SEARCH FOR EXOTIC PARTICLES USING ICAL AT INO

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Outline of the talk

- Introduction
- Iron CALorimeter (ICAL)
- Physics possibilities of ICAL
- Studies of Exotic particles using ICAL
- Summary

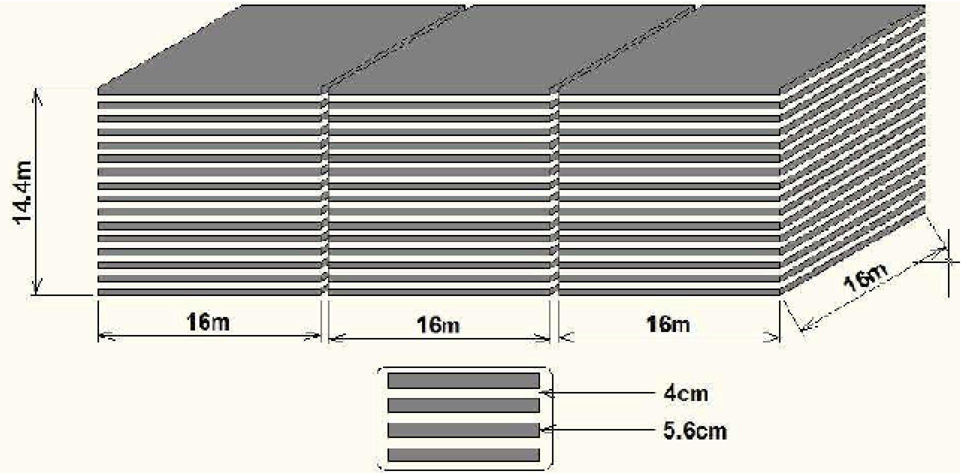
Introduction

- Underground experiments at Kolar Gold Field (KGF) during 1965-1992 motivates further research in India.
- Evidence for atmospheric neutrinos (ν_{μ}) [1]was first found by the TIFR-Osaka-Durham group at KGF.
- In last few decades there is a good progress in the neutrino sector and now it is an-active area of research in High Energy Physics (HEP).
- India-based Neutrino Observatory (INO) [2] is a proposed underground facility which aims to explore the different aspects of neutrino physics and new physics.
- It is a multi-institutional effort, planned to be built under 1 km rock cover, all around, at Bodi Hills, in Theni district, in TamilNadu.

[1] Phys Letters **18**, (1965) 196
[2] www.ino.tifr.res.in

◆ Iron CALorimeter (ICAL)

ICAL	
No. of Modules	3
Size of a Module	16 kton
Dimension	16 m x 16 m x 14.5 m
Magnet	
No. of iron plates	150 Layers
Plate dimensions	2 m x 4 m x 0.056 m
Material	Low carbon steel
Magnetic field	1.3 Tesla



Active detector element	
Resistive plate chamber	Glass, Avalanche mode
Dimensions	2 m x 2 m x 0.035 m
Time & position resolution	1 nsec, 3 cm (X & Y plane)

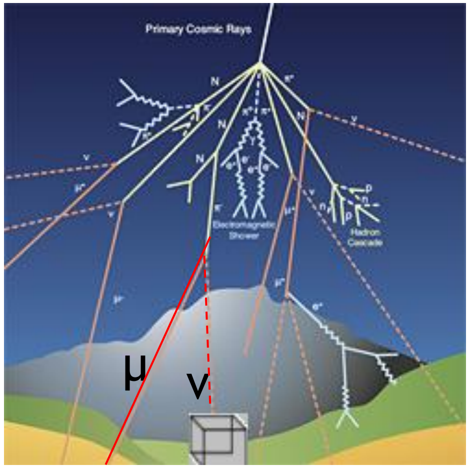
- So it is a good tracking device with better energy and direction resolution.

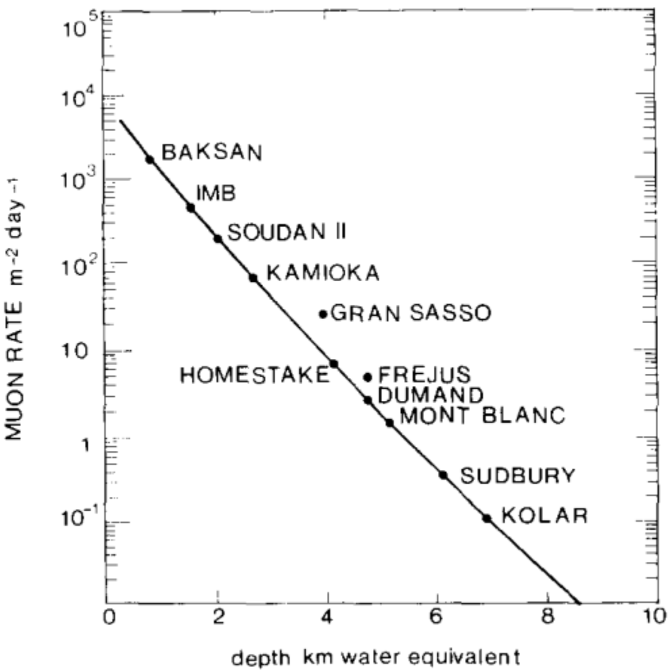
Physics possibility of ICAL

- For an underground laboratory the only the penetrating particle is neutrino and then high energy cosmic ray muon whose intensity depends on the location depth.
- The ICAL is mainly focused on Neutrino Physics using atmospheric neutrinos.

✓ Precise measurement of the neutrino oscillation parameters.
✓ Determination of the sign of the mass squared difference δ_{23} and the matter effect.
✓ Determination of the maximal of the mixing angle θ_{23}.
✓ Determination of the leptonic CP phase.
✓ The existence of the sterile neutrino.

- As the ICAL is a tracking detector with large size, it will be able to explore the new physics along with the neutrino physics.





Search for Exotic Particles using ICAL

1. Decay of Dark Matter Particle (DMP)

- Motivation
- Simulation of DMP in ICAL

2. Magnetic Monopole (MM)

- Overview
- Detection mechanism and detection by other experiments
- Interaction of MM with matter
- Simulation of MM in ICAL

1. Decay of Dark Matter Particle (DMP)

❖ *Motivation*

✓ The motivation of doing the **dark matter search** at INO through its **decay** comes from the earlier observation of **few anomalous events** in two phases of the detector (cosmic ray neutrino experiment & proton decay experiment) at **KGF** from 1965 – 1992.

❖ *Why so called anomalous events?*

- These events are characterized [3] by,

1. Several tracks with one being a penetrating track like muon originating from a single vertex. ($\geq$ 3 tracks)

2. Vertex located either in air or in the thin detector materials. (70-100 cm from the rock wall)

3. Tracks from the vertex are obtained with large opening angle.

3. These were the 25% of the total observed events.

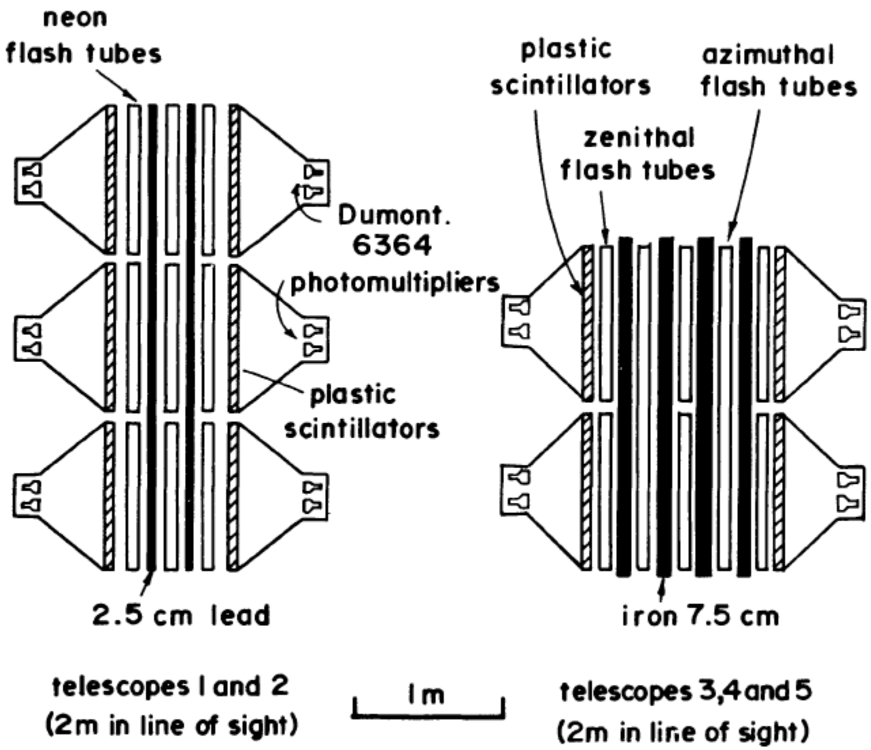
- As they are observed at KGF called as **Kolar Events** due to their special nature.

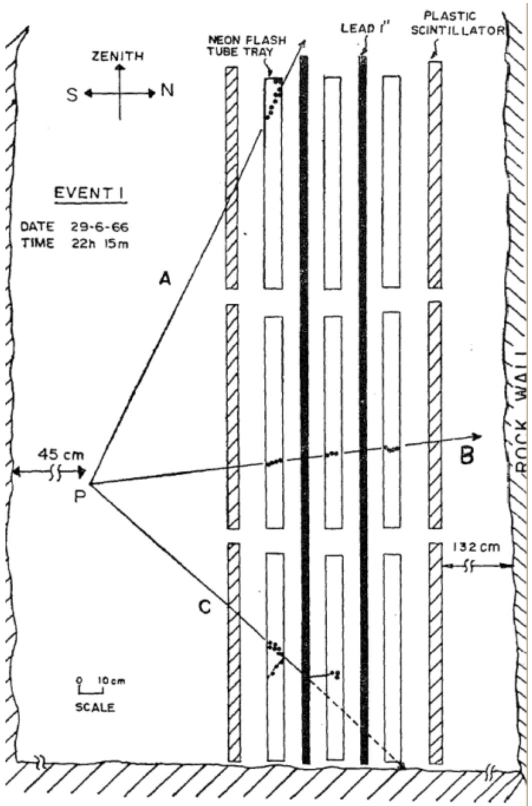
[3] M.R.Krishnaswamy et al, Pramana, **5**, 59 (1975)

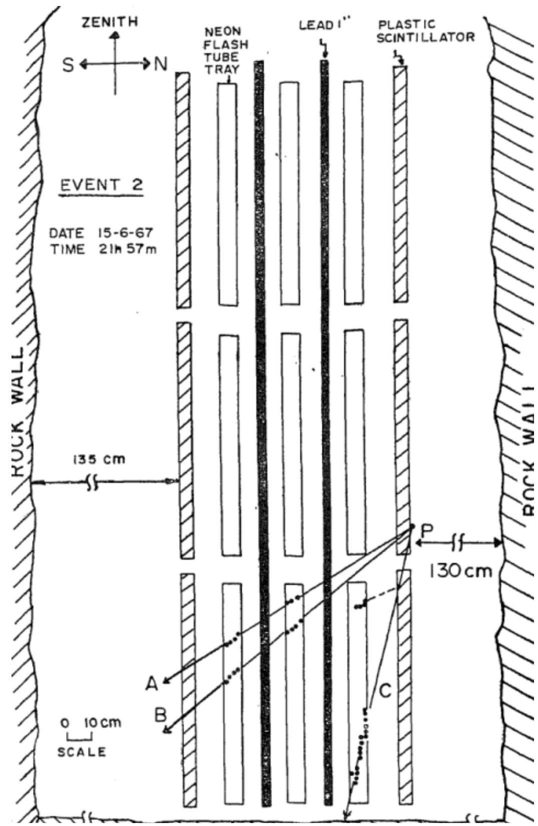
❖ *Display of Kolar Events in neutrino telescope* [3]

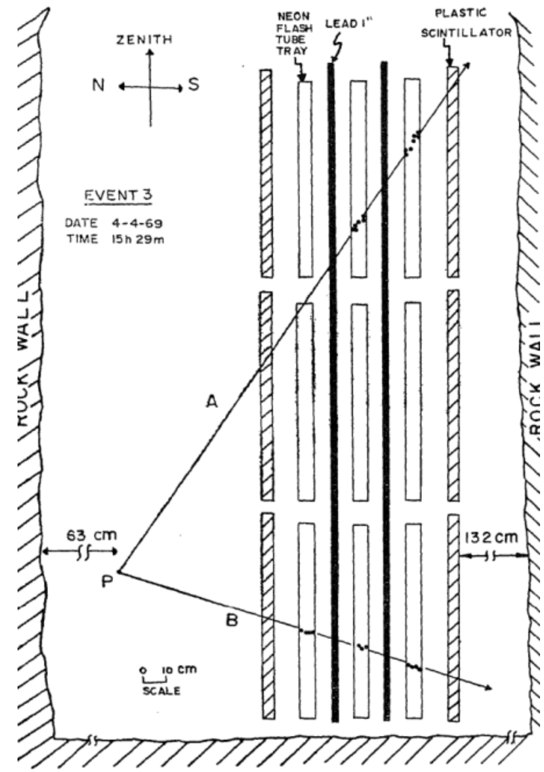
✓ PHASE I

- 1965 - 1969
- 7600 feet (7000 hg/cm^2)
- Bombay – Osaka – Durham Collaboration
- Neutrino experiment







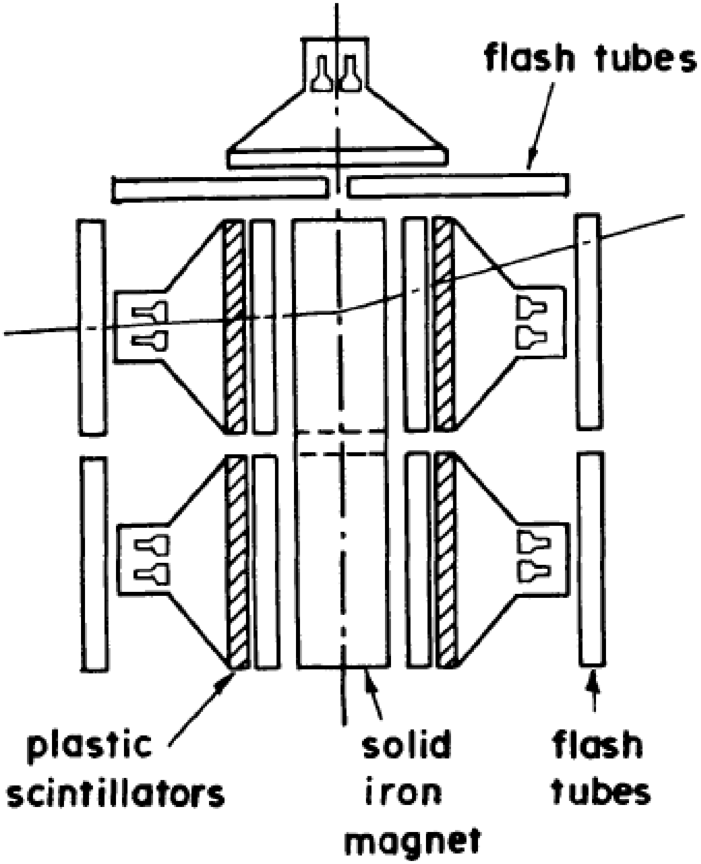


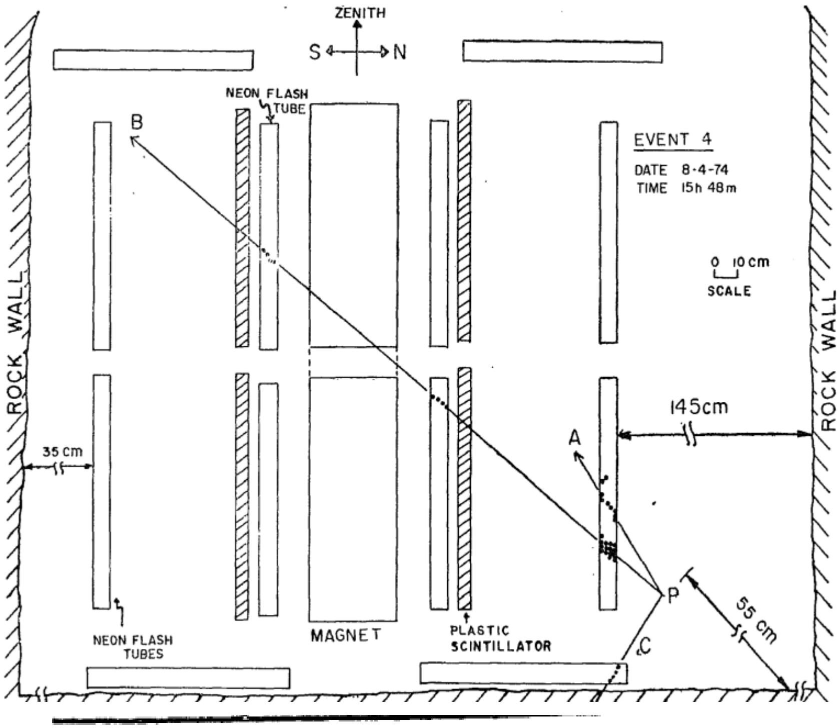
Event No.	No. of tracks	Projected Distance of 'P' from rock (Detector)	Projected zenith angles of tracks	Characteristics of penetration (minimum amount of material traversed)	Nature of particles
1	3	57±5 cm (Tel. 1)	*a.* 25° upwards *b.* 96° *c.* 48°	22·5 g/cm²* 5 cm of Pb 13 g/cm²*	e, μ or hadron μ or hadron e, μ or hadron
2	3	130±10 cm (Tel. 1)	*a.* 56·50° *b.* 51° *c.* 12·5°	6·1 cm of Pb 6·5 cm of Pb 32·5 g/cm²*	μ or hadron μ or hadron e, μ or hadron
3	2	63±5 cm (Tel. II)	*a.* 35° upwards *b.* 72°	9·3 cm of Pb 5·2 cm of Pb	μ or hadron μ or hadron

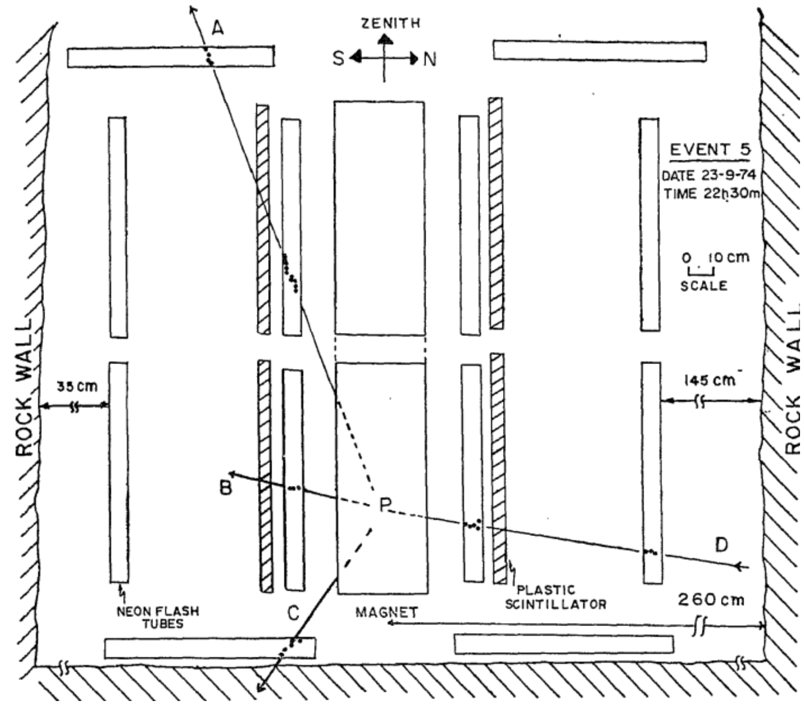
❖ *Display of Kolar Events in magnet spectrograph* [3]

✓ PHASE II

- 3655 feet (3375 hg/cm^2)
- Muon experiment
- Magnet Spectrographs
- Area : 8 m^2

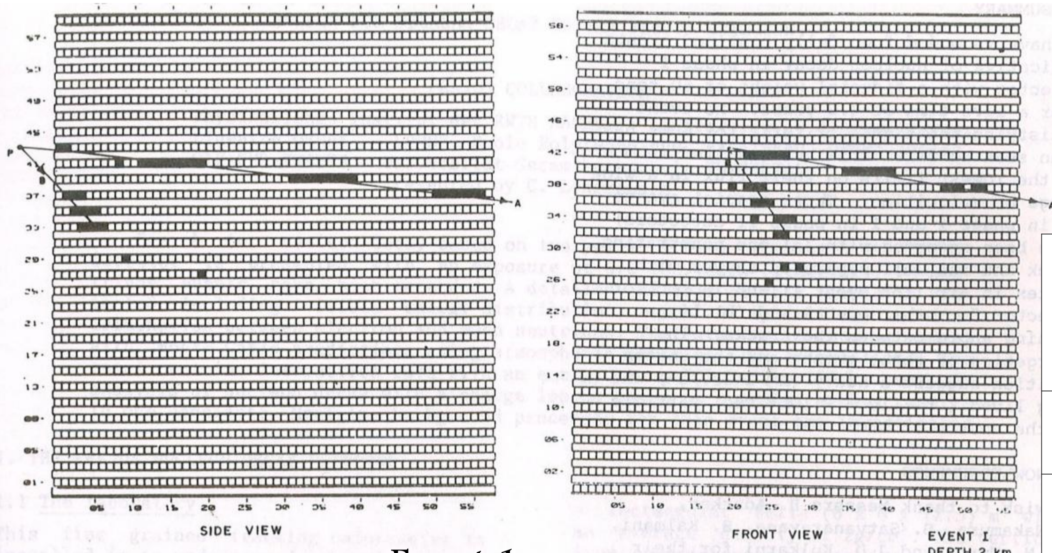




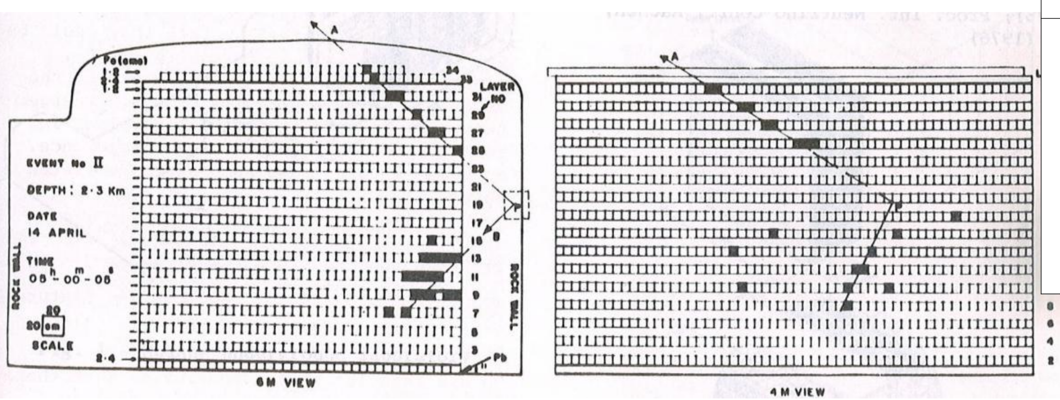


Event No.	No. of tracks	Projected Distance of 'P' from rock (Detector)	Projected zenith angles of tracks	Characteristics of penetration (minimum amount of material traversed)	Nature of particles
4	3	55±5 cm (Mag. Spec.)	*a.* 35° upwards	6 g/cm²*	e, μ or hadron
			b. 52° upwards	40 cm of iron	μ
			c. 35°	6·5 g/cm²*	e, μ or hadron
5**	3 + 1 (primary)	260±15 cm (Mag. Spec.)	*a.* 20° upwards	58 cm of iron	μ (> 1 GeV)
			b. 75° upwards	21 cm of iron	μ (probably)
			c. 37°	33 cm of iron	μ (probably)
			d. 81° upwards	..	New particle (probably)

❖ Display of Kolar Events during 1986 [4]



Event 1



Event 2

Event No.	Penetrating track(GeV)	Shower (GeV)	Opening angle(deg)	Vertex
1	> 1.3	> 2.6	32	Air
2	> 0.4	> 2.5	69	Air or rock
3	> 1	≥ 5	41	Inside detector

[4] M.R.Krishnaswamy et al, Proc. XXIII Int.Conf. on High Energy Physics, Berkeley(ed.) S Loken(World Scientific, 1986)

❖ *Interpretation of Kolar events.*

These particles were interpreted[3] as,

1. Non-contemporary tracks.

   3375 gm/cm^2 – 1 muon in 5 hrs

   7000 gm/cm^2 – 1 muon in 6 days

2. Interactions due to atmospheric muons.

   angular distribution of muon : $1.1 \times 10^{-10} \sec\theta \exp[-9 (\sec\theta - 1)]\ cm^{-2}\ sec^{-1}\ sr^{-1}$

   $\theta > 45$ degree muon flux is very small

   But all the events are with higher angle.

3. Normal inelastic neutrino interaction.

decay product of a heavy particle obtained by the interaction of neutrino with rock having life time approximately 10^{-8} sec and with a mass in the range 2 – 5 GeV.

But there is no experimental observation of such particle obtained from such interaction. Because the experiments were made at CERN[5] and Fermilab[6] using neutrino beam to search such type of particles.

[5]H. Faissner et al., Phys.Lett., B**60**, 401 (1976)
[6] A.C. Benvenuti et al, Phys. Rev. Lett. **32**, 125 (1974)

❖ *Reinterpretation of Kolar events.*

- The CDMS II[7] detector recently claimed the observation of 3 dark matter events in the mass range of 8.2 GeV using silicon detector. So recently these are reinterpreted as due to the decay of dark matter particles[8].
- Means in Kolar events we have seen only one hemisphere with mass of around 2 – 5 GeV. After including both the hemisphere its mass will be around 5 – 10 GeV.

- It also explained, why they were not observed in accelerator. Because there they were looking for new particle produced in neutrino interaction.

✓ So the detection of dark matter particle at INO using ICAL is carried by indirectly detecting its decay products in the form of Standard Model particles.

[7] hep-ex: arXiv:1304.4279(2013)
[8] M V N Murthy et al., Pramana **82**, 609 (2014)

❖ *Assumptions for the DMP simulation in ICAL*

- For the simulation it is considered that the DMP decay to only lepton pairs.

  ❖ $\chi \rightarrow l^{+} + l^{-} \quad (l = e, \mu, \tau)$

- All lepton channels are considered separately with 100% branching ratio (B).

- Since the DMPs are non-relativistic, it is assumed that they are at rest. So the decay will be isotropic.

- So their decay is simple two body decay processes, where the energy of the daughter particle is obtained by using the mass of the DMP (M) and the daughter particle mass (m).

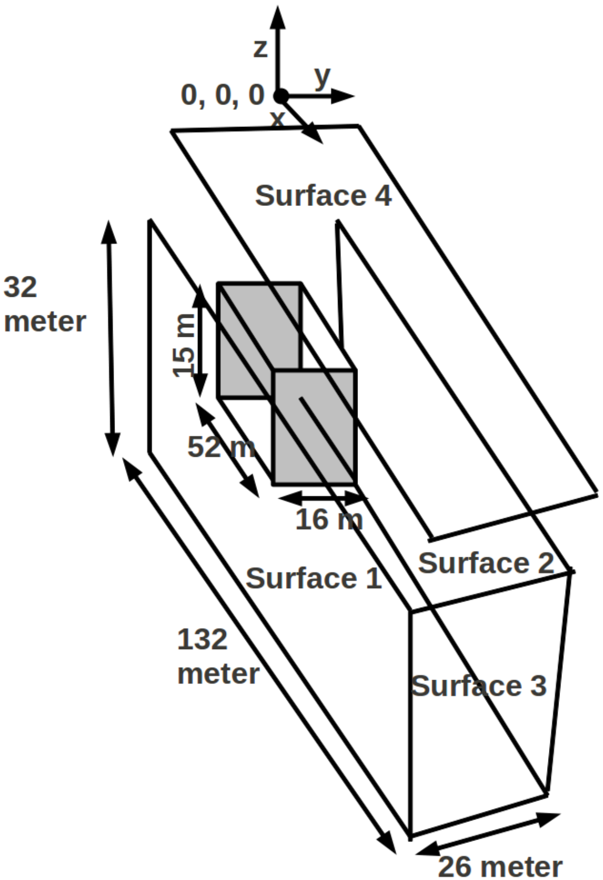
- For a particle anti-particle pair their mass will be same.

  ❖ $|P_1| = |P_2| = \frac{1}{2M}\sqrt{M^4 + 2m^4 - 4m^2(M^2+1)}$

✓ The DMP is present every where. So the simulation is carried whole over the ICAL cavern. To detect all the decay products of the DMP few additional detectors are used in addition to the ICAL detector.

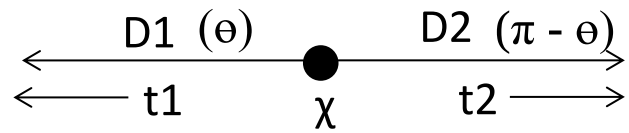
The detector for DMP Decay Study

- The ICAL cavern size is 132 m x 26 m x 32 m. The three modules of ICAL will occupy only 52 m x 16 m x 15 m. So the rest of the place can be used for DMP detector installation.
- Considering ICAL starting from one end of the cavern, as shown in Fig surface 1, surface 2, surface 3 and surface 4 are the scintillator detectors (SDs) lining the walls of the cavern.
- One layer is used in simulation for each surface of thickness 4 cm.
- The scintillator lining on top will also act as cosmic ray veto if a few layers can be used.
- If 2 m x 2m RPC is used instead of scintillator, then total 3000 are needed for a single layer on each surface. This is 10 times less than that for the ICAL, where around 30, 000 RPCs are used.



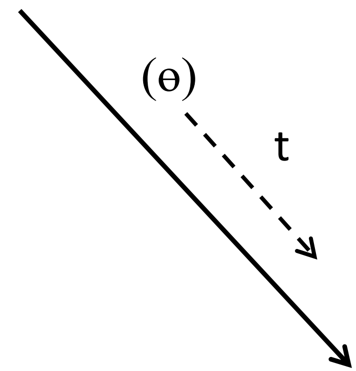
▪ *DMP decay simulation at INO*

- Two events are started from a single vertex with an opposite in direction.
- $\cos\theta$ and ϕ are smeared uniformly due to the isotropic decay nature of DMP.
- The mass of DMP is taken as input. DMP mass is started from 1 GeV to 50 GeV with a mass bin of 1 GeV.
- A sample of 5,000 pairs of events are used for each mass bin.



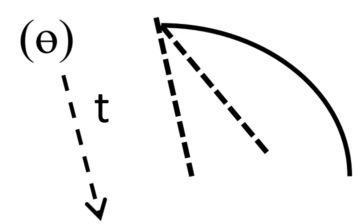
DMP

- The simulation is carried in two different region inside the ICAL cavern.



Muon

- ✓ Simulation in AIR region.
- ✓ Simulation inside ICAL
- ✓ Detector acceptance

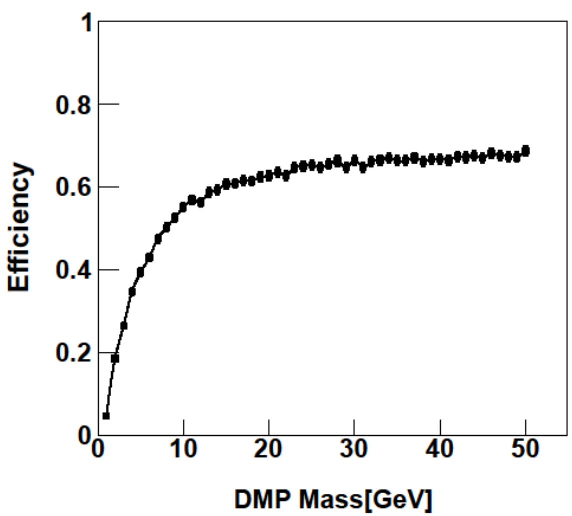


Neutrino

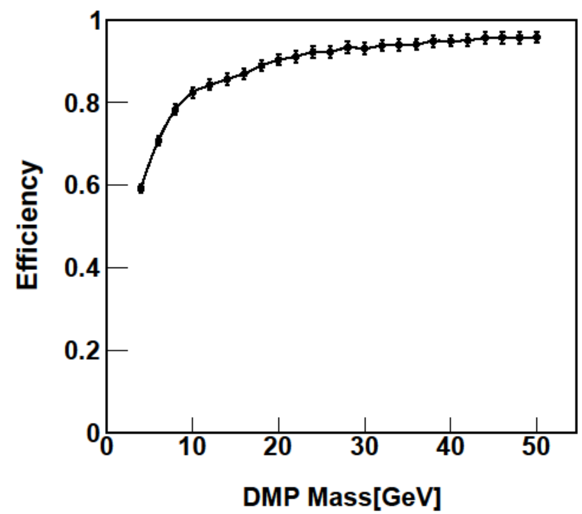
✓ *Simulation in Air*

- The simulation in Air region is carried using GEANT4 simulation toolkit.
- Events are generated whole over the cavern excluding the ICAL region.
- In primary generator action the events are selected in such a way that out of 2 particles, one will enter to ICAL and another one will enter to SD. So at least energy of one will be able to measure using ICAL.
- The events are selected by considering their reconstructed momentum (obtained from ICAL) within 3 times the incident momentum and then reconstructing back the hit position in the scintillator using the reconstructed vertex and direction cosine. This is only for $(\chi \rightarrow \mu^{+} + \mu^{-})$.

$(\chi \rightarrow \mu^{+} + \mu^{-})$



$(\chi \rightarrow \tau^{+} + \tau^{-})$

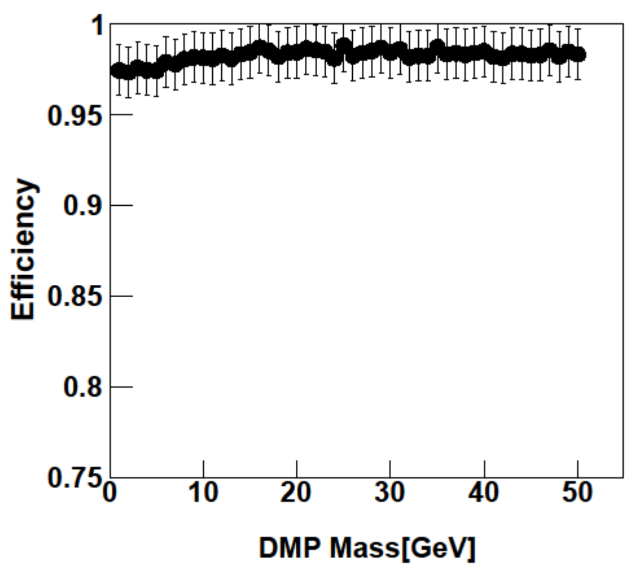


Continue ………………….

- If one layer of SD will be there then it is difficult to distinguish them from cosmic ray muon or a muon produced in the rock proceeding to ICAL.
- So to improve further at least 3–4 layers of detector should be there. From timing it will be able to identify them.
- At least 6–8 layers are needed for good resolution.
- In this case the efficiency will be obtained by separately reconstructing the direction for SD and ICAL and then by reconstructing the vertex.
  - ❖ Time of Flight (TOF) method is used to obtained the fiducial volume of the DMP detector if the vertex will be in air.

✓ Simulation inside ICAL ($\chi \rightarrow \mu^+ + \mu^-$)

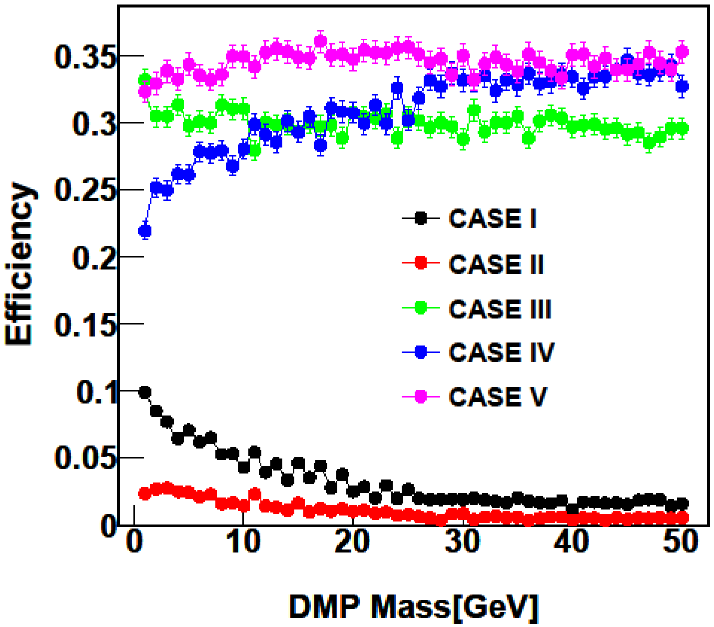
- This problem is not there inside the ICAL. Timing and curvature will be able to separate them from background like cosmic ray muon and neutrino.
- Monte-Carlo simulation using muon look-up table.
- Events are generated inside the ICAL within a volume of $40 \times 14 \times 12\ m^3$
- For each energy and theta bin momentum resolution and direction resolution are used separately for μ^+ and μ^- from muon look-up table.
- The events are selected by measuring invariant mass of two body system and if their difference with incident mass is small, then these events are used for detection efficienc



✓ *DMP detector acceptance* ($\chi \rightarrow \mu^{+} + \mu^{-}$)

- To get detection efficiency the events are generated whole over the ICAL cavern.
- Using GEANT4 simulation toolkit.
- The efficiency plot is obtained for 5 different cases by taking the ratio between the number of events with hit in the respective detector to the total number of incident events by considering DMP decay to muon pairs.

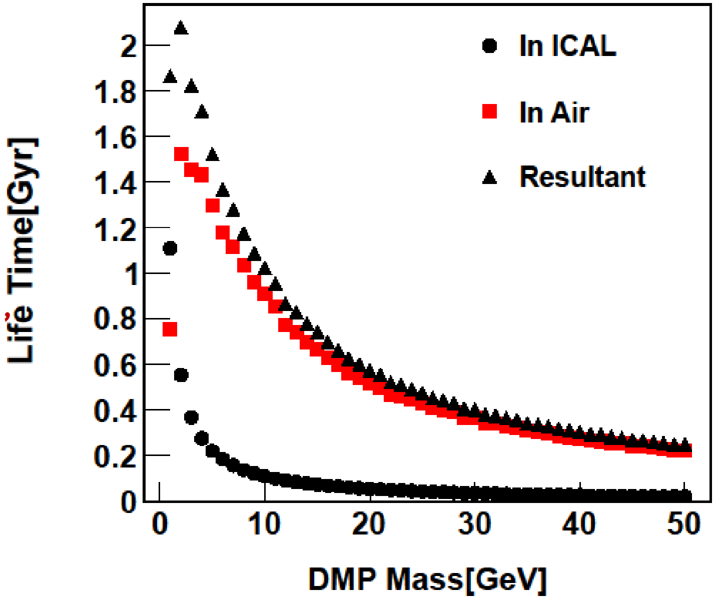
case I: Not detected.
case II: 2 or 1 in ICAL not in SD.
case III: 2 in SD and not in ICAL.
case IV: 1 in ICAL and 2nd one in SD.
case V: 1 in SD and another one is not detected.



Analysis and Results ($\chi \rightarrow \mu^+ + \mu^-$)

Lower limit on the DMP life time :

$$T = \frac{\rho . V . \epsilon . B}{M . R}$$



Where,

ρ is the local dark matter density 0.39 GeV/cc,

V is the detection volume (97344 m^3, 6720 m^3),

ϵ is the detection efficiency,

B is the branching ratio,

M is the DMP mass,

and

R is the decay rate of DMP

- For decay of 0 observed events per year, 2.3 is the upper limit in number of event with 90% C.L. level for 0 back ground.

- R = 2.3/year

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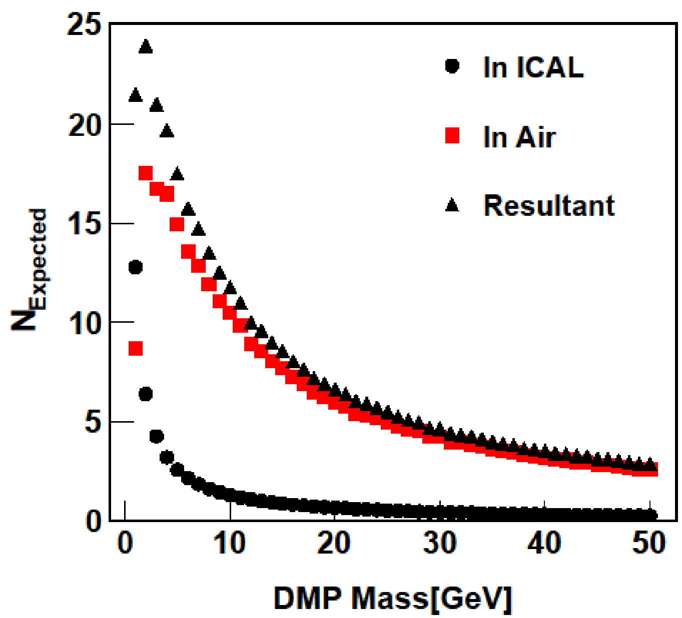
Expected Event Rate :



The number of expected event is obtained by considering the DMP life time is of the order of 2 Gyr (maximum value obtained from the previous plot)

2. Magnetic Monopole (MM)

Overview

- What is Magnetic Monopole?

- 1931 Dirac predicted the possible existence of isolated poles, by considering a charge on the MM and the quantization of an electric charge,

$$eg = n\,\frac{\hbar c}{2\pi} \qquad n = \pm 1, 2, 3, 4\ldots\ldots..$$

- In 1936 M. N. Saha was also derived the same expression, by considering the quantized angular momentum perpendicular to the line joining the point electric charge and MM.

- In 1974 G 't Hooft and Polyakov discovered MM solution of the classical equation of motion for spontaneously broken non-abelian gauge field theories.

$$M_{mm} \geq \frac{M_x}{G}$$

- From cosmological point of view, these are may be created during the big-bang around 10^{-34} sec after the creation of the universe.

Parker,

$$F_M = \begin{cases} 10^{-15}\ cm^2 sec^{-1} sr^{-1} & M \leq 10^{17} GeV \\ 10^{-15}\ \frac{M}{10^{17} GeV}\ cm^2 sec^{-1} sr^{-1} & M \geq 10^{17} GeV \end{cases}$$

Interaction of MM with matter

- $\beta > 10^{-2}$

$$-\frac{dE}{dX} = \frac{4\pi N e^2 g^2}{m_e c^2}\left(\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I_m}\right) - \frac{1}{2} - \frac{\delta_m}{2} - B(|g|) + \frac{K(|g|)}{2}\right)$$

$$B(|g|) = \begin{cases} 0.248 & |g| = 137e/2 \\ 0.672 & |g| = 137e \end{cases}$$

$$K(|g|) = \begin{cases} 0.406 & g = 137e/2 \\ 0.346 & g = 137e \end{cases}$$

- $\beta \leq 10^{-2}$

$$-\frac{dE}{dX} = 20\left(\frac{g}{137e}\right)^2\beta \, \frac{GeV}{gm\ cm^{-2}}$$

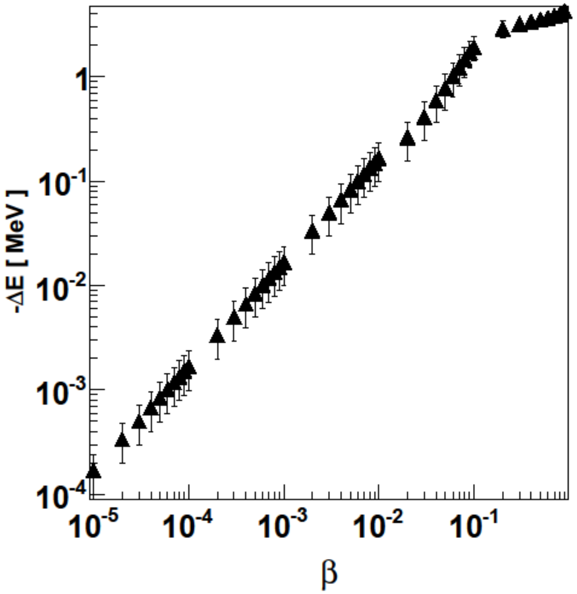


Figure 1 : Energy loss of an MM in 2cm thick RPC gas (Freon, Isobutane, SF_6).

- *Detection Mechanism and detection by other experiments.*

1. Induction Method

   expt. at Stanford University by Cabrera in early 80's

2. The Ionization ($\frac{dE}{dX}$) Method

   MACRO, SLIM, Soudan 2……….

3. The Time of Flight Method

   Most of the gaseous based detector such as MACRO ………

4. Monopole catalysis of Nucleon Decay

   IceCube……..

5. Cerenkov Radiation

   AMANDA, Baikal, Kamiokande…..

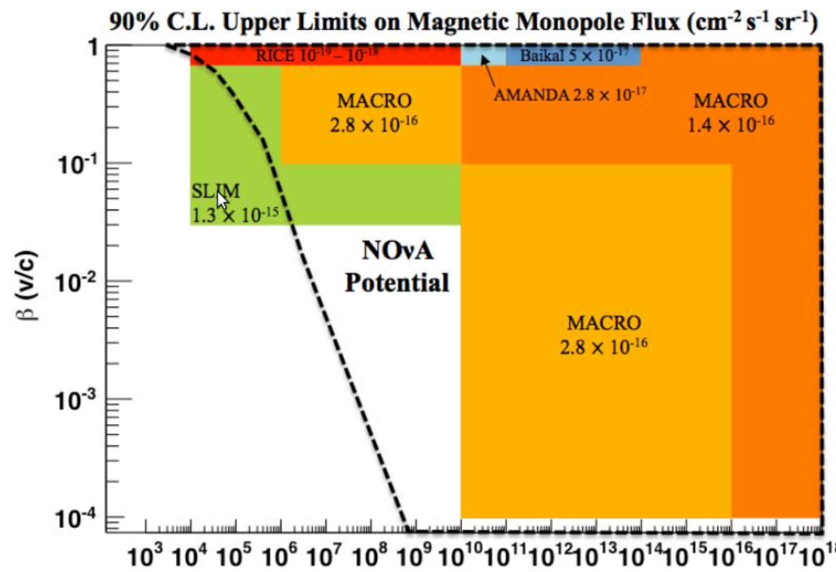


Figure 2: Upper limits on MM flux obtained by different experiments

6. Non Helical path in presence of magnetic field

   Accelerator based experiments such as CDF, Oklahoma…..

▪ *Simulation of the MM for ICAL*

- The MM mass is ranging from 10^5 to 10^{17} GeV and β ranging from 10^{-5} to 0.9.
- The simulation is carried using GEANT4 simulation tool-kit.
- To simulate the MM events for the ICAL at INO
  → rock (2.89 gm/cm^3) + ICAL
- Particles are incident from the surface of the rock, so that they will move through the rock before detection in ICAL.

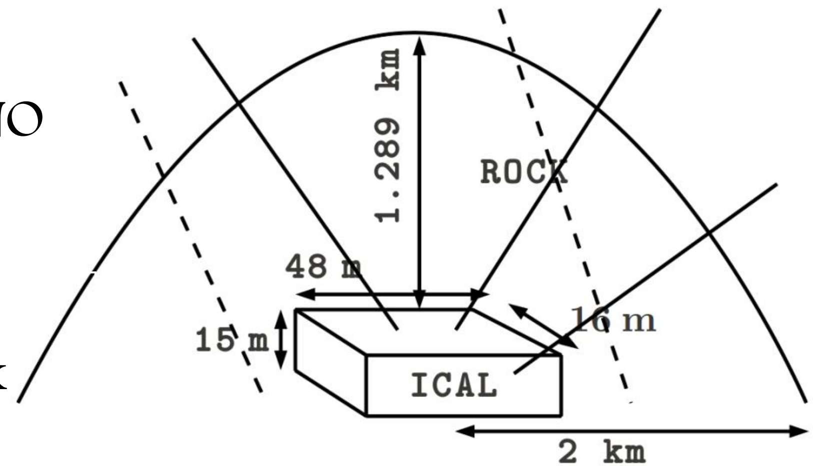


Figure 3: Schematic view of the ICAL detector with rock.

- To simulate an isotropic flux,
  cosθ smeared → $\pi/2 - \pi$ (down-ward)
  φ smeared → 2π
- As ICAL is using RPC, the energy loss of an MM in the gas thickness produce a saturated pulse which only carries "hit" and "time" information.

Analysis and Results

- The time & position information of each hit is used to reconstruct the velocity of a particle (straight line fitting).

✓ Background :

relativistic MM (high energy muons)

sub-relativistic MM (chance coincidence rate)

- The chance coincidence rate can be minimized by choosing minimum number of layers for velocity reconstruction.

✓ Minimum number of layers : 10

✓ Total number of events : 10,000

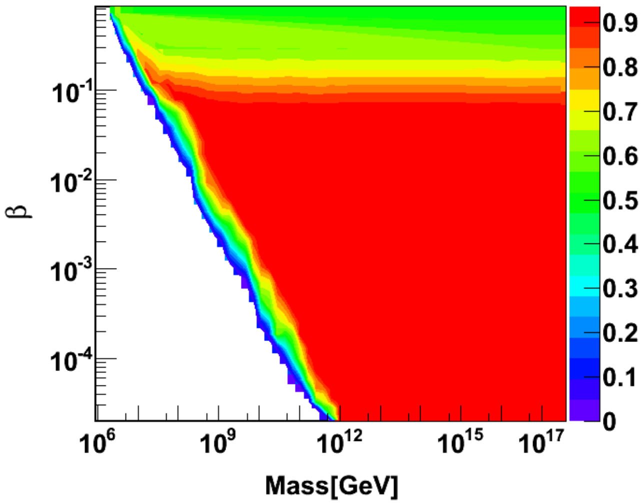


FIG 4 : Efficient region of an MM using ICAL in the mass – β plane.

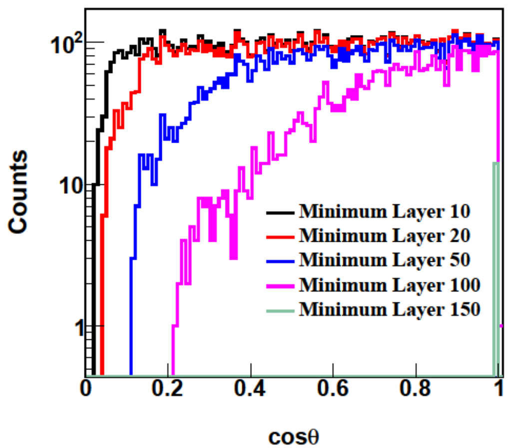


FIG 5 : Reconstructed cosθ distribution for an MM

- Reconstructed cosθ distribution for MM by considering minimum number of layers as 10, 20, 50, 100 & 150 for β reconstruction in ICAL.
- For minimum layers 10 & 20 all of them come from the upper half of the hemisphere.

❖ This efficiency is used to calculate the expected events and the upper bound on the MM flux.

Continue ………………….

Expected Event Rate :

N_{Ex} = $f(cm^{-2}\ sr^{-1}\ sec^{-1})\ A(cm^2)\ \Omega(sr)\ T($

Where f is the MM flux,

A is the area of cross-section of the I

Ω is the solid angle obtained by it,

T is the counting time period,

and

ϵ is the detection efficiency.

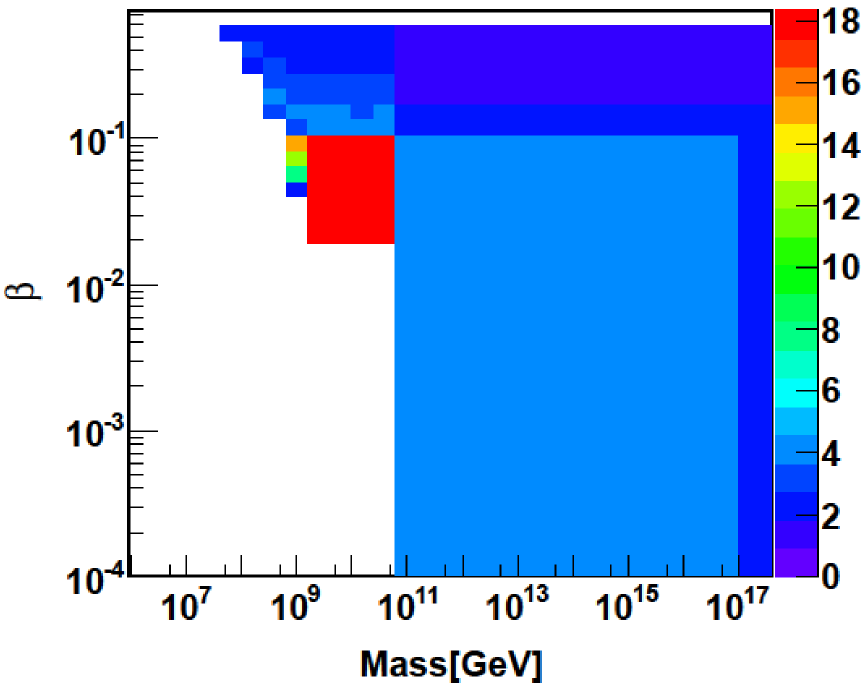


FIG 6 : Expected events obtained for ICAL in 10 years of counting period using flux upper bound from the MACRO and SLIM experiments.

If we choose f= 10^{-15} cm^{-2} sr^{-1} sec^{-1},

A = 16 m X 48 m = 768 m^2,

Ω = 2π, T = 1 Yr,

And ϵ = 1, we get a rate N_{Ex} = 1.5 events per year.

Upper limit in Flux :

$$f_{upper} = \frac{N_{upper}(N_{obs}, N_{BG})}{A(cm^2)\,\Omega(sr)\,T(sec)\,\epsilon}$$

Where,

N_{upper} is the upper limit in observed even

N_{obs} is the number of observed events,

and

N_{BG} is the number of back ground events.

- For zero observed event and zero background N_{upper} is 2.3 at a 90% C.L. using Frequentist method.

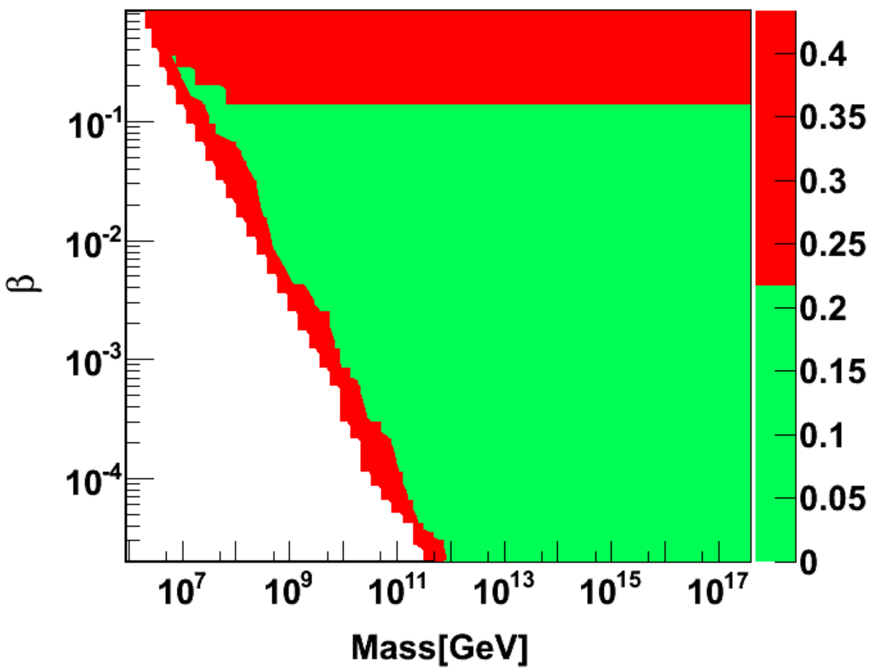


FIG 6 : Upper Limit in Flux obtained by ICAL with 90% C. L. for 10 Yrs in units of 10^{-15} cm^{-2} sr^{-1} sec^{-1}.

- *Simulation of the MM for ICAL engineering module.*

➢ An engineering prototype module of the ICAL is planned to be built over ground at Madurai in the next 2 – 3 years.

➢ Its dimensions 8 m x 8 m x 7.5 m.

➢ Its mass is 1/8th of that of a single ICAL module.

➢ The various parameters of the detector are the same except for the scaling down.

➢ The simulation of an MM for prototype ICAL is similar to the ICAL, only that the events are generated at a height of 10 km atmosphere from the top surface of the detector as it is on the surface.

✓ Background : cosmic ray muons

✓ Above the surface there is the possibility of covering the lower mass region which is not possible for the underground ICAL due to the energy loss of the MM in around 1 km rock cover.

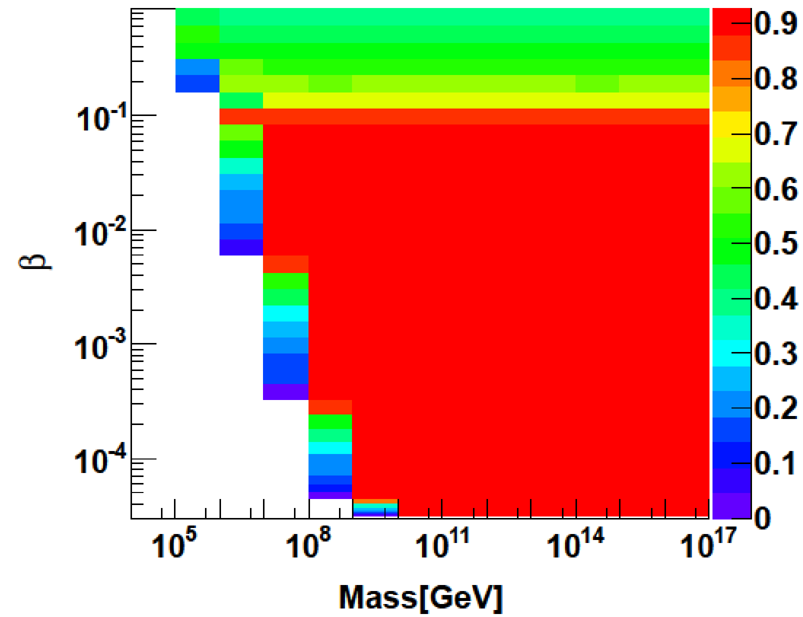


FIG 7 : The ICAL prototype detection efficiency for an MM in its mass – β plane.

Summary

- Like other underground experiments the Iron Calorimeter at INO has also sensitive to new physics in addition to neutrino physics.
- The ICAL will not only clarify these Kolar events, it will also be able to put the limit on the life time of DMP with lower mass.
- As we saw in the previous slides we would expect more Kolar events than KGF as the detector size is larger than KGF detectors.
- In another aspect due to its large size it will also detect Magnetic Monopole and will be able to put limit on the flux of it for intermediate and GUT mass with sub-relativistic velocity.

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Thank You