Ultra High Energy Muons Analysis at INO-ICAL Using Pair-Meter Techniques:

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Working With

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Outline :

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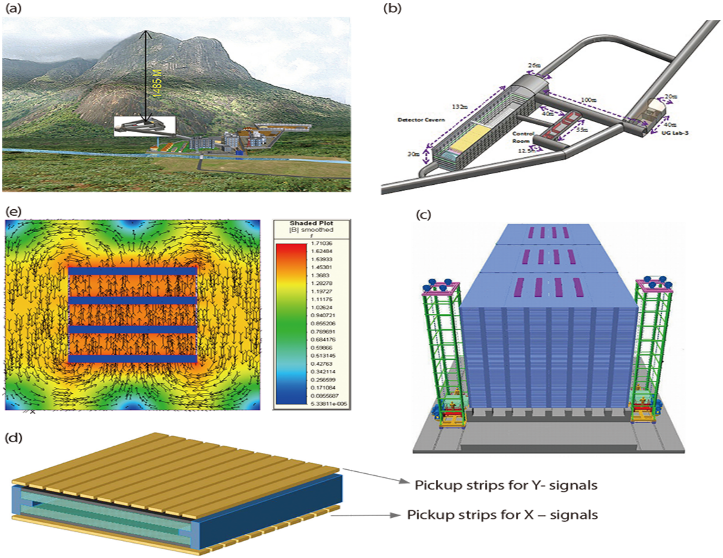
- Muons Track at ICAL in Low and High energy Range.
- Pair Meter Techniques.
- Pair Production Cross Section.
- Average number of Burst Calculation Above a threshold.
- CCFR Detector.
- Penetration Depth of electron in Iron Plates.
- Advantage of Pair Meter Techniques for Cosmic Rays Analysis.
- Muons Burst in Iron Plate for various Energy.
- Conclusion.

Introduction

- Due to the penitrating power of muons, their energy measurement require techniques which differ from those employed for photons, hadrons and electron.
- The existing direct and indirect method of muons spectrometry in experiments at accelerators and in cosmic rays(magnetic spectrometers, transition radiation detectors) involve grave technical problems and fundamental limitations in the energy region $\geq 10^{13}$ eV.
- These disadvantages are absent in the method for estimating the muon energy by energy of secondary cascade formed by muons in thick layers of matter mainly due to the process of direct production of electron-positron pairs.
- Using these techniques we can observe very high energy muons (1 TeV-1000 TeV) in a large mass underground detector operating as a pair meter at INO-ICAL.
- This energy range corresponds to primary cosmic rays approx energies of 50TeV - 50PeV.


(a)
1485 M
(b)
26m
132m
Detector Cavern
100m
40m
55m
Control Room
12.5m
30m
20m
40m
UG Lab-3
(e)
Shaded Plot
|B| smoothed
T
1.71036
1.62484
1.53933
1.45381
1.3683
1.28278
1.19727
1.11175
1.02624
0.940721
0.855206
0.769691
0.684176
0.59866
0.513145
0.42763
0.342114
0.256599
0.171084
0.0855687
5.33811e-006
(c)
(d)
Pickup strips for Y- signals
Pickup strips for X – signals

Momentum Reconstruction Efficiency :

The momentum reconstruction efficiencies(ϵ_{rec}) is defined as the ratio of the number of reconstructed events, n_{rec}, to the total number of generated events, N_{total}. We have

$$\epsilon_{rec} = n_{rec}/N_{total},$$

$$\text{with error, } \delta\epsilon_{rec}=\text{sqrt}(\epsilon_{rec}(1-\epsilon_{rec})/N_{total}) \ .$$

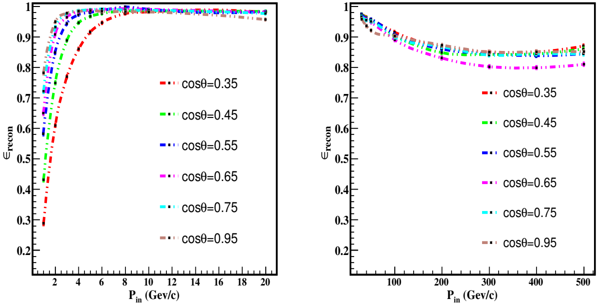


Figure 1 : Momentum reconstruction efficiency as an input momentum for different $\cos\theta$ values at low and high energy.

Relative Charge Identification Efficiency:

Relative charge identification efficiency is defined as the ratio of the number of events with correct charge identification to the total number of reconstructed events,

$$\epsilon_{cid} = \mathrm{n}_{cid}/\mathrm{n}_{rec},$$

$$\text{with error, } \delta\epsilon_{cid} = \mathrm{sqrt}(\epsilon_{rec}(1-\epsilon_{cid})/\mathrm{n}_{rec}).$$

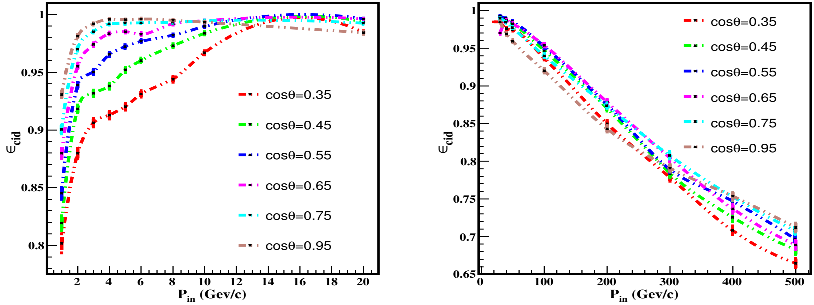


Figure 2 : The relative charge identification efficiency as a function of the input momentum for different $\cos\theta$ values at low and high energy.

Low Energy Muons tracks within the ICAL detector:

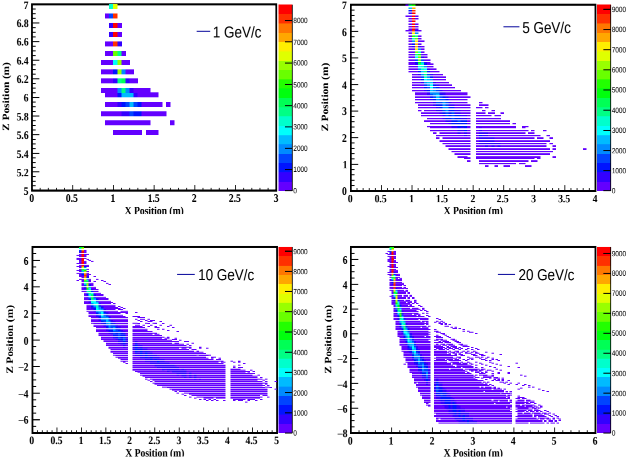


Figure 3 : Low energy muons track stored in X-Z plane of the detector going in the downward direction.

High Energy Muons track within the ICAL detector :

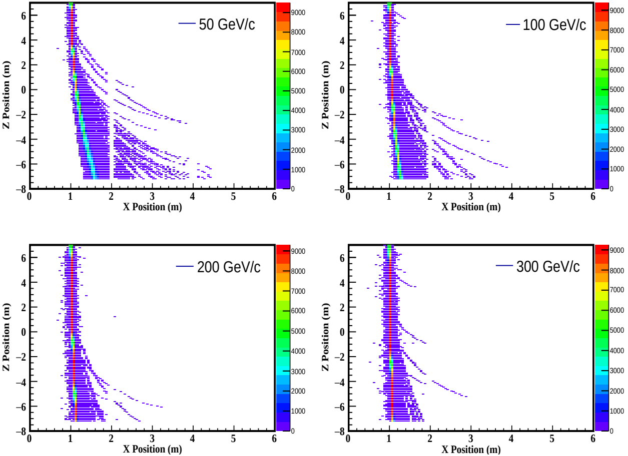


Figure 4 : High energy muons track stored in X-Z plane of the detector going in the downward direction.

ICAL Efficiency and Limits Using Magnetic Field:

- Detector efficiency analysis suggest that momentum reconstruction is 80-90 percent in 100-400 GeV then it becomes constant(fig.-1).
- Charge Id efficiency falls in higher energy region so we will do our analysis till 400GeV, where cid efficiency is 70 percent(fig.-2).
- So one can not use ICAL code for momentum and charge Id analysis above 400 GeV.
- Curvature will be straight for higher energy muons so one can not use curvature method to reconstruct momentum in higher energy region.
- Finally one can do our analysis for surface cosmic muons in the energy range 1600-2000GeV because muons lose around 1600 Gev energy to reach at the detector from rock surface.

Interaction Processes- Theoretical Consideration:

- Excitation and Ionization (Knock-On) :
  Energy is transferred from the muon to an atomic electron via the coulomb fields involved.
- Bremsstrahlung(Braking Radiation) :
  The emission of a photon (γ) as the muon is scattered by the nuclear coulomb field.
- Direct Electron Pair Production :
  The materialization of an electron-positron pair from a virtual γ emission as the muon is scattered by the nuclear coulomb field.
- Photonuclear Interaction:
  One of the virtual photons accompanying the muons interacts strongly with a nucleon in the atom.

Interaction Processes- Theoretical Consideration :

- Whenever a force is applied to a charged particle it is accelerated and classically it must radiate energy in the electromagnetic form.
- Bremsstrahlung occurs when a charged particle passes close to an atomic nucleus and is accelerated by the electric field present and results in the emission of a single photon.
- According to quantum mechanics this emitted phton is either a real photon or a virtual photon which may subsequently materialize as an electron-positron pair.
- The process which produces a single real photon is called the bremsstrahlung process.
- The materialization of a particle pair from the virtual photon is known as direct pair production.

Direct Pair Production:

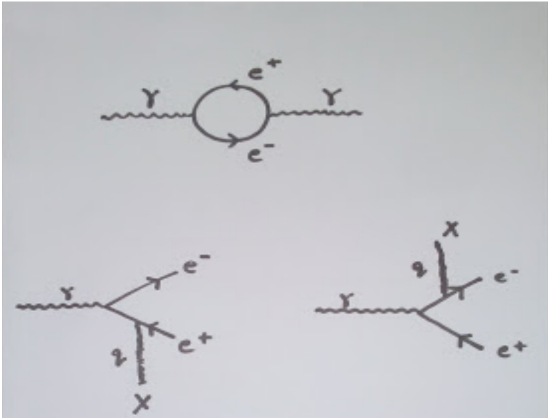


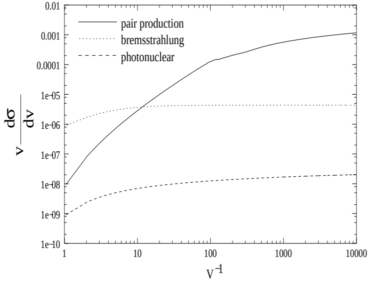
Figure 5 : Diagram of a virtual particle-antiparticle pair and photon pair production of electron.

Pair Meter Techniques:

- Creation of a(e^+,e^-) pair by virtual photon in the coulomb field of the nucleus(for momentum conservation).

  $$\mu + \text{nucleus} \rightarrow \mu + \text{e}$$
- It is one of the most important process for muon interaction.
- At Tev muon energies, pair creation cross section exceeds those of other muon interaction processes in a wide region of energy transfer: $100 \text{ Mev} \leq E_0 \leq 0.1E\mu$
- Average energy loss for pair production increases linearly with muon energy, and in Tev region this process contributes over 50 percent of the total energy loss rate.
- Capability and effectiveness of the pair meter method for high energy muons has been tested and demonstrated by the NuTeV/CCFR collaboration.

Differential Cross Sections[1] for Muon:



- The Cross section for e^+ e^- pair production by a muon with energy E_μ with energy transfer above a threshold E_0 grows as $\ln^2(2m_e\ E_\mu/m_\mu E_0)$ where m_μ and m_e are the muon and electron masses respectively.
- Defining $v=E_0/E_\mu$, above $v^{-1}=10$, this cross section dominates those for other muon energy loss process which generate observable cascades in its passage through dense matter.

Average No. of Burst Calculation[1]:

- The dependence of the pair meter production cross section on E_μ / E_0 then allows one to infer the muon energy by counting the number of interaction cascade M in the detector with energies above a threshold E_0.
- Expression for differential pair production cross section is given by[1]:

$$\mathrm{v}\frac{d\sigma}{dv} \simeq \frac{14\alpha}{9\pi t_0}\ln\left(\frac{km_e E_\mu}{E_0 m_\mu}\right) \qquad (1)$$

- where $\alpha = 1/137$, k $\simeq$1.8 and t_0 is the radiation length(r.l.) of the material , for iron $t_0 = 13.75$ gm/cm^2 .
- The Average number of interaction cascades M above a thereshold E_0 is given by :

$$\mathrm{M}\ (\mathrm{E}_0,\mathrm{E}\mu) = \mathrm{T}t_0\ \sigma(\mathrm{E}_0,\mathrm{E}_\mu) \qquad (2)$$

- where T is thickness of the target and $\sigma(\mathrm{E}_0,\mathrm{E}_\mu)$ is the integrated cross section(in unit of cm^2/gm),

$$\sigma(\mathrm{E}_0,\mathrm{E}_\mu) \simeq \frac{7\alpha}{9\pi t_0}\left(\ln^2\left(\frac{km_e E_\mu}{E_0 m_\mu}\right)+\mathrm{C}\right) \qquad (3)$$

where C $\simeq$ 1.4.

INO-ICAL detector Dimentions:

INO-ICAL	
No. of Modules	3
Modules dimention	16m X 16m X 14.5m
Detector dimention	48m X 16m X 14.5m
No. of Layers	151
Iron Plates thickness	5.6cm
Gap for RPC trays	4.0cm
Magnetic Field	1.5Tesla

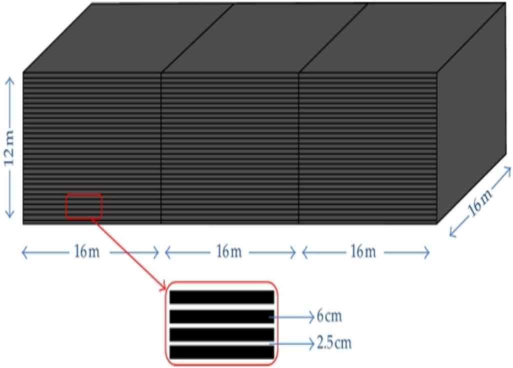
A muon traversing a 151X5.6 $\simeq$ 845cm.

In this detector corresponds to a path-length of $\simeq$ 480 r.l.

We can assume a average path-length for a muon of 450r.l.

We can calculate the number of cascades produced by it using equation (2).

Schematic view of INO-ICAL Detector:



CCFR Detector

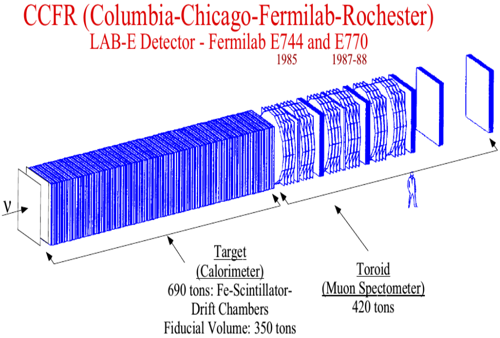
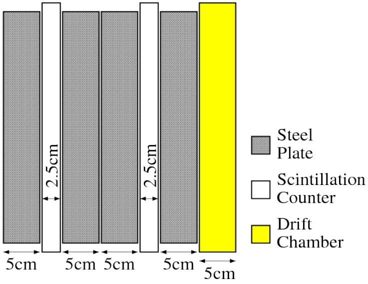


Fig. 2. The CCFR neutrino detector: an iron-scintillator target calorimeter followed by an iron toroidal muon spectrometer



Counting the burst using Pair Meter:

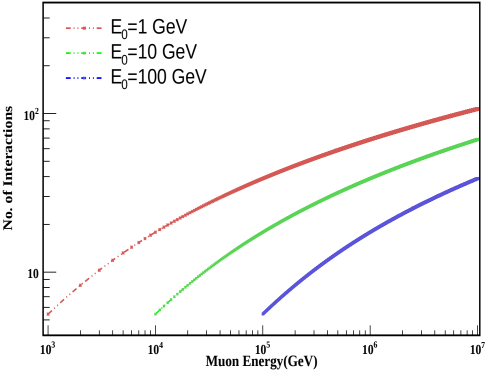
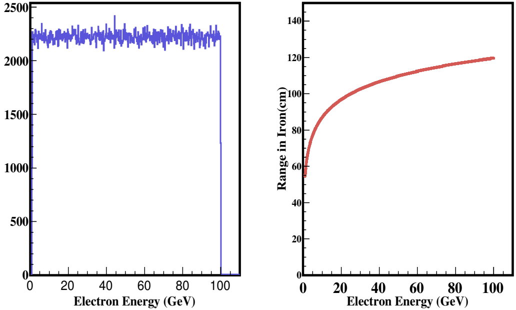


Figure 6 : Average number of cascades above a threshold E_0 vs muon energy for E_0=1 GeV and 10 GeV, with T fixed to 450 r.l.

Penetration Depth of Electron in Iron Plates:



- E=E_0 e^{-x/x_0} where x is distance travelled in the iron plate and x_0 is the Radiation length.

Operating ICAL using Curvature Method:

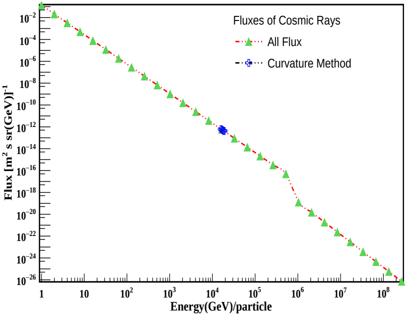


Figure 7 : Primary cosmic flux vs Energy of Primary particle and possibility for ICAL to cover the enrgy spectrum using Curvature Method.

- Energy Spectrum for Cosmic rays:
  $\phi \simeq \mathrm{KE}^{-\alpha}$ $\alpha \simeq 2.7$
  KNEE(3PeV) $\alpha : 2.7 \rightarrow 3$

Operating ICAL using Pair Meter Techniques:

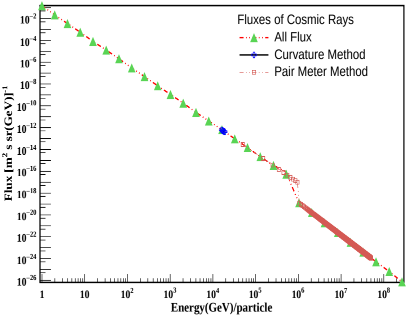


Figure 8 : Primary Cosmic Rays flux vs energy of primary particle and possiblity for ICAL to cover the energy spectrum using Pair Meter Technique.

- Energy Spectrum for Cosmic rays:
  $\phi \simeq \mathrm{KE}^{-\alpha}$ $\alpha \simeq 2.7$
  KNEE(3PeV) $\alpha : 2.7 \rightarrow 3$

10 TeV Muon Burst in Iron Plates:

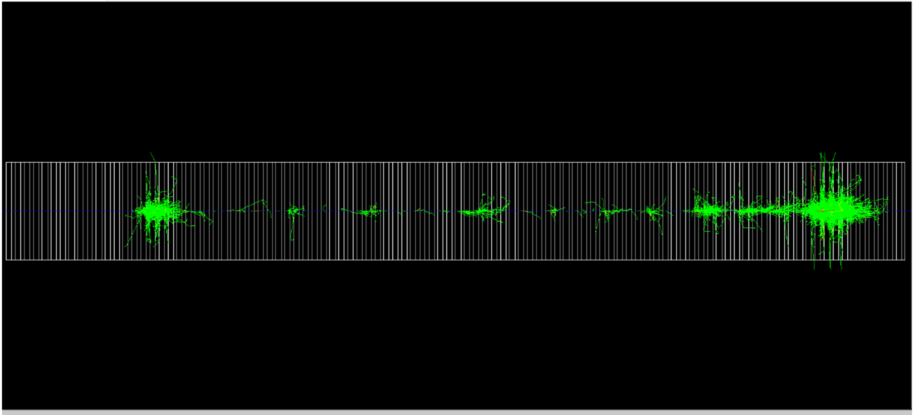


Figure 9 : Cascade Generation in the Iron Chamber , blue line(muon) and green line (electron and positron).

100 TeV Muon Burst in Iron Plates:

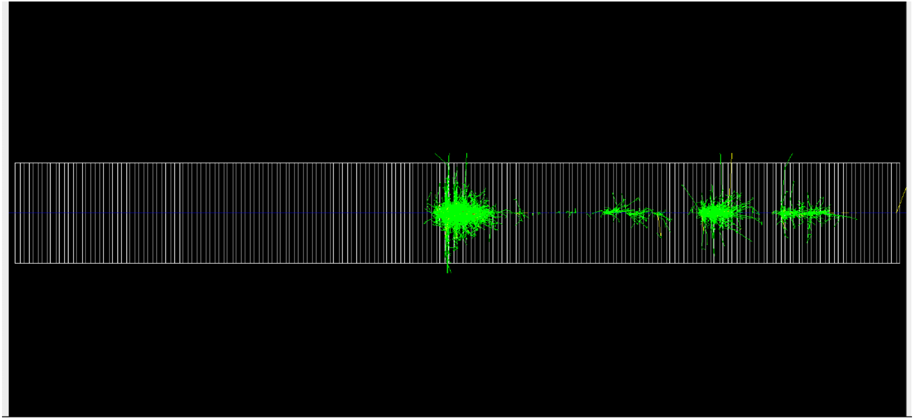


Figure 10 : Cascade Generation in the Iron Chamber , blue line(muon) and green line (electron and positron).

500 TeV Muon Burst in Iron Plates:

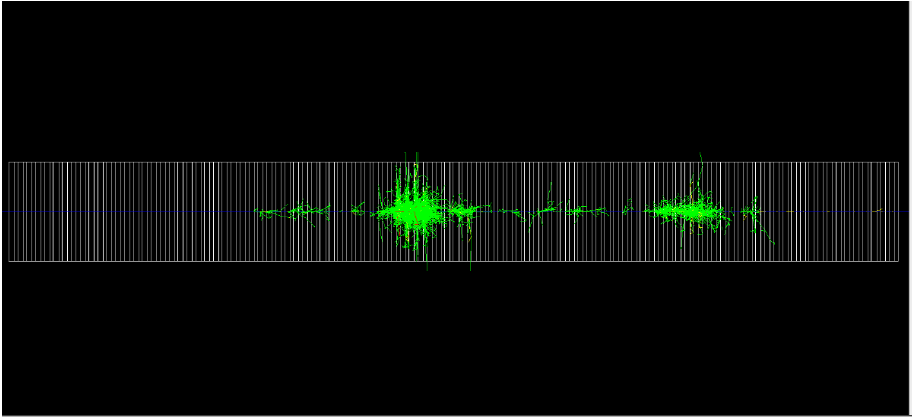


Figure 11 : Cascade Generation in the Iron Chamber , blue line(muon) and green line (electron and positron).

Summary and Conclusions:

- Underground Muon energy measurement for an energy range of E_μ of 1-1000 TeV are possible with a 50 kTon INO-ICAL detector.
- This will enable a better handle on the very high energy muon fluxes between several TeV to about 5 PeV, and consequently illuminate our estimate of the background muon and neutrino fluxes for ultra high energy neutrino detectors.
- The observable muon energy range discussed in our results also corresponds to a range of 50TeV - 50PeV in primary cosmic ray energies. This range is crucial to an understanding of the origin of knee and our calculations demonstrate the feasibility and potential resulting from muon measurement for a better understanding of the origin of the knee.

References :

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THANK YOU