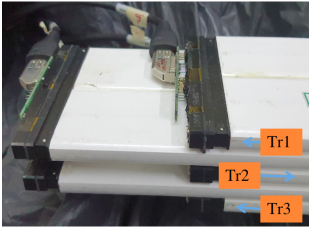


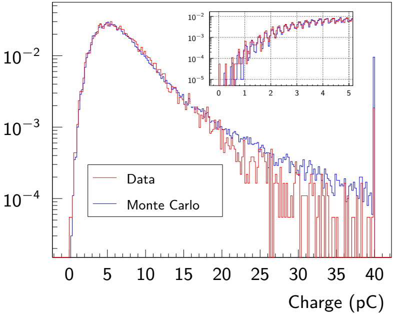

Relevant data [1] obtained at 2.5 overvoltage are used in simulation.

[1] M. Jangra et. al, "Characterization of Hamamatsu SiPM for Cosmic Muon Veto Detector at IICHEP," Springer Proc. Phys., vol. 277, pp. 815-819, 2022.

# Digitization: Charge Measurement

1. Conversion of deposited energy into the number of photons ($N_{pe}$), accounting for energy loss along the fiber, considering a proximity of 30 photons in the nearest SiPM.
2. Introduction of random fluctuations in $N_{pe}$.
3. Charge collected in the SiPM is computed with a 0.26 pC per photo-electron.
4. Incorporation of random noise and SiPM pedestal, followed by signal digitization using a 12-bit ADC.

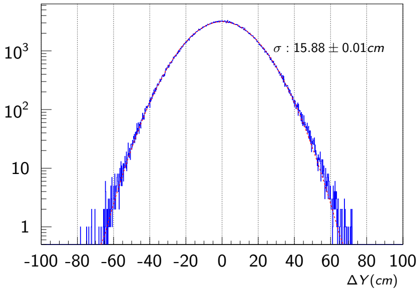


# Digitization: Timing Measurement

1. Calculation of SiPM time based on a measured fiber velocity- 16.2 cm/ns.
2. Accounting for measurement uncertainty at the SiPM, with a Gaussian width $\approx 3$ ns/$\sqrt{N_{pe}}$.
3. SiPM time digitization using a 10-bit TDC.

Uncertainties in muon position from timing.

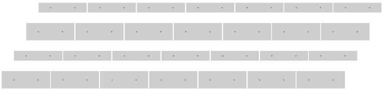


# Hits and Cluster Formation

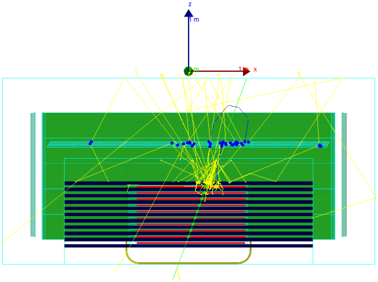
The CMV detector geometry detects a minimum of two valid layers of hit per reconstructed muon. Closely spaced strips can result in two hits in a layer. Multiple hits may arise from muon ionization and delta rays. Electromagnetic/hadronic interactions also contributes.

To meet efficiency requirement, hit is formed when two or more SiPMs have signal above certain threshold. Delta-ray/Noise hits are combine with muon hits to form clusters as is indistinguishable.

Layer Staggering.



Multiple hits due to secondary particles.

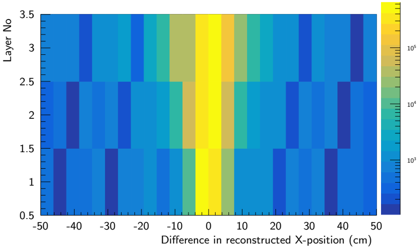


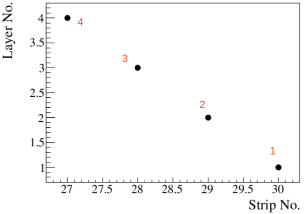
# Cluster Formation (Continued)

Clusters in different layers are related if within 12 cm. Super-clusters require 2 valid clusters/hits in each wall.

Clusters combine to form doublets, then triplets if related. In the top wall, triplets and doublets combine to quartets:
Doublets: 1-2, 1-3, 1-4, 2-3, 2-4, 3-4.
Triplets: 1-2-3, 1-2-4, 2-3-4.
Quartets: 1-2-3-4.

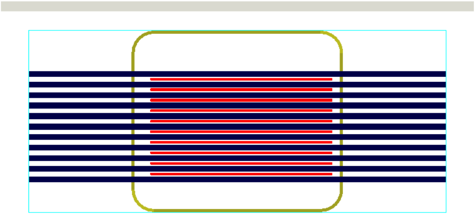
Super-clusters are fitted with a straight-line to determine the expected muon position at the center of each wall.



# mini-ICAL track Reconstruction/Extrapolation

- **Track Reconstruction:** Track finding, Track fitting
- **Track fitting:**
  - Kalman filter-based algorithm in presence of magnetic field [2]
  - Linear least-square method used without magnetic field [3].
- **Track Extrapolation:**
  Inside topmost ironlayer: Prediction-Step of K-F algorithm.
  Outside non-magnetic region: Linear Extrapolation.



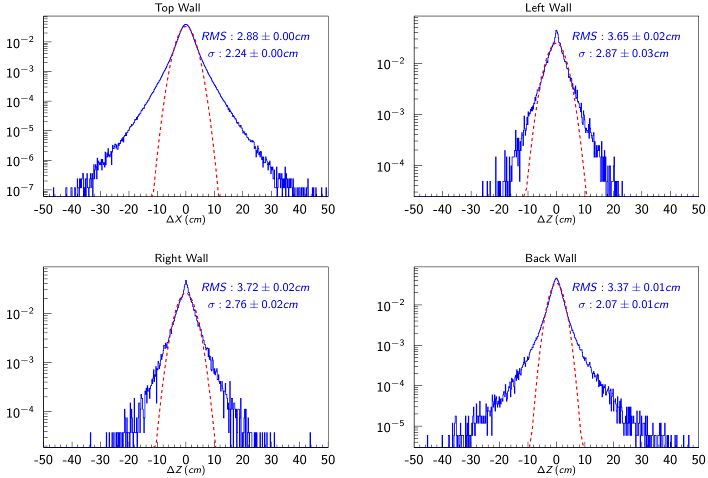
[2]K. Bhattacharya et al., "Error propagation of the track model and track fitting strategy for the Iron CALorimeter detector in India-based neutrino observatory," Comput. Phys. Commun., vol. 185, pp. 3259-3268, 2014, arXiv:1510.02792.

[3]S. Pal, Development of the INO-ICAL detector and its physics potential, thesis.

# Extrapolation Results without Magnetic field

# of layers > 6 and $\chi^2/ndf < 2$

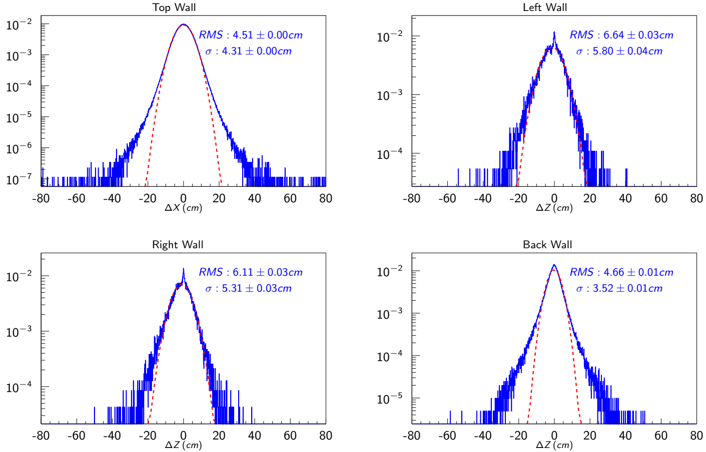
Difference between avg. super cluster position and extrapolated position.



# Extrapolation Results with Magnetic field

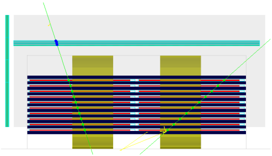
# of layers > 6 and $\chi^2/ndf < 2$

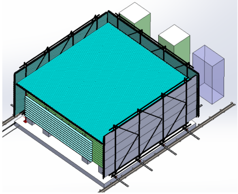
Difference between avg. super cluster position and extrapolated position.

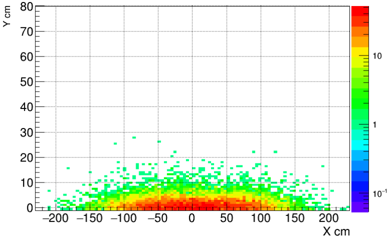


# Effective Area of the CMVD

mini-ICAL triggered by muon from front-side.



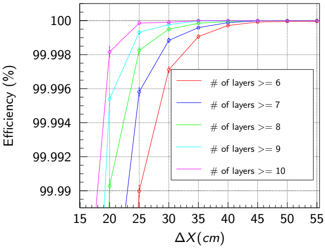




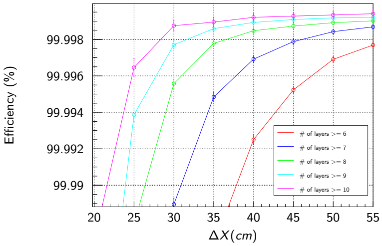

Extrapolated X-Y position on the topmost layer when there is a valid trigger in miniICAL and the muon is coming from the front side. Thus ≈ 30 cm of 4.5 m from the front-side would be excluded in the data.

# Expected Veto Efficiency

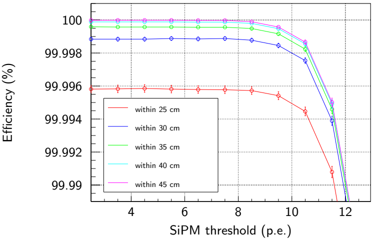
## Without Magnetic Field




## With Magnetic Field




## Variation of SiPM threshold



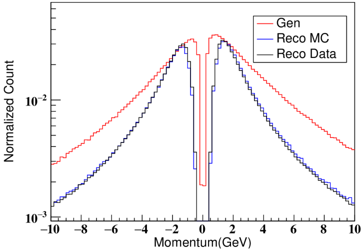
# Conclusion

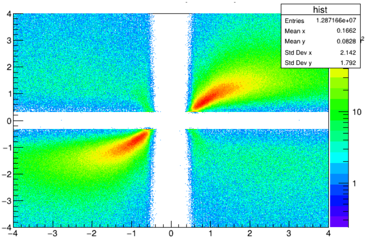
To meet our stringent requirements:

1. Firstly, exclude events 30 cm proximity to the front side of the detector.
2. Secondly, look for extrapolated position of well-fitted tracks:
   - If extrapolated positions fall within the detector boundaries, consider superclusters within a 30 cm radius from this point.
   - For tracks with extrapolated points outside the detector boundaries, evaluate their distance from the detector's edges and assess their 2D distance from the associated supercluster.

**Thank You for Attention !**

# BackUp: Momentum Distribution



# BackUp: SiPM Charge Spectrum