Neutrino Physics with Long Baselines and a Large Mass Iron Calorimeter

Raj Gandhi

Harish-Chandra Research Institute
Allahabad, India

BNL

May 27

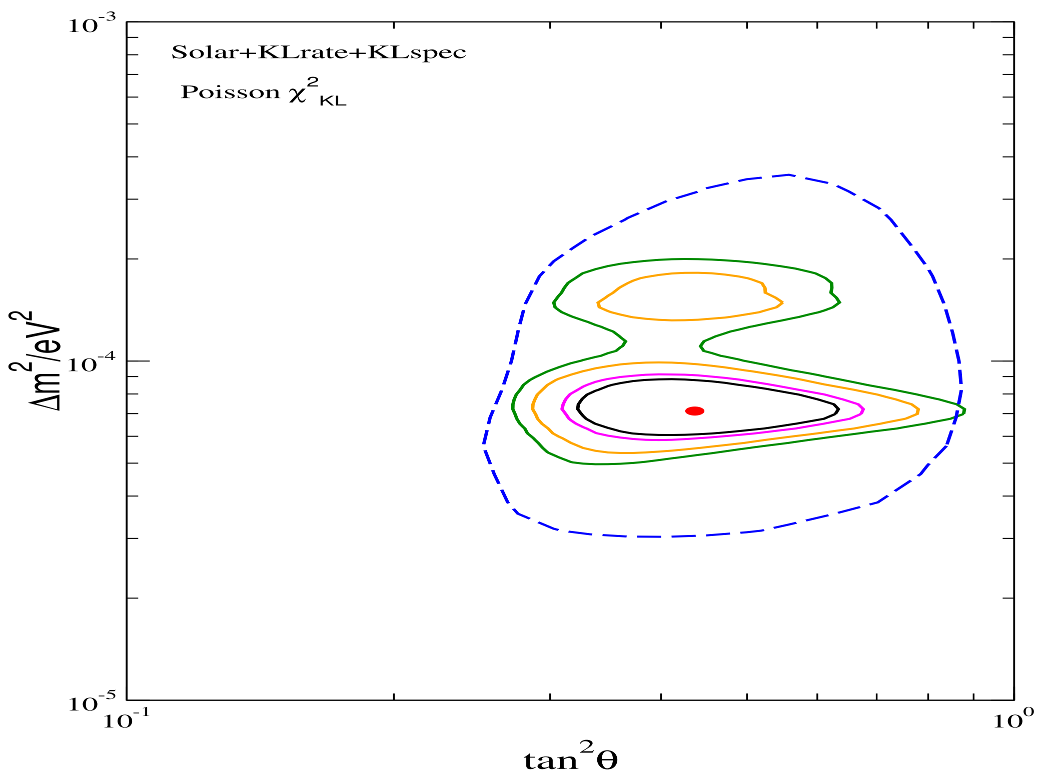
(with Anindya Datta)

2002: The Year of the Solar Neutrino

– **April 20 :** Direct Evidence of ν_e flavour conversion from the SNO NC data

–**December 6:** Evidence in favour of the LMA solution to the solar neutrino problem from KamLAND

All Solar Expts + KamLAND



- Splits the allowed region into two zones at 99% C.L. low-LMA (LMA1) and high-LMA (LMA2)

A. Bandyopadhyay et al. hep-ph/0212146

Neutrinos: Present Status and Future Goals

- Remarkable results from experiments in the last 3-4 years, notably SuperK, SNO, CHOOZ and KamLAND have clarified the sitiuation in an essential way

- Deficits and Anomalies of the past in solar and atmospheric neutrinos have now been firmed up into evidence for neutrino oscillation and mass

- Significant handle on some important mass and mixing parameters related to $\nu_\mu \to \nu_\tau$ and $\nu_e \to \nu_\mu$ oscillations

• **Approximate best-fit values/bounds gleaned from experiment so far:**

•

$$\Delta m_{21}^2 \sim 7 \times 10^{-5} eV^2$$

•

$$\sin^2 2\theta_{21} \sim 0.8$$

$\rightarrow$ **from solar neutrino and KamLAND data** •

$$\Delta m_{32}^2 \sim 3 \times 10^{-3} eV^2$$

•

$$\sin^2 2\theta_{23} \sim 1$$

$\rightarrow$ **from atmospheric neutrino data**

•

$$\sin^2 2\theta_{13} \leq 0.1$$

$\rightarrow$ **from CHOOZ results**

• Importantly, the results have defined and clarified much more sharply than before the future goals for our community

These are:

– Improve precision on parameters we already know

– Conclusively prove that atmospheric oscillations occur by observing an L/E dependance in the event rate

– Measure θ_{13}

– Determine the sign of Δm^2_{32}

– Search for CP violation in the lepton sector;

Is δ_{CP} non-zero?

- **Broadly speaking, the goal over the next 1-2 decades will be the precise measurement of the elements of the full 3 $\times$ 3 lepton mixing matrix and the pattern/hierarchy of the neutrino masses**

Some Physics Aspects related to the measurement of neutrino parameters

- For long baselines, one can neglect oscillations driven by Δm^2_{21} as a first approximation. This leads to the following simplified expressions in vaccuum

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.267\Delta m^2_{32}L/E_\nu)\ ,(1)$$

$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.267\Delta m^2_{32}L/E_\nu)\ ,(2)$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(1.267\Delta m^2_{32}L/E_\nu)\ .(3)$$

- We thus note the following:

– The importance of θ_{13}

– Vaccuum oscillations cannot determine the sign of Δm^2_{32} — matter effects are required

– Mode with ν_μ/ν_e in the initial/final state required

• **In the simplified scenario of constant mixing, one can write :**

$$P(\nu_e \to \nu_\mu) = s_{23}^2 \sin^2 2\theta_{13}^m \sin^2 \Delta_{32}^m, \qquad (4)$$

where

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{\left(\frac{A}{\Delta m_{32}^2} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}} \qquad (5)$$

and

$$\Delta_{32}^m = \frac{1.27 \Delta m_{32}^2\,(\mathrm{eV}^2)\, L\,(\mathrm{km})}{E_\nu\,(\mathrm{GeV})} \sqrt{\left(\frac{A}{\Delta m_{32}^2} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}} \qquad (6)$$

and A is the matter amplitude:

$$A = 2\sqrt{2}\, G_F\, Y_e \rho E_\nu = 1.52 \times 10^{-4}\,\mathrm{eV}^2\, Y_e\, \rho\,(\mathrm{g/cm}^3) E_\nu\,(\mathrm{GeV})\,. \qquad (7)$$

• Again, we note the following:

– For anti-neutrino oscillations, A changes sign –$P_{\nu_e \to \nu_\mu}$ is enhanced and $P_{\bar{\nu}_e \to \bar{\nu}_\mu}$ suppressed – Comparison of these two rates provides a way to determine the sign of Δm^2_{32} – Similarly, CP violation can be searched for using these rates

• Such comparisons need a detector which can discriminate the sign of the charged lepton

• A Magnetized Large Mass Iron Calorimeter is being seriously considered in India and feasibility studies are underway for the Indian Neutrino Observatory (INO)

(http://www.imsc.ernet.in/ ino)

What are the Characteristics and Physics Capabilities of such a Detector

- **Characteristics:**

– Magnetized Iron (50 -100 kT) with RPC or glass spark chambers

– Excellent muon track and charge identification, with 5% energy resolution

– E_{th} 1-2 GeV possible

– Backgrounds due to pion and kaon decays can be greatly reduced by kinematic cuts

– Superior L/E range as high density contains many HE events

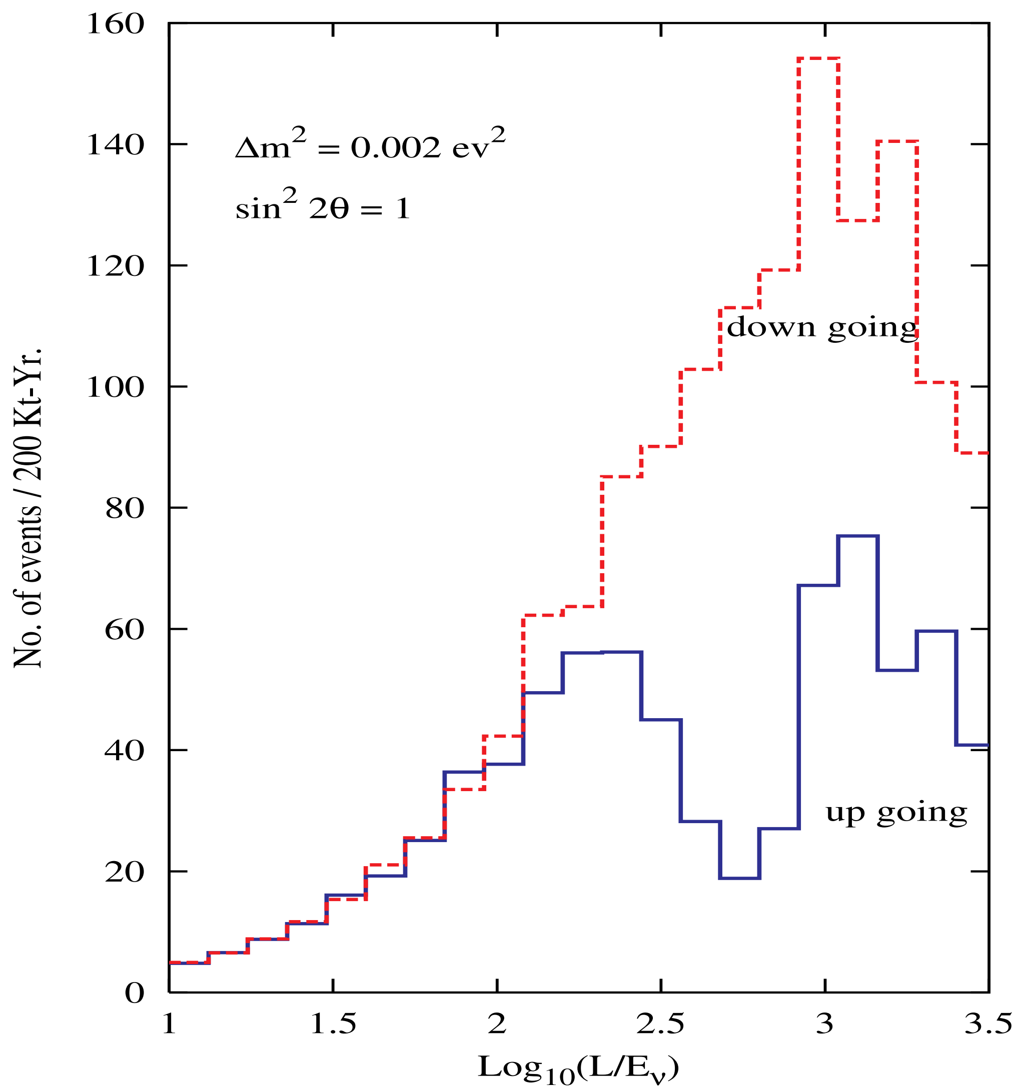
- **Physics Capabilities:**

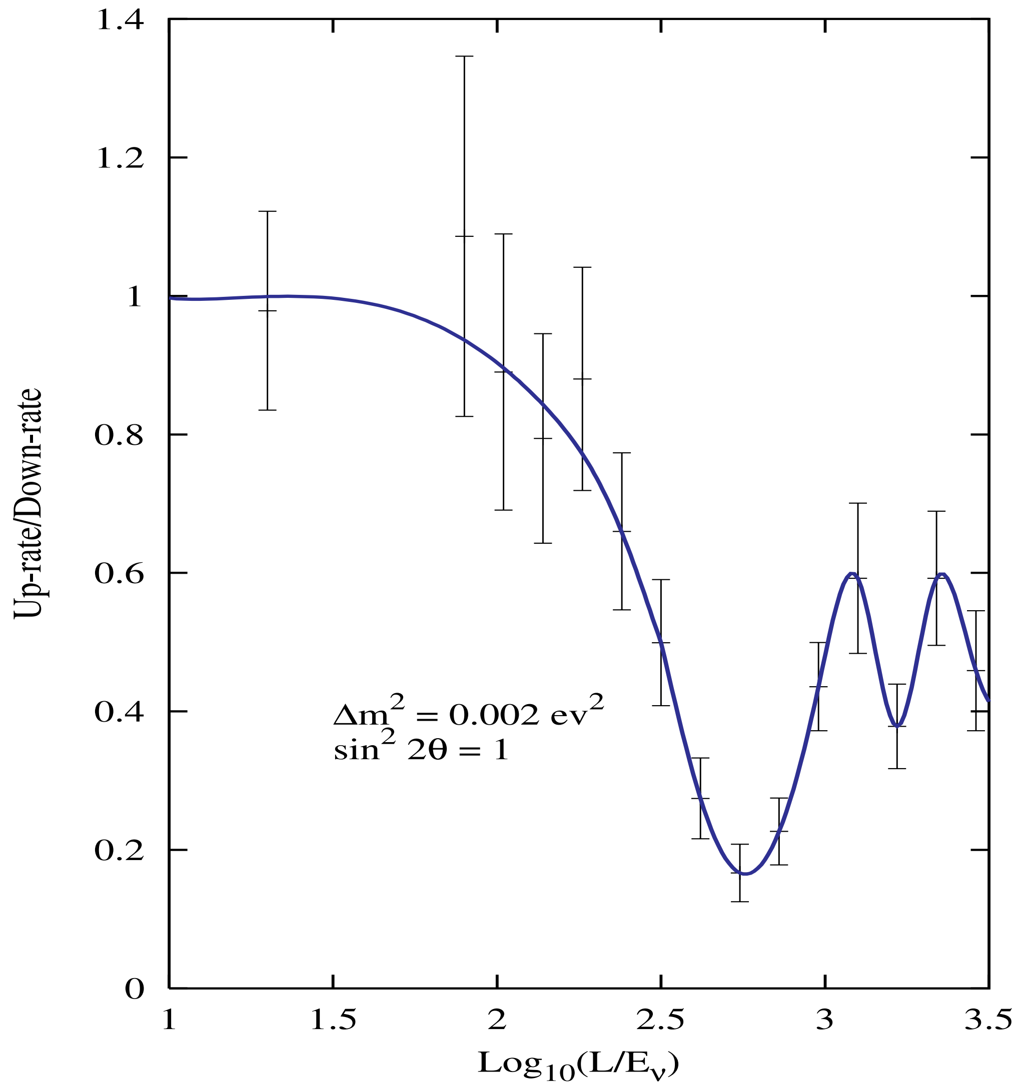
– **Atmospheric Neutrinos**

– **Detection of HE Cosmic-Ray Muons in the PeV range**

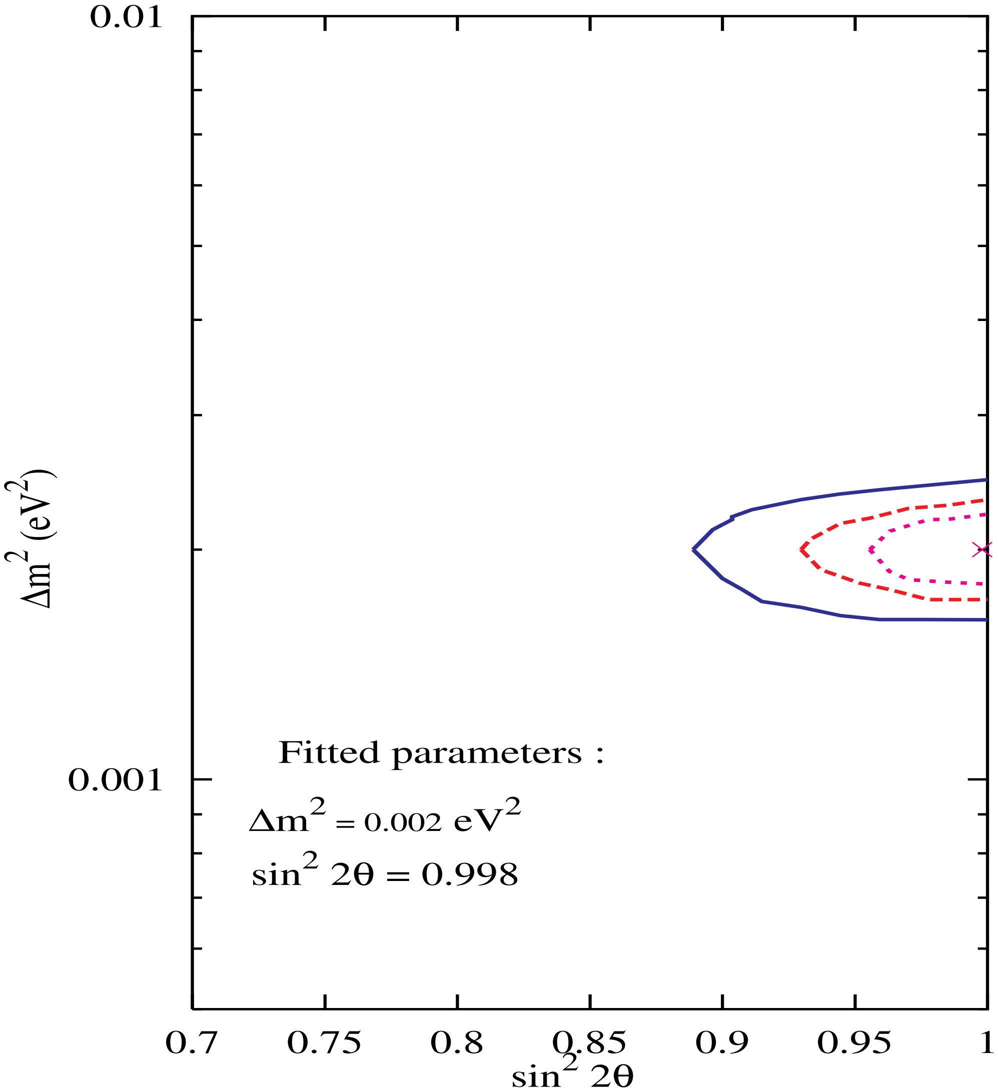
– **As an end detector for a Neutrino factory**

• **Atmospheric Neutrinos: Clean detection of L/E dependance of event rate, providing unambiguous signature of oscillations**





1.4
1.2
1
0.8
0.6
0.4
0.2
0
1
1.5
2
2.5
3
3.5
Up-rate/Down-rate
Log10(L/Eν)
Δm² = 0.002 ev²
sin² 2θ = 1

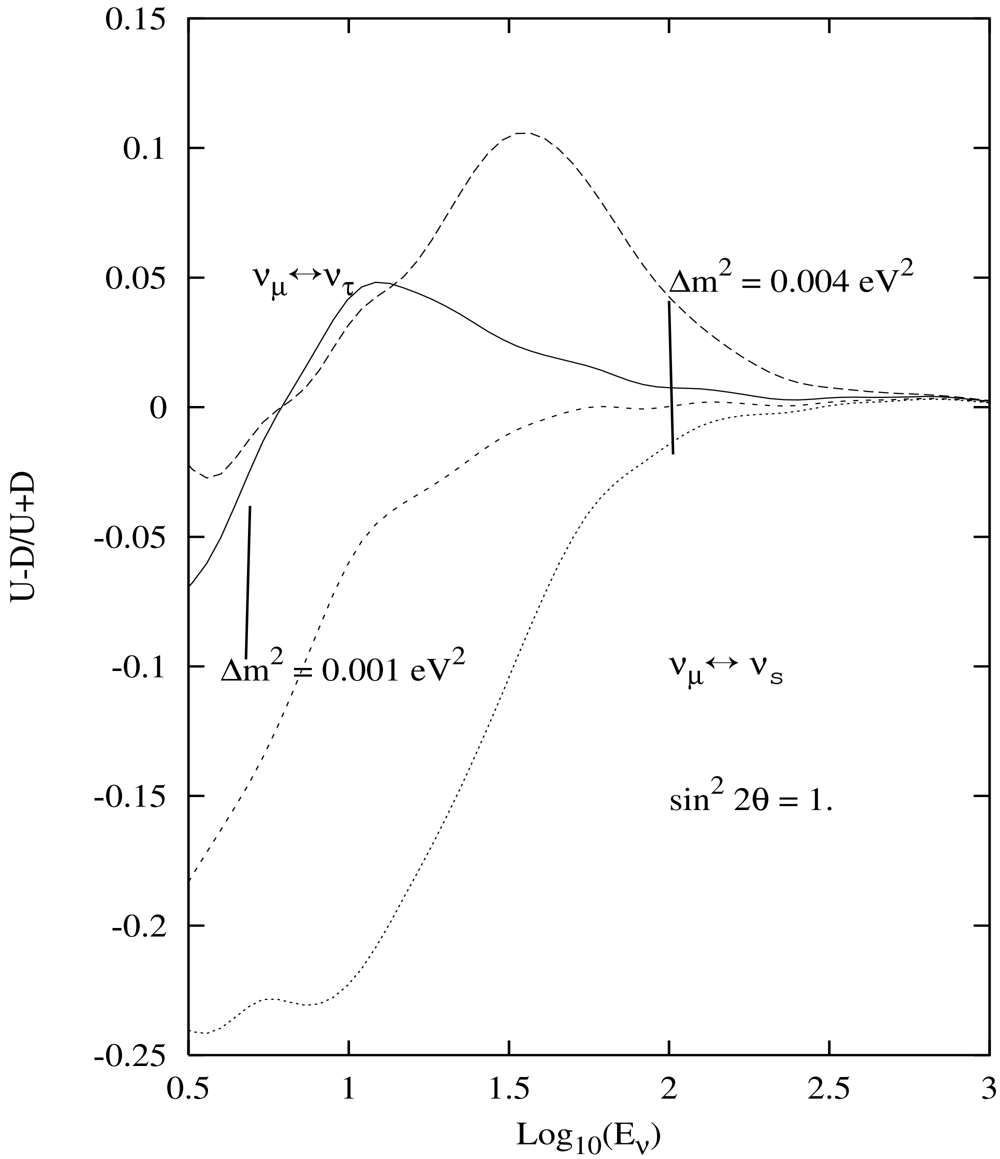

0.01
0.001
Δm^2 (eV^2)
0.7
0.75
0.8
0.85
0.9
0.95
1
$\sin^2 2\theta$
Fitted parameters :
$\Delta m^2 = 0.002$ eV^2
$\sin^2 2\theta = 0.998$

- **Discriminating between $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_s$**

– Upgoing ν_μ oscillating to ν_τ will have CC interactions leading to the τ decaying via a muon-less channel 80% of the time

– Upgoing ν_μ oscillating to ν_s will have neither CC nor NC interactions – The muonless decays are read to be NC events by a Fe Detector

– UP/DOWN rates of muonless events differ in the 2 cases



0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
0.5
1
1.5
2
2.5
3
U-D/U+D
$\mathrm{Log}_{10}(E_\nu)$
$\nu_\mu \leftrightarrow \nu_\tau$
$\Delta m^2 = 0.004\ eV^2$
$\Delta m^2 = 0.001\ eV^2$
$\nu_\mu \leftrightarrow \nu_s$
$\sin^2 2\theta = 1.$

CPT Violation Tests with A Fe Calorimeter

– There is mounting evidence against sterile neutrinos both from solar and atmospheric experiments.

– If light sterile neutrinos do not exist, and LSND is correct and confirmed by MiniBoone, the totality of neutrino data can perhaps only be explained by CPT violation in the neutrino sector

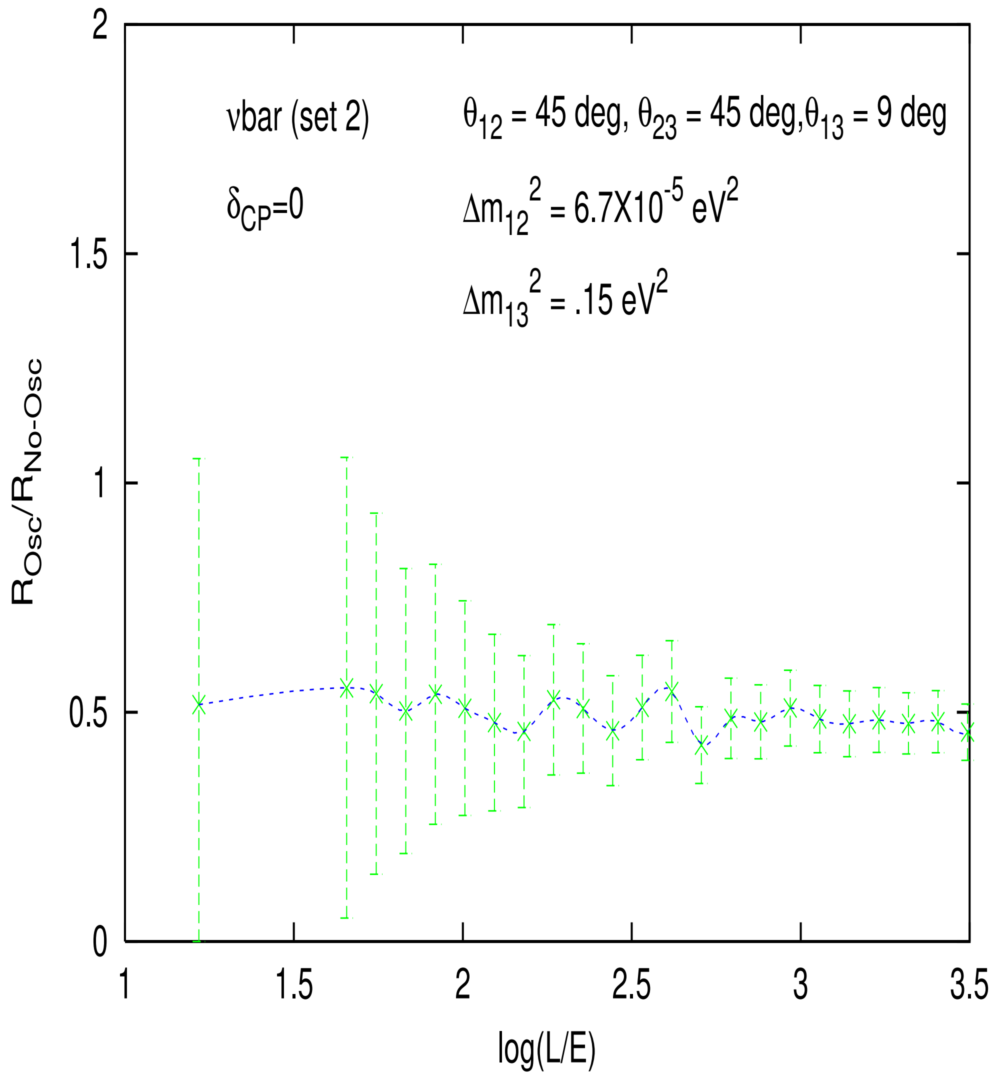
– In this scenario, mass splittings in the anti-neutrino sector are not necessarily the same as those in the neutrino sector

– Experiments like KamLand and LSND thus correspond to anti-neutrino sector mass-splittings.

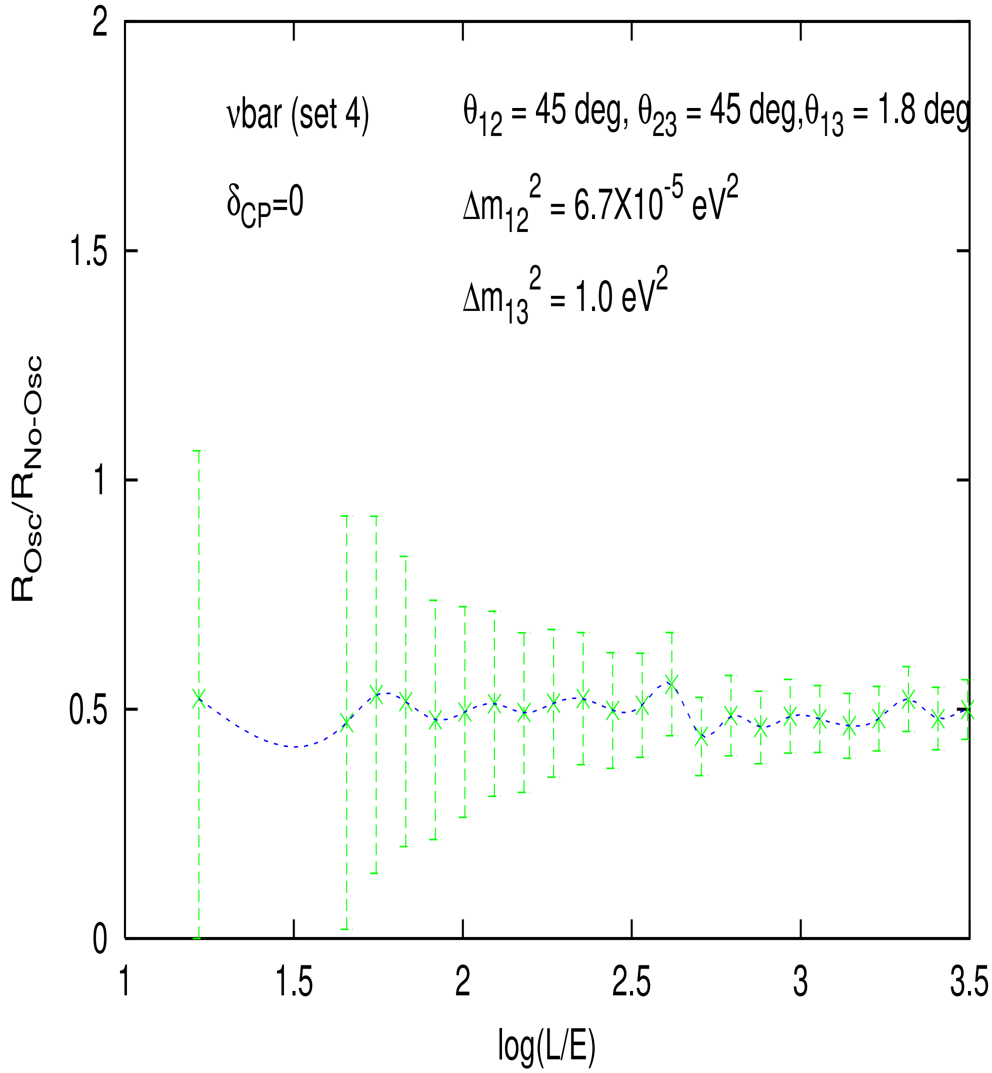
There are thus six mixing angles and 4 mass splittings in toto

G. Barenboim et al. hep-ph/0212116

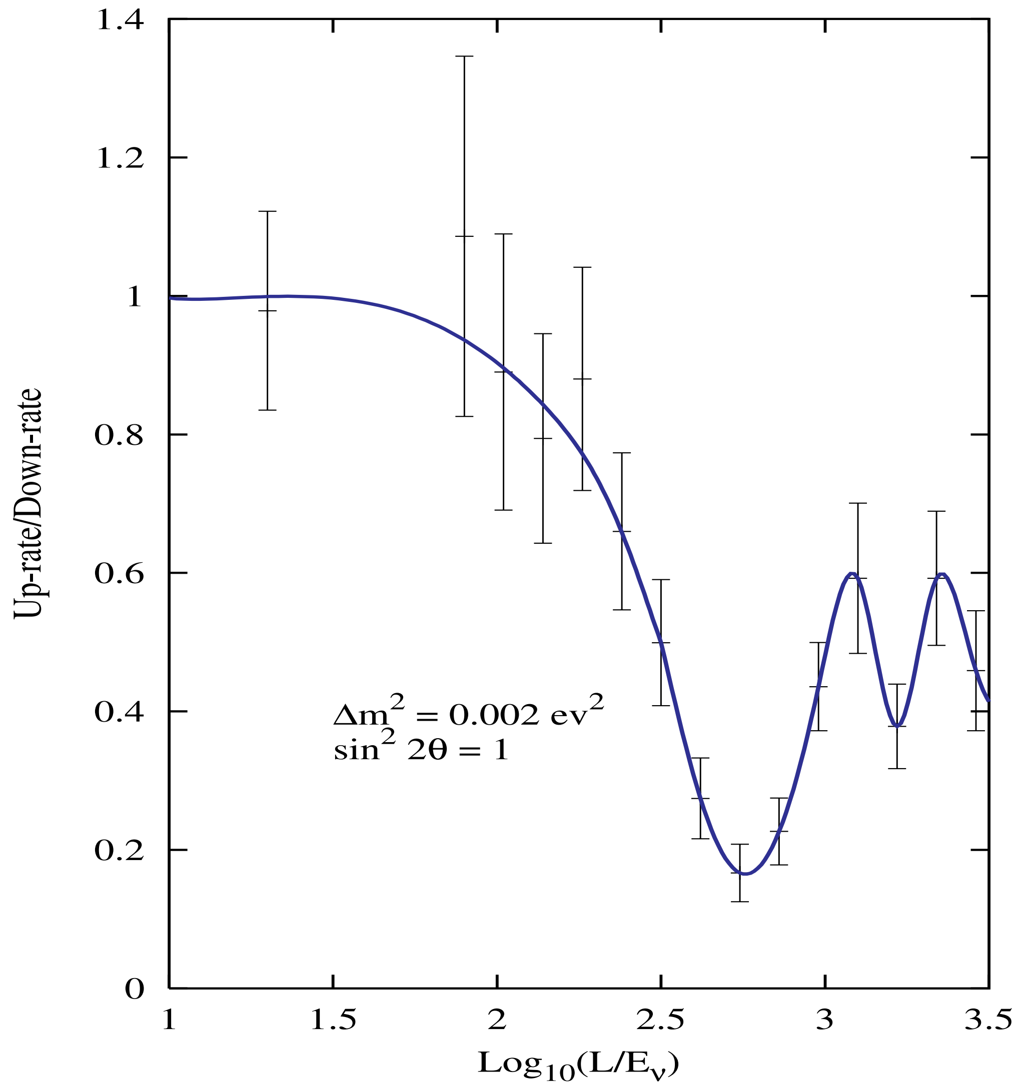
–This hypothesis can be very easily verified in a Fe detector sensitive to muon charge



vbar (set 2)
θ_{12} = 45 deg, θ_{23} = 45 deg, θ_{13} = 9 deg
δ_{CP}=0
$\Delta m_{12}{}^2$ = 6.7X10^{-5} eV^2
$\Delta m_{13}{}^2$ = .15 eV^2
$R_{Osc}/R_{No\text{-}Osc}$
log(L/E)



vbar (set 4)
θ_{12} = 45 deg, θ_{23} = 45 deg,θ_{13} = 1.8 deg
δ_{CP}=0
Δm_{12}^2 = 6.7X10^{-5} eV^2
Δm_{13}^2 = 1.0 eV^2
$R_{Osc}/R_{No\text{-}Osc}$
log(L/E)
0
0.5
1
1.5
2
1
1.5
2
2.5
3
3.5



1.4
1.2
1
0.8
0.6
0.4
0.2
0
Up-rate/Down-rate
1
1.5
2
2.5
3
3.5
$\mathrm{Log}_{10}(L/E_\nu)$
$\Delta m^2 = 0.002\ ev^2$
$\sin^2 2\theta = 1$

Physics with A Fe Calorimeter and a Neutrino Factory Beam

– Reach and measure of $sin^2 2\theta_{13}$

– The sign of Δm^2_{32}

– Determining if CP violation is present in the leptonic sector

Calculations performed assume the following:

– Muon energy resolution within 5%

– Muon detection threshold is 2 GeV

– All measurements involve wrong sign muon detection, thus backgrounds are low

– Backgrounds due to decays of charm,pions and kaons taken into account

– p_T^2 cut invoked to reduce backgrounds

– Matter effects incorporated using full PREM model

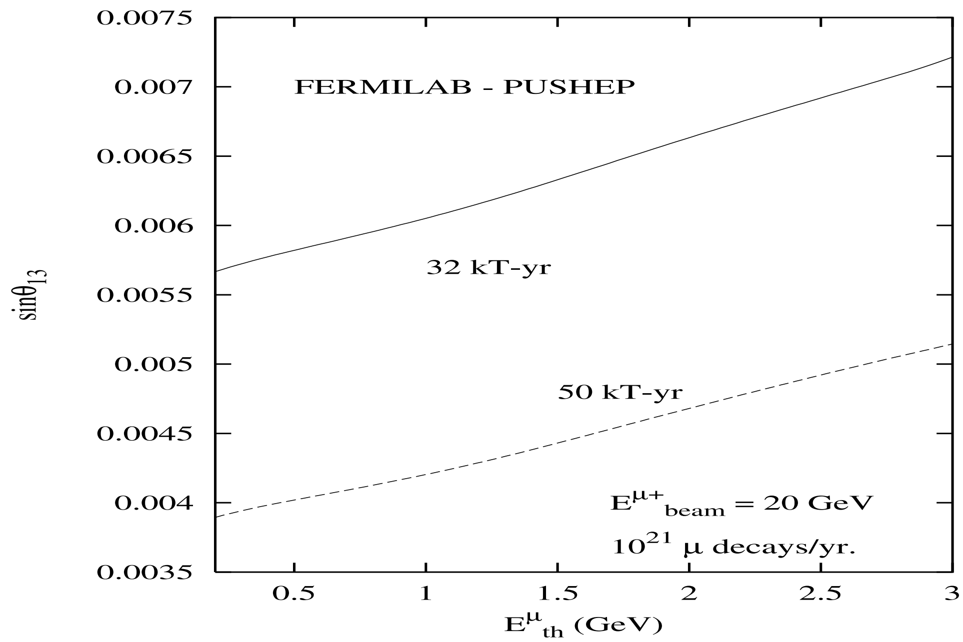
– Present best fit values from solar/atmospheric data used

– 100% charge id capability assumed

– Two different locations, RAMAM in NE India and PUSHEP in South India considered.

- **Reach of $sin^2 2\theta_{13}$**

– **The reach is defined as the value required to collect 10 signal events for a given kT-yr exposure**



– **Fermilab-Pushep baseline is 11296 km**

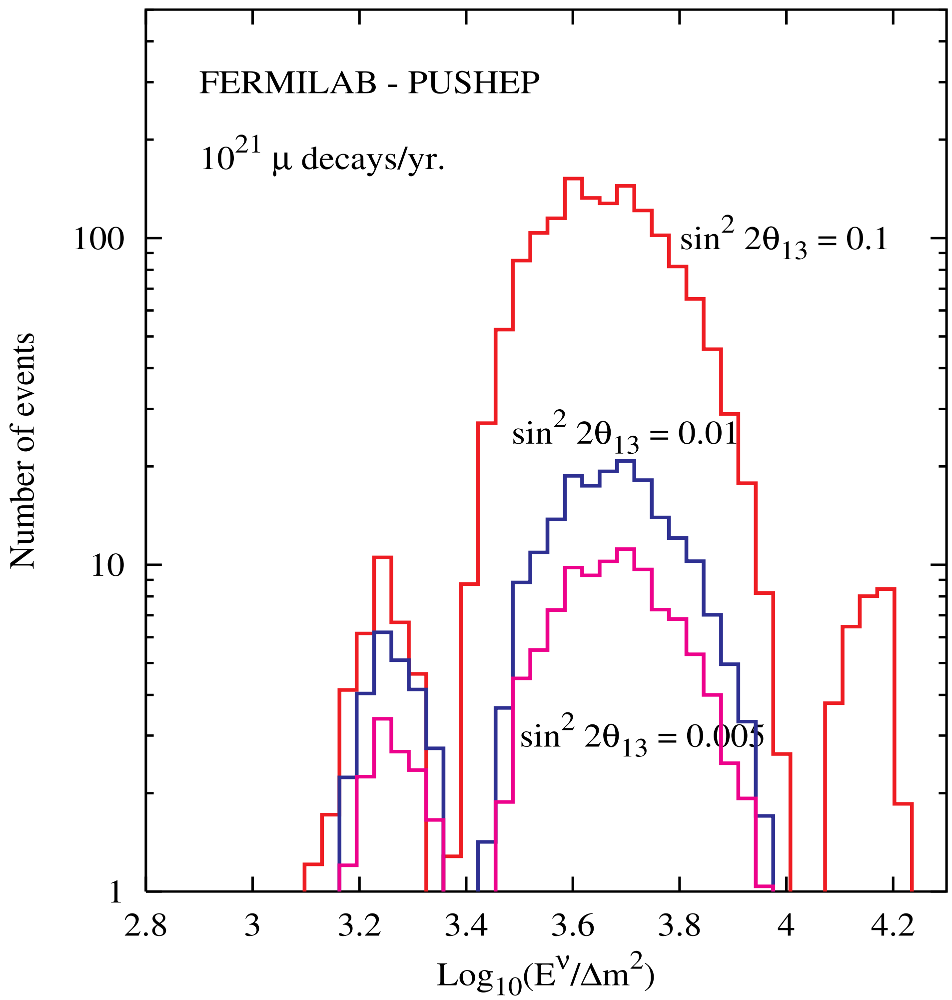
– **CHOOZ bound is $sin^2 2\theta_{13} < 0.1$**

–**Reach is $sin^2 2\theta_{13} = 8.8 \times 10^{-5}$ for 50 kT-yr exposure and 2×10^{-4} for 32 kT-yr**

– Obtaining a measure of θ_{13}

– Wrong sign muon rate sensitive to $sin^2 2\theta_{13}$

– Matter effects important for long baselines

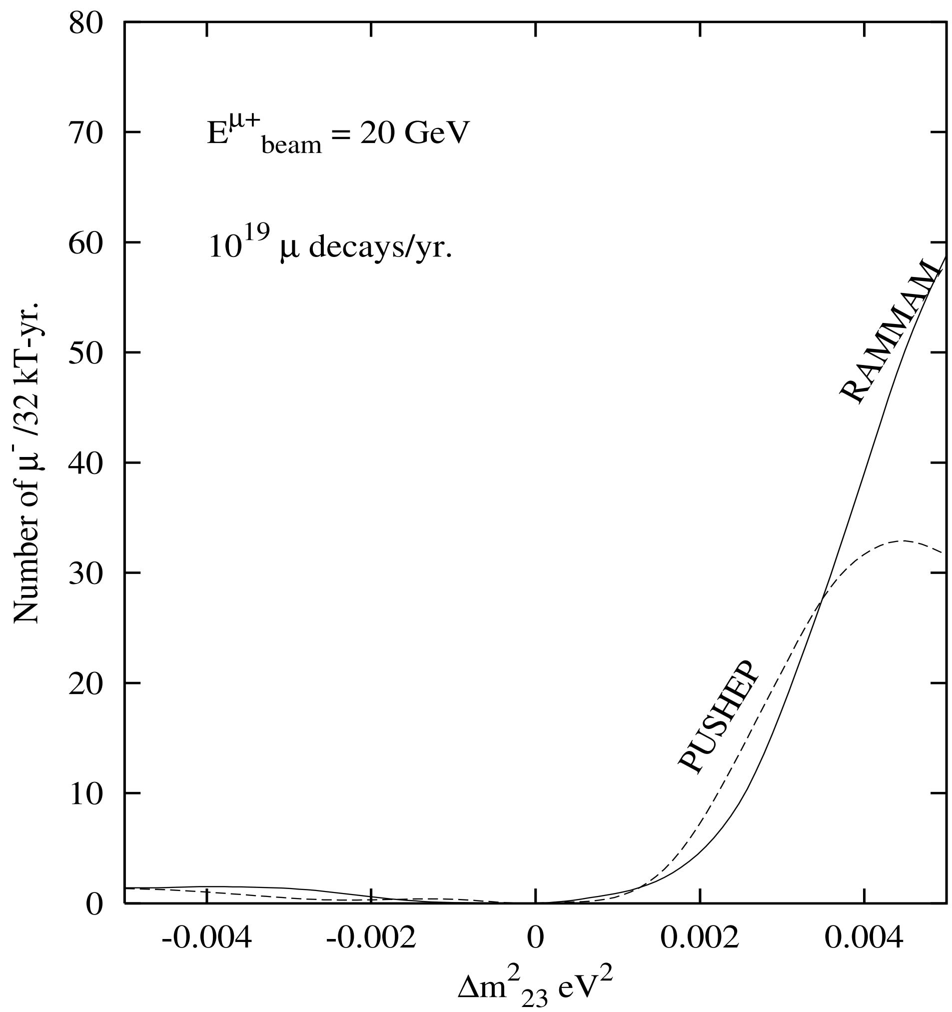


– Note event rate peaks nicely in 10-20 Gev range for currently favoured values of Δm^2_{32}

Sign of Δm^2_{32}

– For anti-neutrino oscillations, A changes sign

–$P_{\nu_e \to \nu_\mu}$ is enhanced and $P_{\bar{\nu}_e \to \bar{\nu}_\mu}$ suppressed

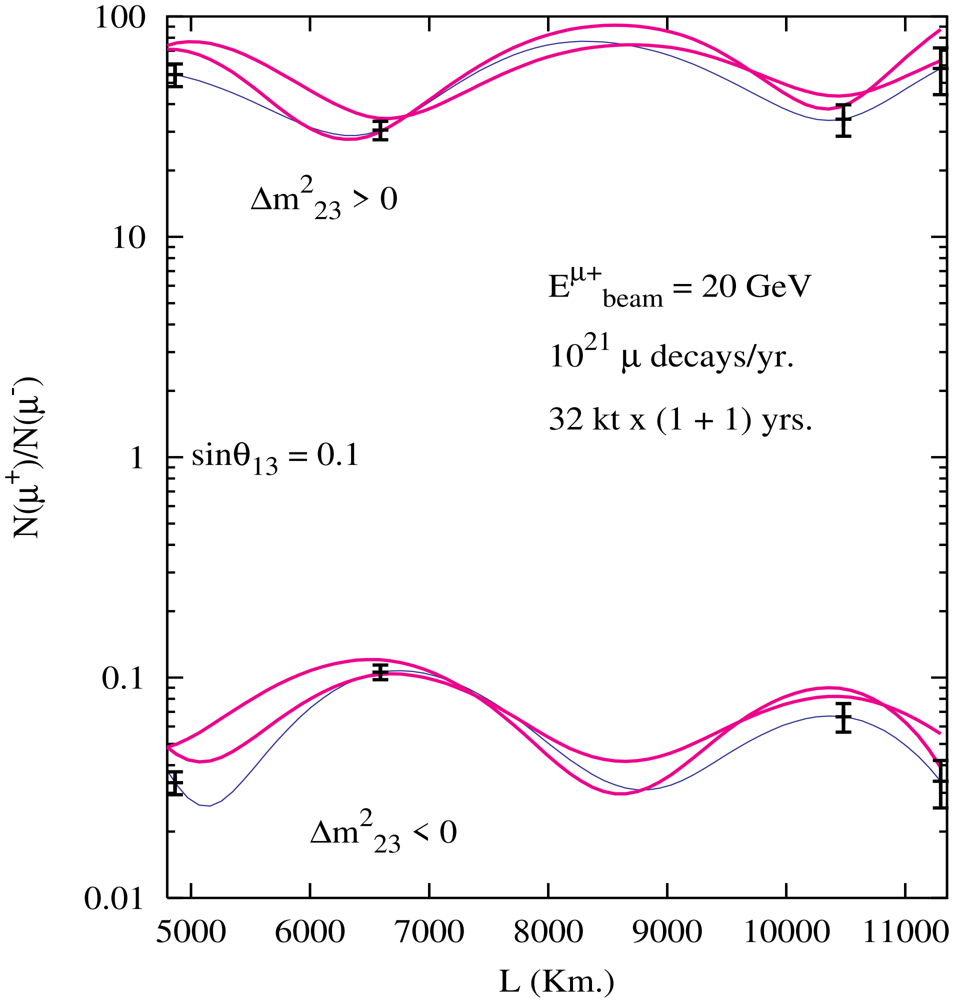


Presence of CP violation in the Lepton sector

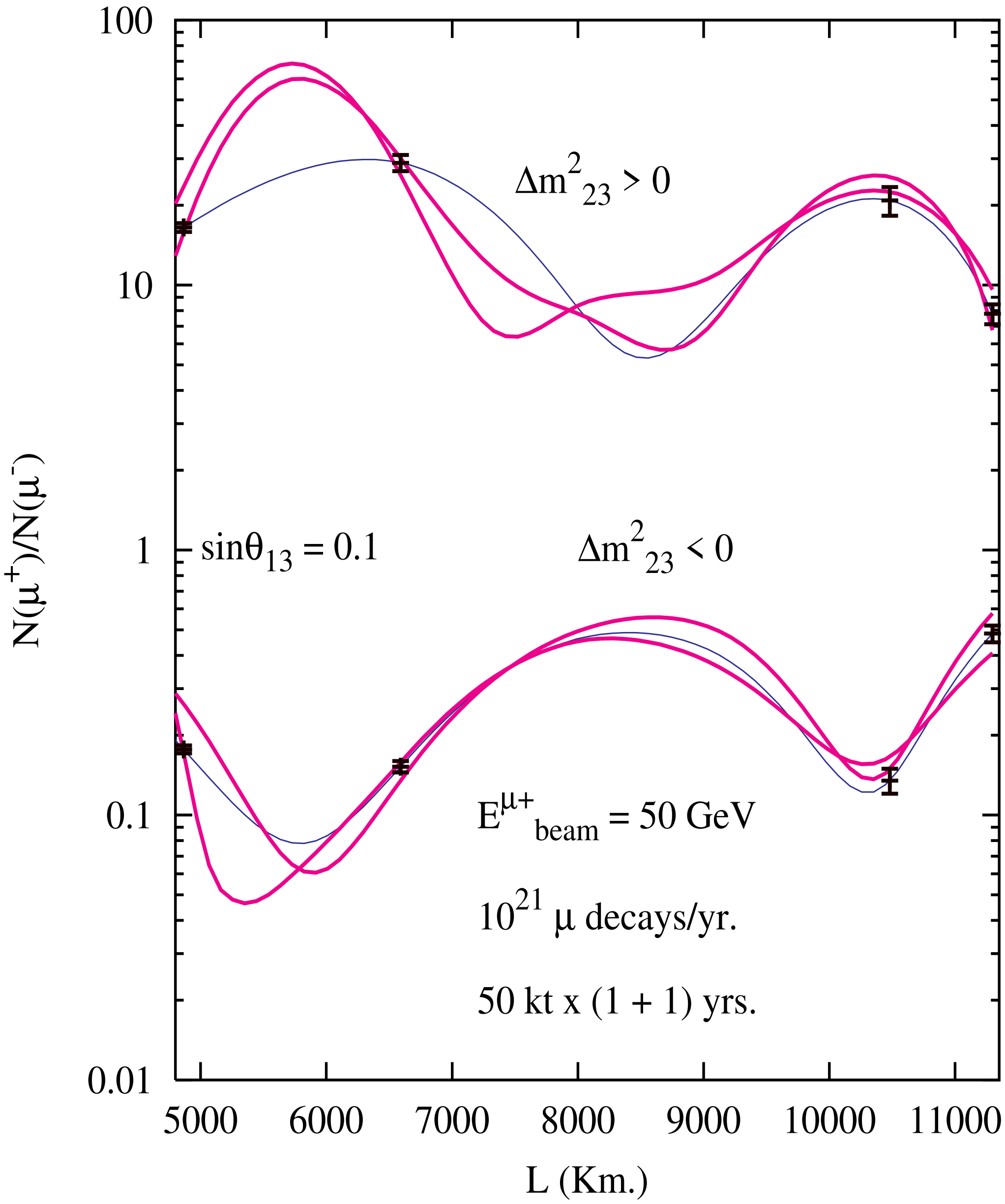
–Matter CP effects usually difficult to disentangle from those due to presence of non-zero CP phase in mixing matrix

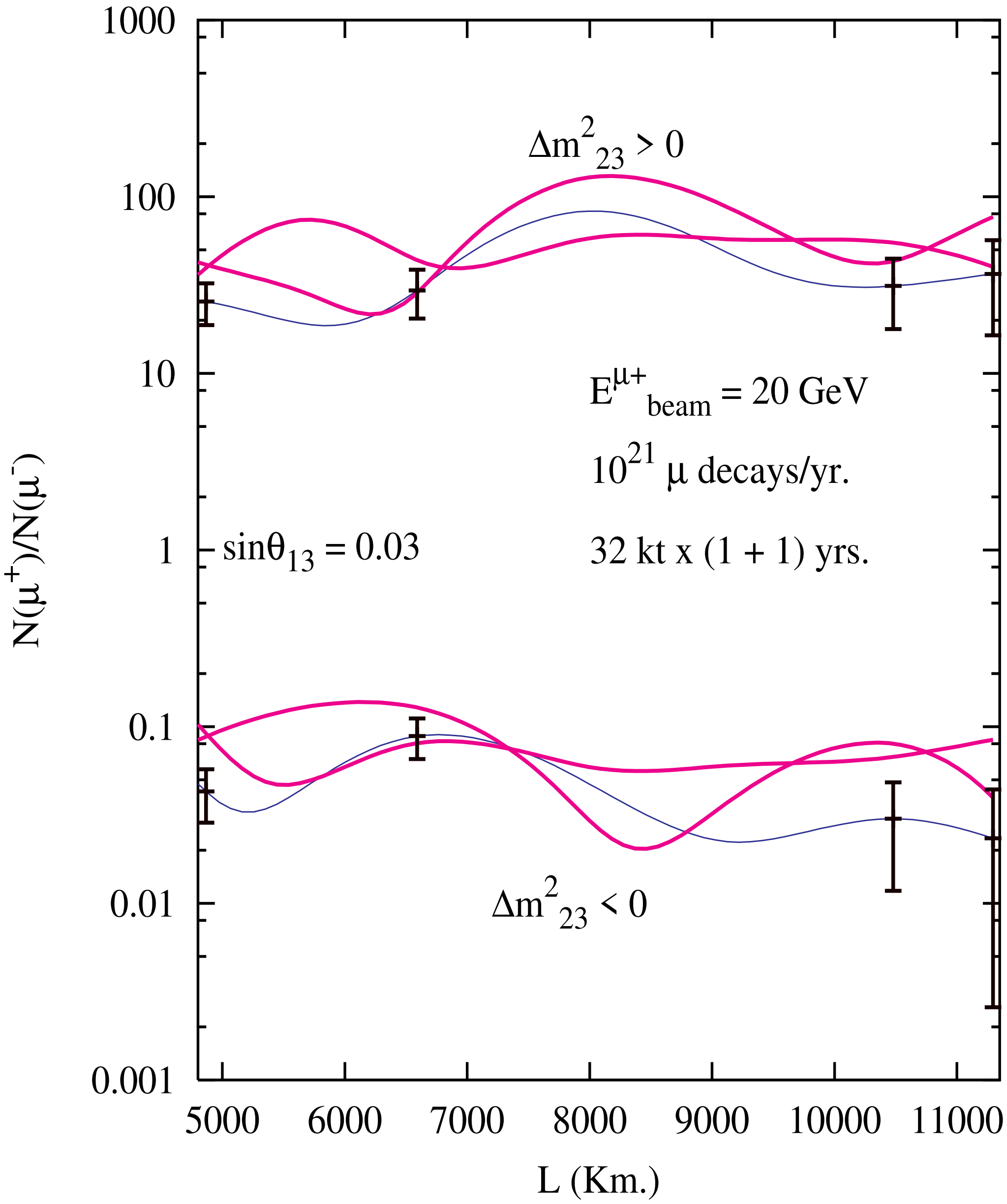
–Rates for particles and their CP conjugates depend sensitively on θ_{13}, E, baseline, Δm^2_{21} and δ_{CP}

–Equal-time runs with μ^+ and μ^- required, with measurement of wrong sign muon rate in each case

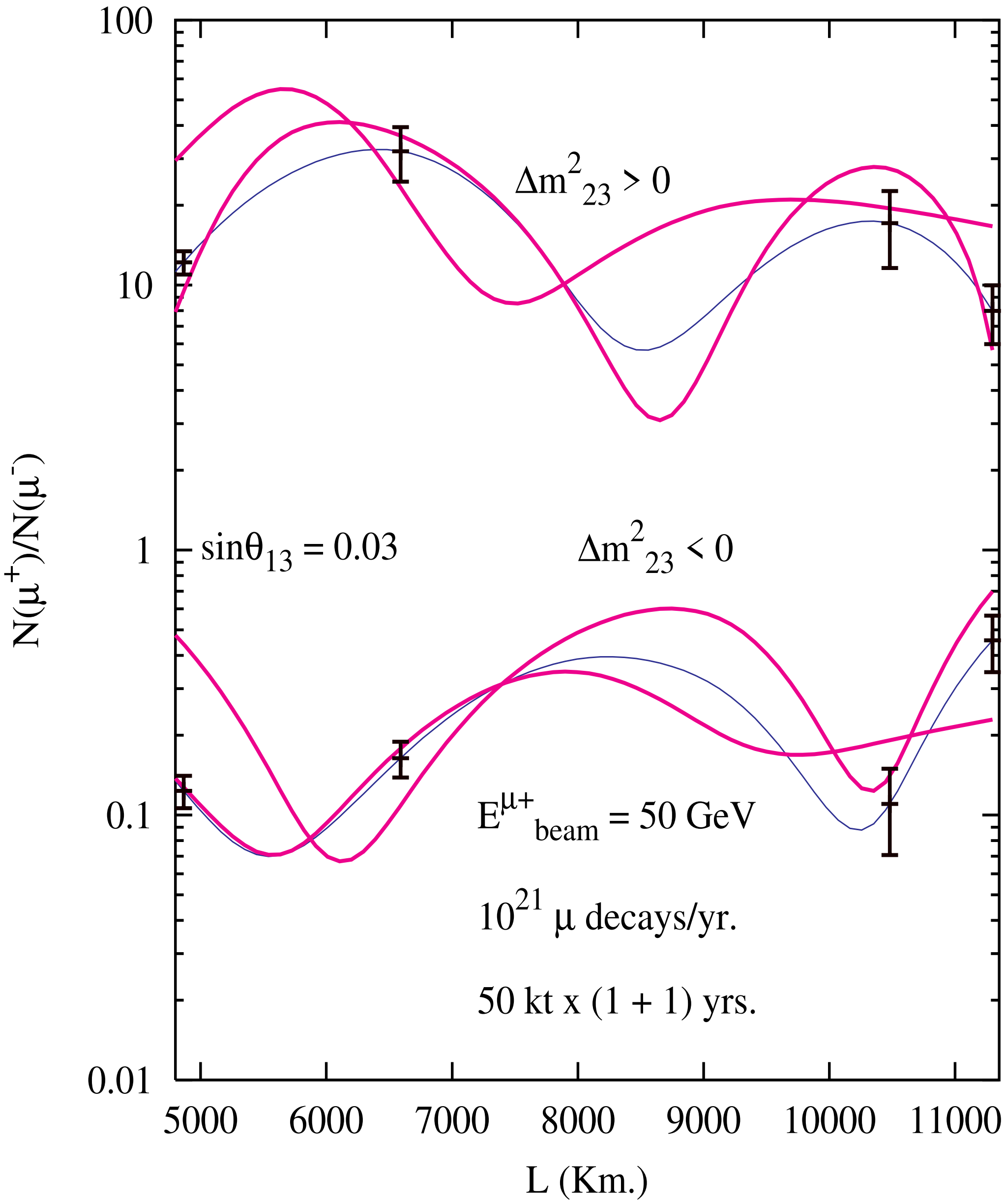


100
10
1
0.1
0.01
5000
6000
7000
8000
9000
10000
11000
L (Km.)
$N(\mu^+)/N(\mu^-)$
$\Delta m^2_{23} > 0$
$E^{\mu+}_{beam}$ = 20 GeV
10^{21} μ decays/yr.
32 kt x (1 + 1) yrs.
$\sin\theta_{13} = 0.1$
$\Delta m^2_{23} < 0$


100
10
1
0.1
0.01
5000
6000
7000
8000
9000
10000
11000
L (Km.)
N(μ+)/N(μ-)
Δm²23 > 0
Δm²23 < 0
sinθ13 = 0.1
Eμ+beam = 50 GeV
10²¹ μ decays/yr.
50 kt x (1 + 1) yrs.



1000
100
10
1
0.1
0.01
0.001
5000
6000
7000
8000
9000
10000
11000
L (Km.)
N(μ+)/N(μ-)
Δm²23 > 0
Δm²23 < 0
E^μ+_beam = 20 GeV
10^21 μ decays/yr.
32 kt x (1 + 1) yrs.
sinθ13 = 0.03



100
10
1
0.1
0.01
5000
6000
7000
8000
9000
10000
11000
L (Km.)
$N(\mu^+)/N(\mu^-)$
$\Delta m^2_{23} > 0$
$\sin\theta_{13} = 0.03$
$\Delta m^2_{23} < 0$
$E^{\mu+}_{beam} = 50$ GeV
10^{21} μ decays/yr.
50 kt x (1 + 1) yrs.

CONCLUSIONS

Substantial and germane physics program possible with Large mass Iron Calorimeter

Atmospheric, UHE, Nu Factory Neutrino Detection with 100% Charge id for muons

Many major goals of next 1-2 decades addressed by such a detector

INO collaboration set up for such a detector in India, funding outlook positive

Geotechnical site studies, Detector R/D , Physics Simulation studies in progress, proposal submission by end 2003

International Feedback, participation and collaboration sought

www.imsc.ernet.in/ĩno