Probing VHE Cosmic Ray Muons

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- These studies would be very useful for all UHE neutrino telescopes like AMANDA, ICECUBE etc, since muons and neutrinos at these energies constitute their most important background.
- There is great variation in QCD predictions of the prompt neutrino and muon fluxes, due to gluon structure function and other uncertainties at low x. Actual measurements of the muon flux would be very useful.

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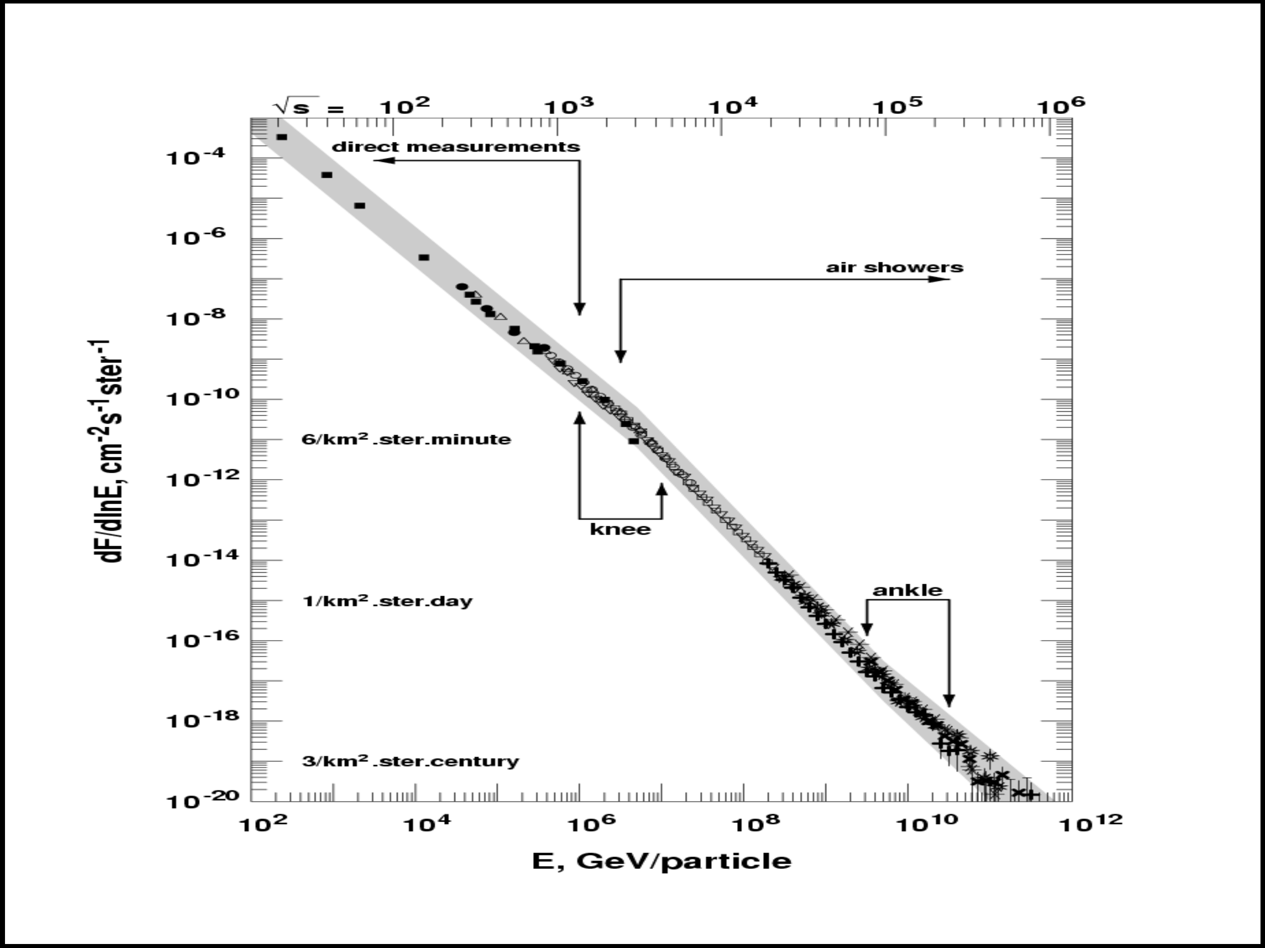
- Muon and neutrino fluxes from CR are strongly co-related, hence measurements of one allow inference of the other.

The CR Spectrum... . . .



The CR Spectrum.......

- A steepening of the spectrum occurs around $E \approx 5 \times 10^6$ GeV, $i.e.$ the index γ describing the power-law behaviour of the differential flux, $dN/dE \sim E^\gamma$, changes from $\gamma \approx -2.7$ to $\gamma \approx -3.1$; leading to the feature called the 'knee'.

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- Muon energy measurement methods which work well in the GeV range (magnetic spectrometry or measuring Cerenkov radiation) are rendered impractical in the TeV range primarily due to requirements of size imposed by the combination of high energies and a steeply falling spectrum.

The Pair Meter method (contd)

- It is necessary to use a new (*i.e* old, Russian) technique the pair meter method, possible in a large, dense matter detector (large mass iron calorimeter). (*Alekseev and Zatsepin (1960), Kokoulin and Petrukhin (1990)*).

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- Measurements of the VHE muon energy spectrum in the surface energy range $2 \times 10^3 - 5 \times 10^6$ GeV,the feasibility of which we discuss here, will correspond to *primary cosmic ray energies of* $2 \times 10^4 - 5 \times 10^7$ *GeV* which cover the knee region) .

The Pair-Meter Technique

- The pair meter technique skirts some of these difficulties of conventional muon sprectrometers by relying on a somewhat indirect method, *i.e.* the measurements of the energy and frequency of electron-positron pair cascades produced by the passage of a high energy muon in dense matter.

The Pair-Meter Technique

- 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 $ln^2(2m_eE_\mu/m_\mu E_0)$, where m_μ and m_e are the muon and electron masses respectively.

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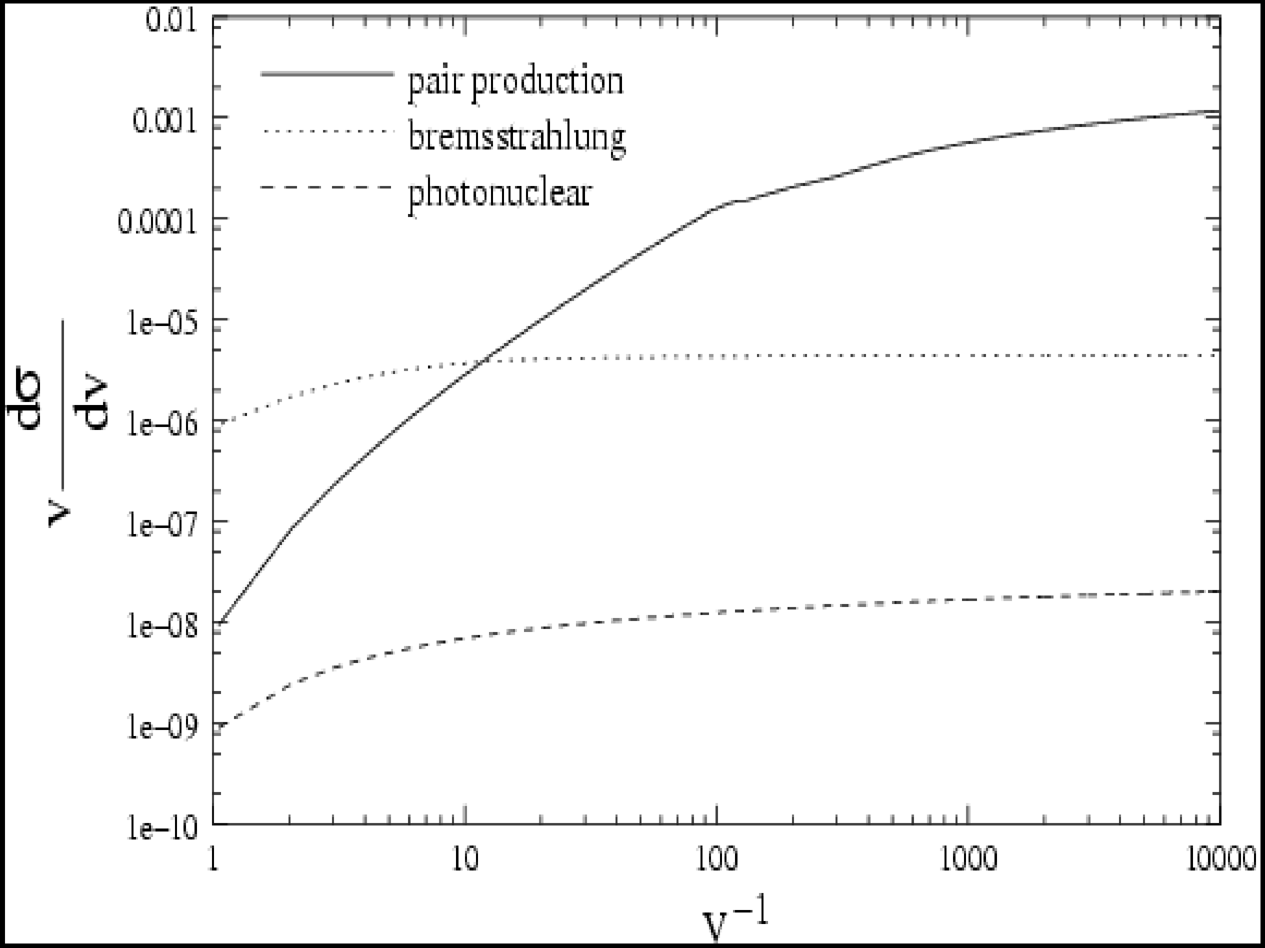
- Defining $v = E_0/E_\mu$, above $v^{-1} = 10$, this cross section dominates those for other muon energy loss processes which generate observable cascades in its passage through dense matter, *e.g.* $\mu - N$ inelastic scattering and bremstrahlung emission.

The Pair Production Cross-Section . . .



The Pair Meter Method.....

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- The dependance of the pair production cross section on E_μ/E_0 then allows one to infer the muon energy by counting the number of interaction cascades N in the detector with energies above a threshold E_0.

The Pair Meter Method.....

- One next needs to make some approximations;

$$v = \frac{E_0}{E_\mu} \ll \frac{2m_e}{m_\mu}$$

and

$$E_0 \gg 2m_e 189\sqrt{e}Z^{-1/3} \simeq 0.3Z^{-1/3}GeV,$$

(Z=atomic number= 26, for iron) both of which are valid for the choice of E_0, E_μ for which we present results below,

The Pair Meter Method.....

- This simplifies the cross-section to

$$v\frac{d\sigma}{dv} \simeq \frac{14\alpha}{9\pi t_0} ln\left(\frac{\kappa m_e E_\mu}{\epsilon m_\mu}\right) \ , \qquad (1)$$

where $\alpha = 1/137$ and $\kappa \simeq 1.8$. t_0 is the radiation lenth (r.l) which is given by

$$t_0 = \left(\frac{4Z(Z+1)}{A_W}\ \alpha r_0^2 N_A\ ln(189 Z^{-1/3})\right)^{-1} \ . \qquad (2)$$

Here A_W is the atomic weight, r_0 is the classical electron radius and N_A the Avogadro number. For iron, this gives $t_0 = 13.75$ gm/cm^2.

The Pair Meter Method.....

- The average number of interaction cascades M above a threshold E_0 for $v \leq 10^{-3}$ is given by

$$M(E_0, E_\mu) = T\sigma(E_0, E_\mu) \ , \tag{3}$$

where T is the thickness of the target in units of t_0 and $\sigma(E_0, E_\mu)$ is the integrated cross section,

$$\sigma(E_0, E_\mu) \simeq \frac{7\alpha}{9\pi t_0}\left(ln^2\left(\frac{\kappa m_e E}{E_0 m_\mu}\right) + C\right) \ , \tag{4}$$

where $C \simeq 1.4.$

The Pair Meter Method.....

- The pair-meter technique has been tested by the Nu TeV/CCFR Collaboration for CR muons in the few TeV range and its feasibility demonstrated in a 690 ton unmagnetized detector. For a large iron detector (≥ 5 kT) they predict an energy resolution of 26% from their results. (*"Tests of a Calorimetric....NU TeV/CCFR Collab; Univ of Rochester Preprint 1469*).

The Pair meter.....

- We now present calculations performed for a 50 kT Iron calorimeter. The dimensions of a detector of this type would correspond to (approx) 15 m $\times$ 15 m $\times$ 45 m. A muon traversing a 20 m path in this detector corresponds to a path-length of ~ 1145 r.l.

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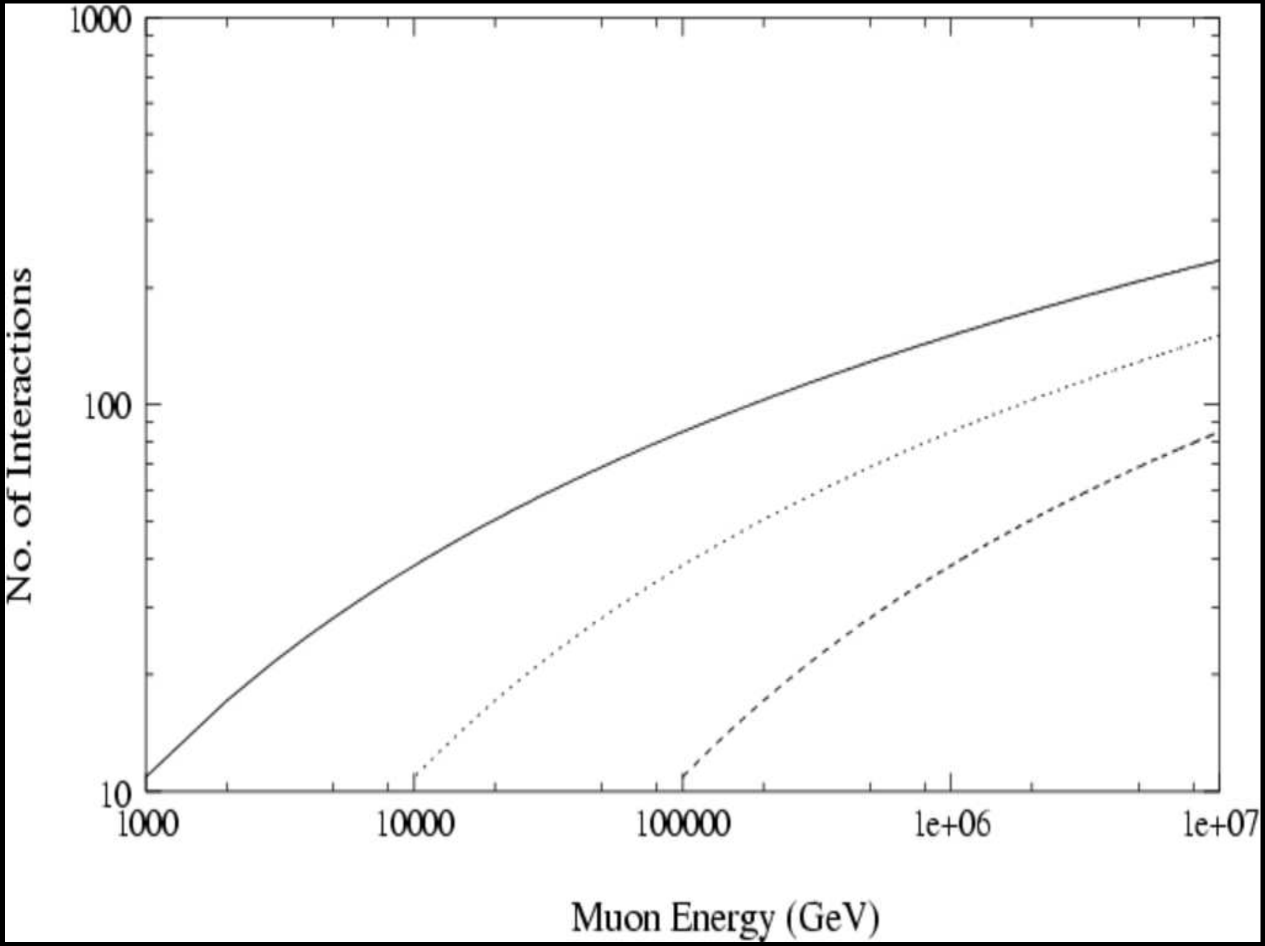
- In what follows, we assume a (conservative) "average" path-length of 1000 r.l for the typical muon and calulate the number of observable cascades produced by it, for different cascade thresholds and muon energies.

Cascade Production by Muons . . .



The Pair Meter Method.....

- In order to get a feel for the numbers, we note that this leads to a $E_\mu = 100$ TeV muon generating approximately 40 cascades, each of energy greater than $E_0 = 10$ GeV and 10 cascades with energy in excess of 100 GeV. By counting the cascades for several choices of thresholds for a traversing muon, one obtains a reliable estimate of its energy. It is also relevant to remark here that the relative energy measurement error, $\delta E_\mu / E_\mu$ in the pair meter is given by

$$\delta E_\mu / E_\mu = \sqrt{\frac{9\pi}{28\alpha T}} \simeq \sqrt{\frac{137}{T}} . \quad (5)$$

The Surface Muon Energy

- It is important to co-relate the inferred muon energies in an underground detector to their surface energies,

$$\left\langle \frac{dE}{dX} \right\rangle = -\alpha - \beta E \ , \qquad (6)$$

where α parametrizes the contribution from ionization of muons and β encapsulates the contribution from bremsstrahlung, pair production and photonuclear processes.

The Muon Surface Energy.....

- The relation between initial energy E_μ^s and degarded energy of muon E_μ after travelling a distance X as,

$$E_\mu^s = \left(E_\mu + \frac{\alpha}{\beta} \right) e^{\beta X} - \frac{\alpha}{\beta} \; . \tag{7}$$

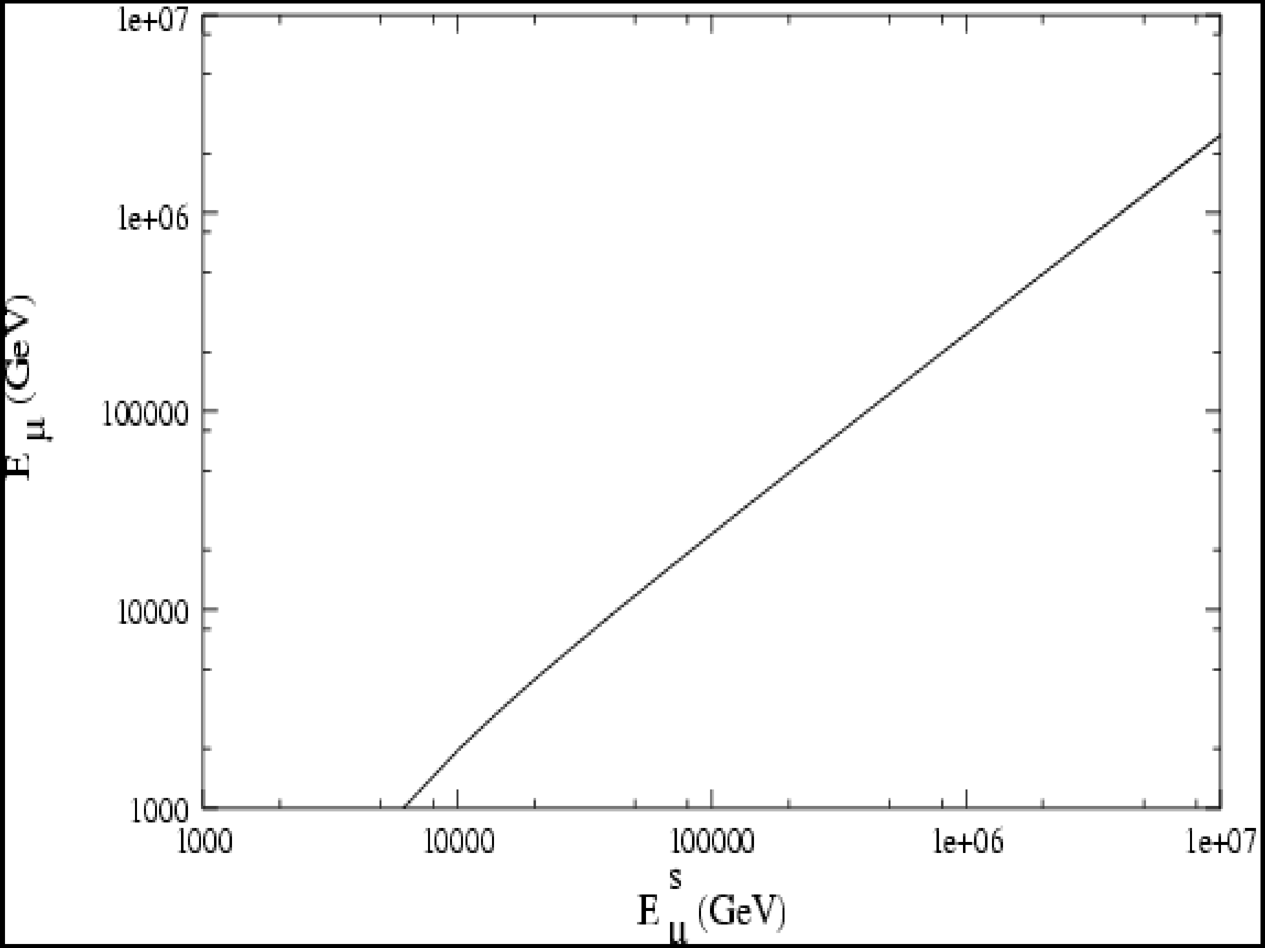
The Muon Surface Energy.....

- Also,the differential muon flux at a depth X is given by,

$$\frac{dN}{dE_\mu} = \frac{dN}{dE_\mu^s} e^{\beta X} \ . \tag{8}$$

where $\frac{dN}{dE_\mu^s}$ is the initial muon flux with surface muon energy E_μ^s.

Cascade Production by Muons . . .



Muon Fluxes

- Muon fluxes at these energies are very uncertain. We have used a set of relatively conservative fluxes; there is wide variation even amongst them. In the TIG flux, the conventional and prompt fluxes have been parametrized as

$$\frac{dN}{dE} = \frac{N_0 E^{-\gamma-1}}{1 + AE} \tag{9}$$

for $E < E_a$. and as

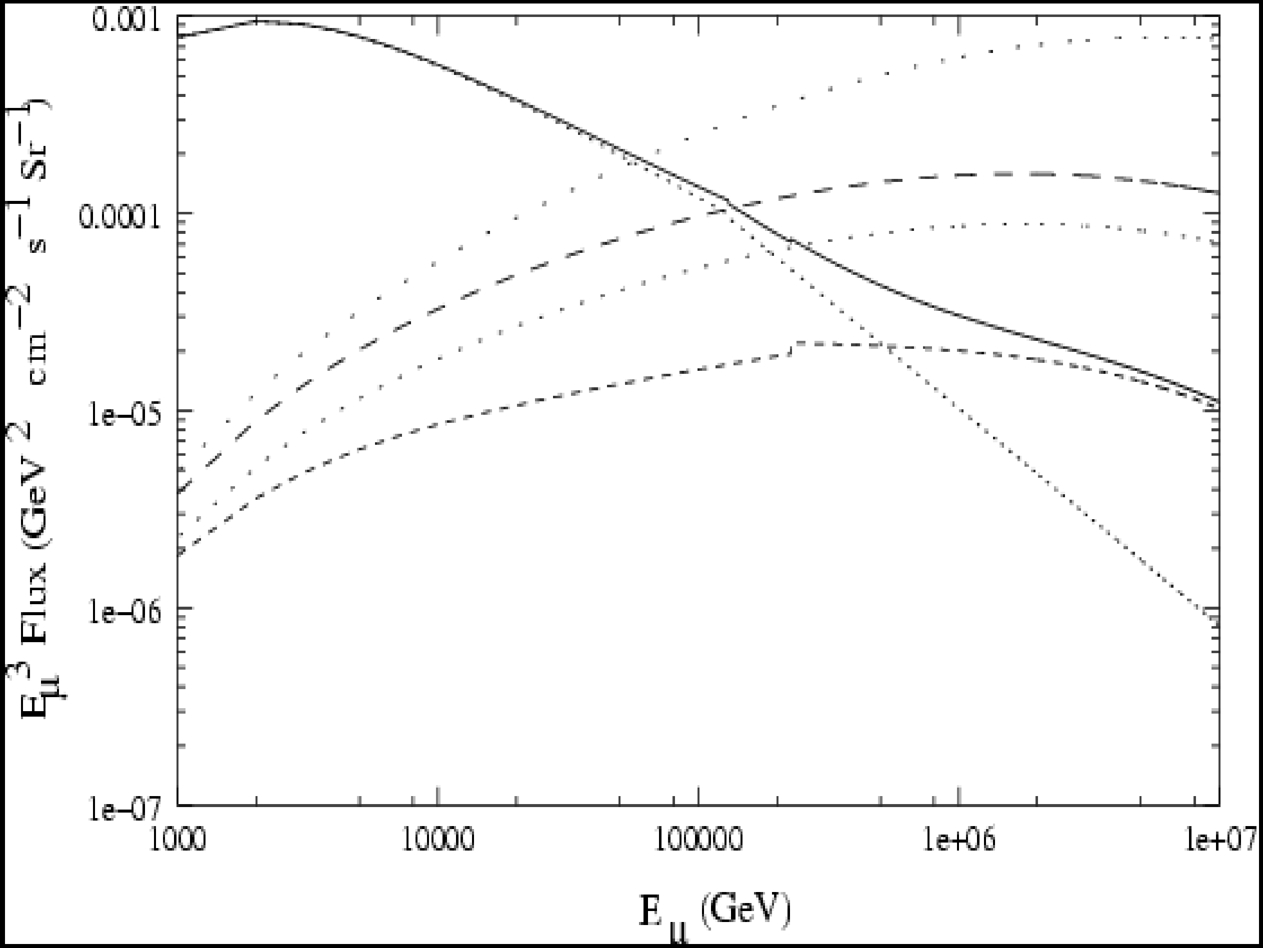
$$\frac{dN}{dE} = \frac{N_0' E^{-\gamma'-1}}{1 + AE} \tag{10}$$

for $E > E_a$.

Muon Fluxes

- For the conventional muon flux $N_0 = 0.2$, $N_0' = 0.2$, $\gamma = 1.74$, $\gamma' = 2.1$, $E_a = 5.3 \times 10^5$, $A = 0.007$. For the prompt muon flux $N_0 = 1.4 \times 10^{-5}$, $N_0' = 4.3 \times 10^{-4}$, $\gamma = 1.77$, $\gamma' = 2.01$, $E_a = 9.2 \times 10^5$, $A = 2.8 \times 10^{-8}$.

Flux vs. Entering Muon enegy . . .



Entering Muons/50 kT/5 yr/sr

	Number of muons per solid angle entering the detecto					
$E_\mu(TeV)$	conv+TIG	conv	TIG	PRS1	PRS2	PR
1	1.035×10^7	1.03×10^7	37461	55482	95489	13
10	52486	51282	1204	2952	5341	10
50	770	696	74	236	431	11
100	127	106	21	73	134	38
200	22	16	6	22	40	12
300	8	5	3	11	19	66
400	4	2	2	6	11	41

Cascades above ϵ_0 GeV/50 kT/5 yr/sr

		Number of events for different			
$E_\mu(TeV)$	$E^s_\mu(TeV)$	$\epsilon_0 = 5GeV$	$\epsilon_0 = 10GeV$	$\epsilon_0 = 20GeV$	ϵ_0
1	6.1	4.99×10^7			
10	40.26	1.13×10^6	755971		
20	83.16	262189	186575	124441	
50	205	34764	26235	18885	11
100	407.58	7434	5803	4363	27
200	813	1630	1307	1017	69
300	1218	686	558	442	30

Summary and Conclusions

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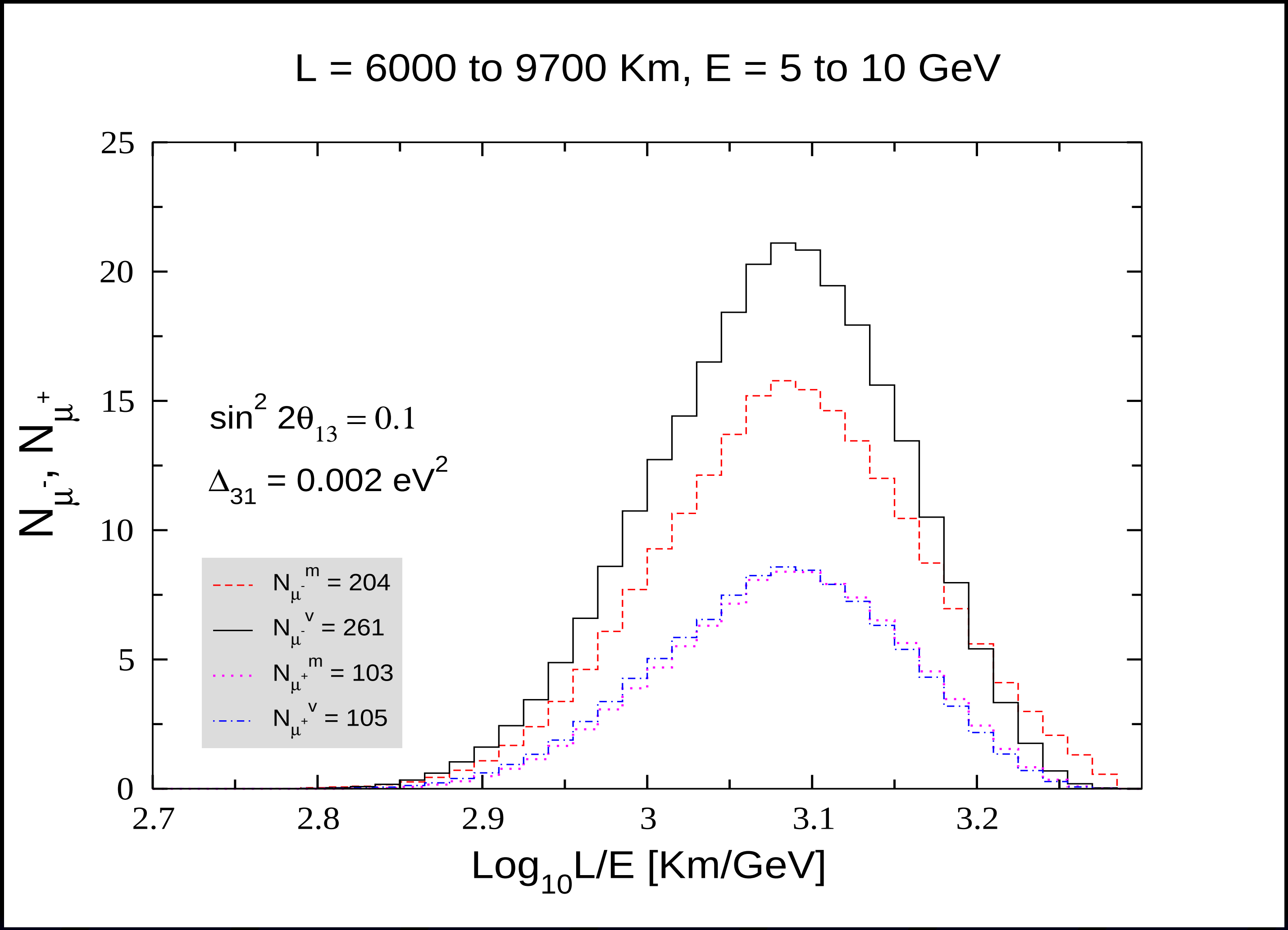
- Underground muon energy measurements for an energy range of E_μ of 1-500 TeV are possible with a 50 kT iron detector running for 5 yrs.
- This will enable a better handle on the very high energy muon fluxes between several TeV to about 2.5 PeV, and consequently illuminate our estimates of the background muon and neutrino fluxes for ultra high energy neutrino detectors and lessen present uncertainties in charm production models.

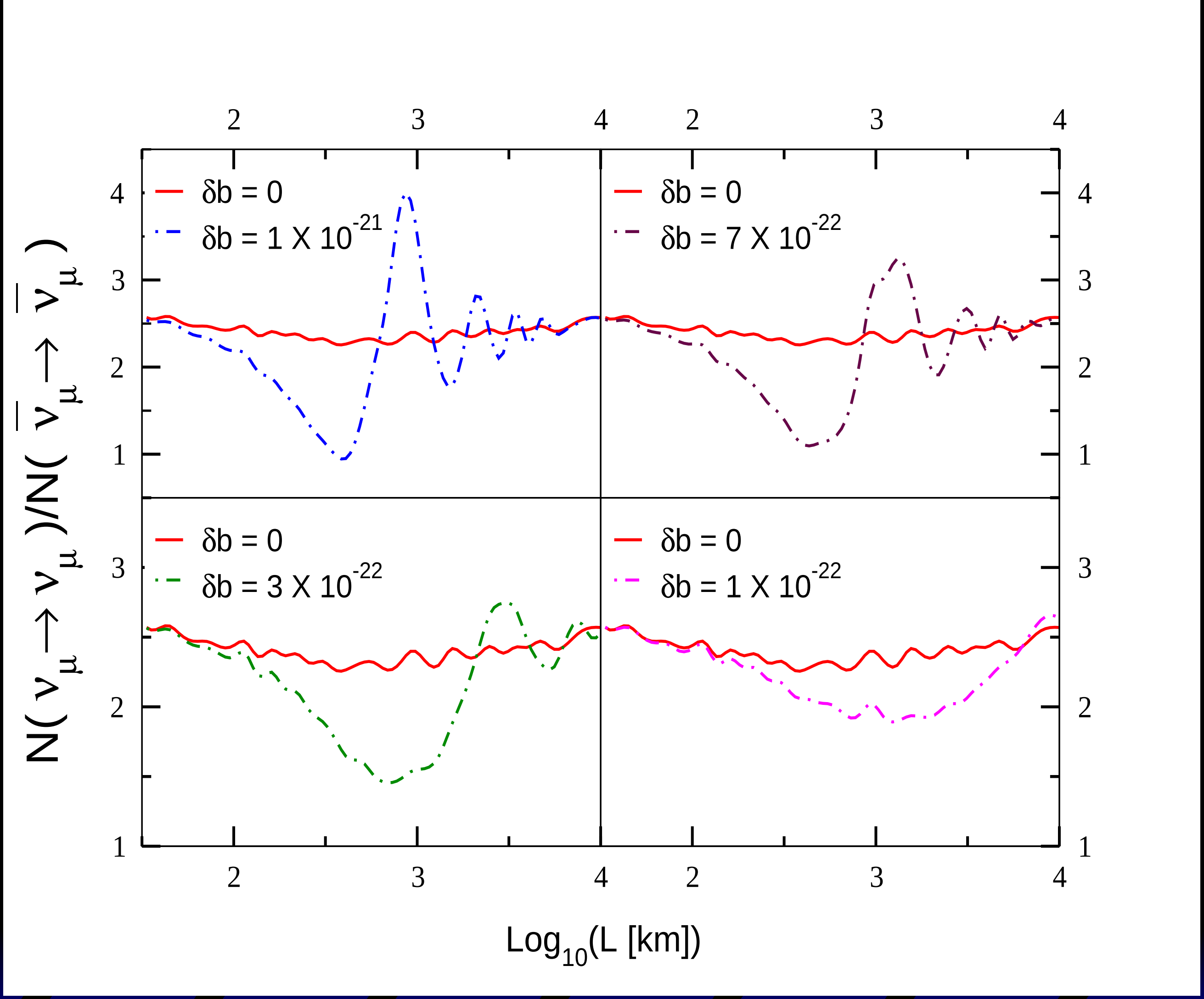
Summary and Conclusions

- The observable muon energy range discussed in our results also corresponds to a range of 50 TeV to 25 PeV 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 measurements for a better understanding of the origin of the knee.

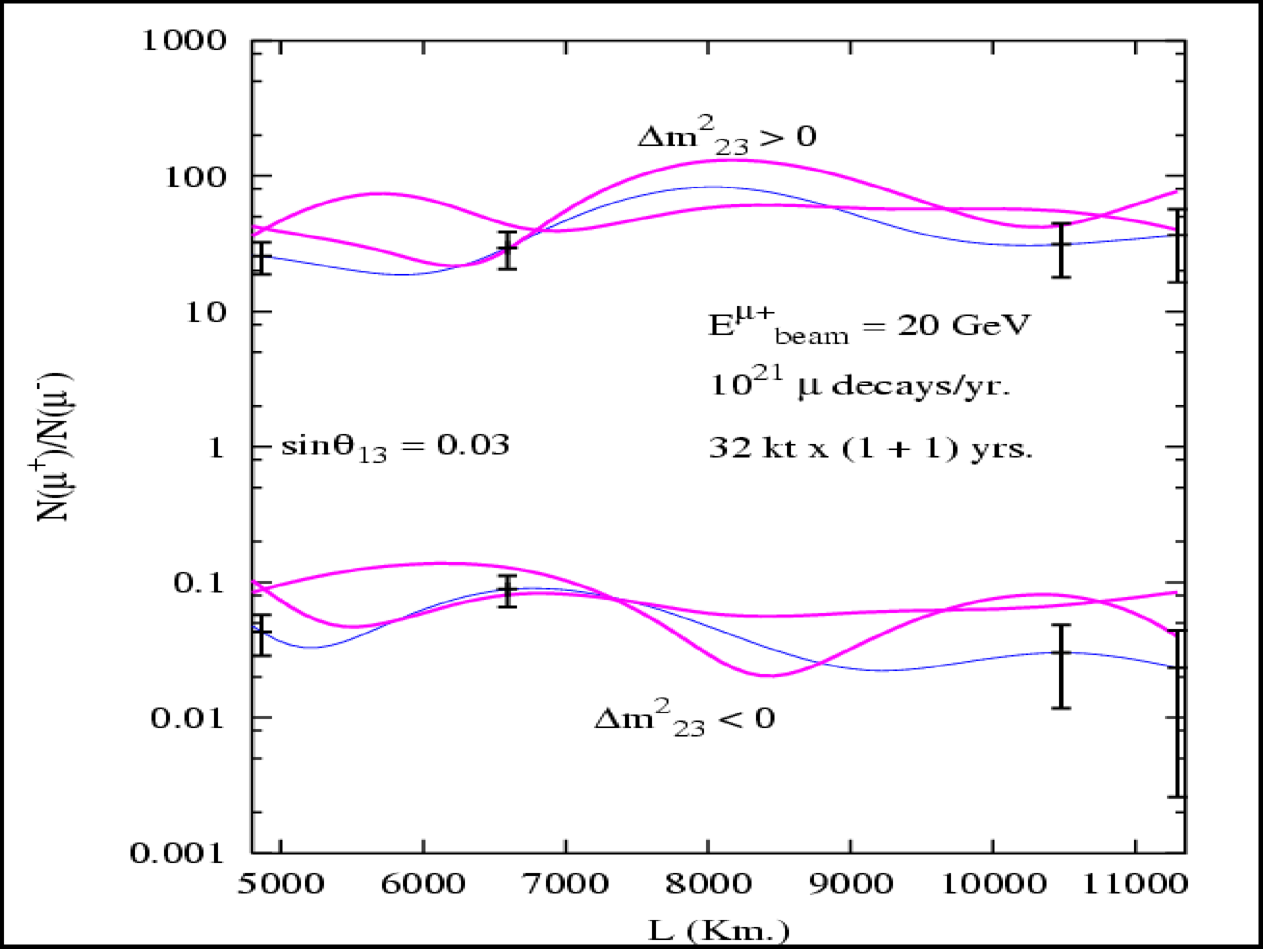
Determination of the Mass Hierarchy . .



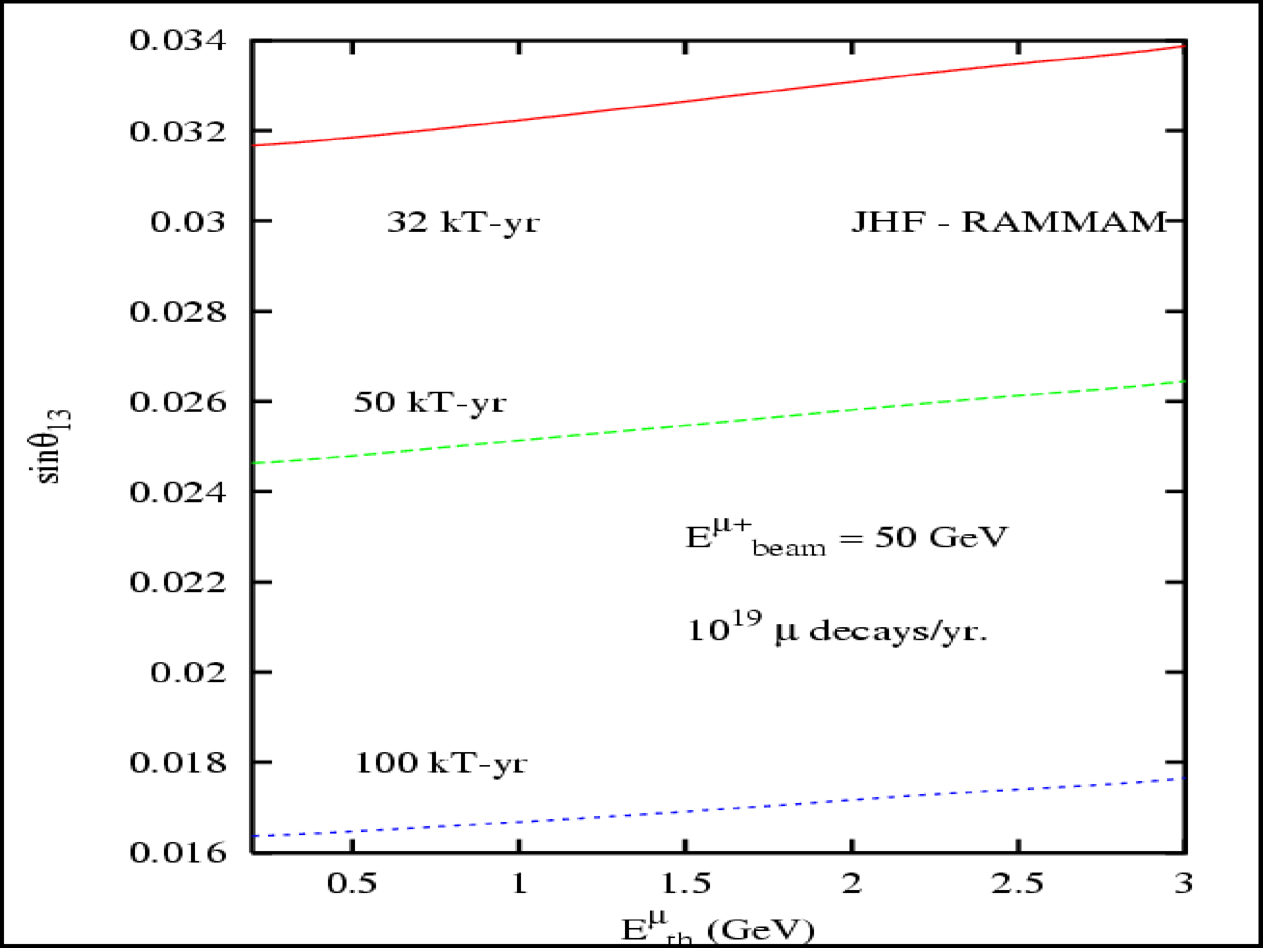
CPT Violation Tests



Neutrino Factory Physics- δ_{CP} . . .



Neutrino Factory Physics- Determining θ_{13} . . .



Summary and Conclusions

- Neutrinos carry the messages of nature from the farthest corners of the Universe. Due to their extremely weak interactions and tiny masses, they occupy a special place amongst the known elementary particles.

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- The smallness of their mass is directly linked to the scale at which new physics is expected beyond the Standard Model. Hence knowledge of their masses and mixings is crucial to our attempts to build a Unified Theory of fundamental interactions.

Summary and Conclusions (contd)

- INO/ICAL, if it is built, will be the world's only large-mass iron calorimeter with a unique capability of identifying the charges of muons produced by neutrinos

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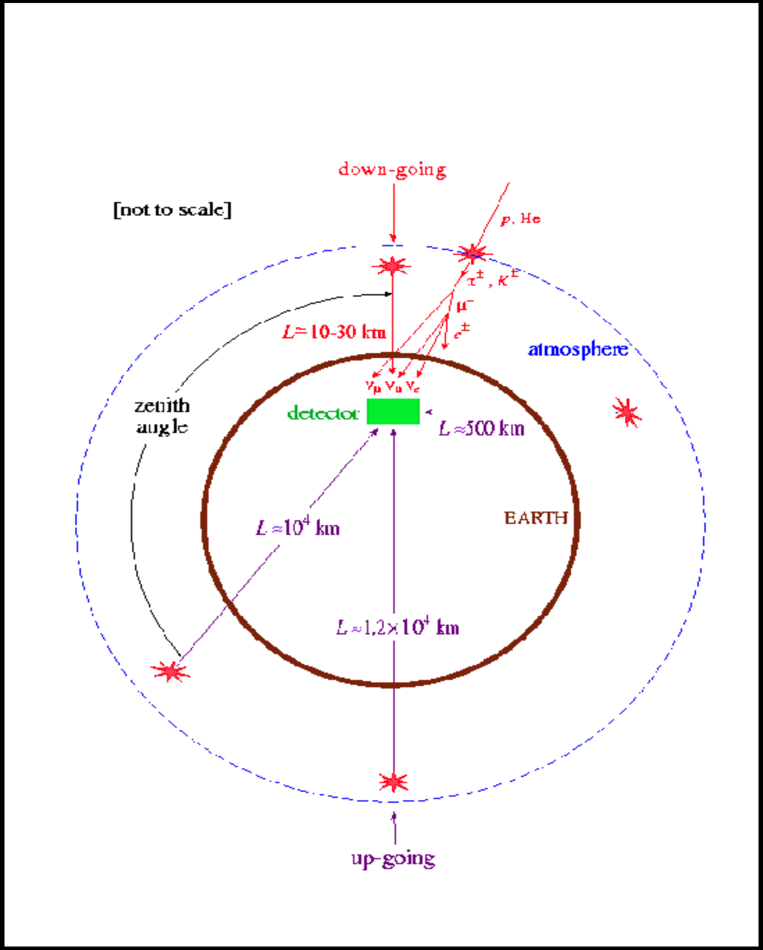
- INO/ICAL, if it is built, will be the world's only large-mass iron calorimeter with a unique capability of identifying the charges of muons produced by neutrinos
- It will answer some of the fundamental open questions in Particle Physics, and will have the capability of detecting atmospheric, UHE and beamline neutrinos, giving India a world-class scientific facility with far-reaching consequences and international impact .

Atmospheric neutrinos . . .



Supports oscillation as a solution over other possibilities like decay, de-coherence etc.

Table

Expt.	Detector mass	Source	L (Km)	$< E_\nu >$ (GeV)	Location
MINOS	FeC 5.4 kT	A CB	15-13000 735	1-100 3	Soudan US
ICARUS	LA TPC 2.35 kT	CB	732	17	LNGS Europe
OPERA	ECC 1.65 kT	CB	732	17	LNGS Europe
T2K	WC 50 kT	OA SB	295	0.76	Kamioka Japan
NOνA	LS APD 50 kT	OA SB	812	2.22	Ash River US

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D-Chooz	LS 11.3 t	R	1.05	0.004	Ardennes France
Reactor-II	LS 200 t	R	1.70	0.004	Diablo Canyon Japan
UNO	WC	A SB/NF	15-13000	1-100	Henderson US
Hyper-K	WC	A SB/NF	15-13000	1-100	Tochibora Japan
INO/ICAL	FeC 50 kT	A SB/NF	15-13000 $\sim 10^4$	1-100	Pushep/Rammam India

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  vs L FOR SOMEWHAT HIGHER VALUES OF THESE PARAMETERS.
- **Up/Down** rates provide additional handles on these violations.