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The Physics Potential for a Large Mass Iron Calorimeter based in India as an End Detector for a Neutrino Factory based in Japan

A Note prepared on behalf of the INO Colaboration

Anindya Datta[a1] and Raj Gandhi[c2],

[a]*Helsinki Institute of Physics, P.O Box 64,*
University of Helsinki, Gustaf Hallstomin Katu 2, Helsinki, FIN 00014
[c]*Harish-Chandra Research Institute, Chhatnag Road, Jhusi,*
Allahabad - 211-019, India

Abstract

We perform sample calculations to examine the physics potential of a large iron calorimeter based at 2 proposed sites in India (Ramam and Pushep), when used as an end detector for a neutrino factory located at JHF. The results are encouraging and indicate that further studies to uncover the full physics possibilities of this source/detector combination will be fruitful.

1 Introduction

Progress in neutrino physics over the last three decades has in large part been acheived due to a sucession of remarkable experiments. Among these, the most recent are KamLAND, SNO, SuperK, Kamiokande, IBM, the Gallium experiments (SAGE, Gallex, GNO), Homestake and CHOOZ, to name a few. Besides providing strong evidence for non-zero neutrino mass and oscillations, along with ranges of possible mass and mixing parameters, they have, importantly, identified the experimental goals and directions the neutrino community must pursue over the next two decades. We briefly mention some of the important ones below:

- Conclusively show that oscillations are responsible for observed flux deficits by demonstrating an L/E dependance of event rates.
- Determine the mass heierarchy of neutrinos, i.e. the signs of the mass-differences squared.
- Measure the parameter θ_{13}.
- Determine whether the leptonic CP phase δ is non-zero, and if so, obtain some measure of its magnitude.

Over the next 5-10 years, the present and next generation experiments will likely give us useful, if possibly incomplete information on the first two goals above, and if we are lucky and θ_{13} is large, some very prelimnary data relevant to this parameter. A statistically significant determination of this important parameter will still elude us, however, even after the results from these experiments are available. In addition, we will in all probability remain in the dark about leptonic CP violation, whose presence or absence is expected to provide a crucial understanding of and a window to physics beyond the Standard Model.

As is well understood by now, neutrino factories may provide the best and cleanest, if not the only way to acheive the last two goals mentioned above. The determination of θ_{13} and δ are both sensitive to the baseline chosen. Many neutrino factory locations and corresponding end-detector sites are under consideration and active discussion all around the world. In what follows, we explore the physics discovery potential of a large-mass Iron Calorimeter based in India, when used as an end detector for a neutrino factory beam originating from the Japan Hadron Facility at Jaeri (JHF).

2 Basic Detector Characteristics, Physics inputs and Kinematic cuts used

The Iron Calorimeter detector, whose design and development is under active investigation by the INO (Indian Neutrino Observatory)Collaboration is contemplated as both a detector for atmospheric neutrinos and as a future end detector for a neutrino factory beam. In this note we focus on the latter application. The basic characteristics of an iron calorimeter detector are well-known. We assume a muon energy resolution of within 5%, and for calculations where the muon detection threshold is fixed, we have assumed it to be 2 GeV.

The calulations below all involve the detection of wong sign muons,(except in one case) for which the backgrounds are comprised of the following: a) In NC interactions, wrong sign muons are products of the decays of produced pions and kaons. b) In CC interactions, if the primary muon is "lost" in the detector, then a wrong sign muon produced in charm, pion and kaon decays would constitute a background.

Such backgrounds can be significantly reduced by a p_T^2 cut, and we employ a cut of 2 Gev^2. The backgrounds fall sharply as a function of energy, and are at the level of 10^{-2} at a muon threshold energy of 2 GeV, and fall to less than 10^{-4} at $E^{\mu}_{th} = 5$ GeV. We conservatively assume a background of 10^{-1} over the entire energy spectrum. We do assume a 100% charge identification efficiency, and a perfect muon identification capability once the cuts and background are put in. This implies the assumption that the segmentation of the detector is fine enough to almost always determine whether a charged muon track has penetrated the detector beyond the reach of the hadronic shower produced in the interaction. In general, we note here that an NC event is identifiable by the absence of a charged muon track and the presence of large (hadronic) shower energy deposited in a small scintillator area. The CC events are identified by the same hadronic characteristics accompanied by a long muon track which penetrates much beyond the shower. We asume for now that the detector segmentation cannot resolve CC electron/positron events, and as such they are indistinguishable from NC events.

In other physics input, we have assumed that the atmospheric neutrino problem is resolved by $\nu_\mu \to \nu_\tau$ oscillations and the solar neutrino problem by the LMA mixing solution for $\nu_e \to \nu_\mu$. Our choices for the various input parameters which we expect will known to a reasonable degree of precision when neutrino factories begin operation are thus consistent with these assumptions. Specifically, we assume the following input parameters: $\Delta m^2_{32} = 0.003$ eV^2, $\Delta m^2_{21} = 5 \times 10^{-5}$ eV^2, $sin^2 2\theta_{23} = 1, sin^2 2\theta_{12} = 0.78$ which are consistent with best fit values determined by most analyses of solar and atmospheric data.

We assume three active flavours of neutrinos and the absence of light sterile neutrinos, and take into account all matter effects using the detailed PREM model for the earth's density profile. The CP violation is assumed to be parametrised by a single phase δ in the lepton mixing matrix. The differential equations for neutrino propagation are solved numerically without analytic approximations.

Calculations are performed using 3 different detector masses selectively, 32 kT, 50 kT and 100 kT. Two different neutrino factory configurations are considered, a) an entry level configuration corresponding to $10^{19}\mu$ decays per year and a upgraded configuration yeilding $10^{21}\mu$ decays per year.

As stated in the introduction, the focus is on baselines from JHF to India keeping the proposed options for locating the INO detector in mind. The two possible locations currently favoured are PUSHEP (N 11^o 31", E 76^o 36.5") and RAMMAM (N 27^o 24", E 88^o 5.5"). In terms of baseline distances, this translates to 4865 km for the JHF-RAMAM baseline and 6591 km for the JHF-PUSHEP baseline.

3 Results and Discussion

THe first set of calculations we have performed explore the reach for θ_{13}. We recall that the CHOOZ bound on this parameter is $sin^2 2\theta_{13} < 0.1$. Its importance lies in it being the driving parameter for $\nu_e \to \nu_\mu$ oscillations, and for CP violation searches. We stress that this is true with or without matter effects. The next generation of experiments will thus have its determination as one of the primary goals.

Figure 1 demonstrates the acheivable values of $sin\theta_{13}$ versus the muon detection threshold energy of the detector. The reach is determined as the value which is necessary to collect 10 signal events for a given kT-yr exposure. We show the reach capabilities for an entry-level configuration ($E^{th}_\mu = 20$ GeV, 10^{19} decays per year). For the median detector size of 50 kT running for 1 year, at a muon detection threshold of 2 GeV, the reach corresponds to $\sim sin\theta_{13} = 0.038$ or $\sim sin^2 2\theta_{13} = 0.0057$ for RAMMAM and a slightly higher value for PUSHEP, as shown. The reach values improve to $\sim sin\theta_{13} = 0.026$ or $\sim sin^2 2\theta_{13} = 0.0027$ for RAMMAM if the energy of the beam is increased to 50 GeV, keeping other variables the same as before. In all of the above , the "passive" parameters $\Delta m^2_{32}, \Delta m^2_{21}, sin^2 2\theta_{23}$ and $sin^2 2\theta_{12}$ are held to their (best-fit) values specified above.

A second method of obtaining a measure of θ_{13} is via matter effects which show up once the baselines are long. In particular, the total right-sign muon rate varies measurably with θ_{13}, as demonstrated in Figure 2 for the JHF-PUSHEP baseline. Here the number of such events are shown as a function of $E_\nu/\Delta m^2_{32}$ for a neutrino factory with 10^{21} muon decays/yr. Clearly, a measure of this important parameter, even if it is small, is possible via this method. Note that the event-rate peaks nicely for neutrinos in the 10-20 GeV range for the currently allowed and favoured range of values of Δm^2_{32} from atmospheric neutrino data.

We next examine the capability to determine the sign of $E_\nu/\Delta m^2_{32}$ that these baselines offer. This is sensitive once again to the wrong-sign muon rate generated by $\nu_e \to \nu_\mu$ oscillations. For small θ_{13}, and if the matter potential $A \sim E_\nu/\Delta m^2_{32} > 0$, then matter effects lead to an enhancement of $\nu_e \to \nu_\mu$ and a suppression of $\bar{\nu_e} \to \bar{\nu_\mu}$. The converse is true if the sign of $A \sim E_\nu/\Delta m^2_{32}$ is reversed.

Figure 3 shows the sign discrimination capability for an entry-level neutrino factory configuration with a 50 kT detector running for a year. For both the RAMMAM and PUSHEP baselines, the sign dependant difference in event rates is easily measurable in terms of wrong sign muon events. For comparison, we also show the difference in event-rates for a JHF-China baseline (1952 km) were a similar detector to be set up there. Figure 4 shows the improvement (or rather, the overkill) possible with a upgraded factory yeilding 10^{21} decays per year with a beam energy of 50 GeV running for one year.

We next examine the discovery potential for what many consider as the holy grail of physics in the lepton sector, i.e. the presence or absence of CP violation. In the standard three generation scenario, this is parametrized by a single phase δ in the lepton mixing matrix. In principle, rates for particles and their CP conjugates will exhibit a difference stemming from terms proportional to $\sin\delta$ in the oscillation probability. Generally, these diferences are small and difficult to dis-entangle from matter oscillation effects, which in long baseline sitiuations dominate differences due to CP. The detectability depends sensitively on $sin^2 2\theta_{13}, \Delta m^2_{21}$, the energy and baseline, among other parameters, besides of course on the magnitude of $\sin\delta$.

One possible clean signature is the ratio of wrong sign muon events for equal exposures when the neutrino factory runs with muons and anti-muons stored in the ring in turn. Thus for negatively charged stored muons, one expects $\bar{\nu_e} \to \bar{\nu_\mu}$ oscillations to produce CC induced positively charged muons, and vice-versa for a run with stored μ^+ in the ring.

In Figure 5(a), we show (as a function of baseline length)the ratio of wrong-sign muon events for a run with negatively charged muons in the storage ring (and, hence, the resultant μ^+ events due to oscillations, denoted by $N(\mu^+)$) to that for a run with positively charged muons (yeilding μ^- events via oscillations, denoted by $N(\mu^-)$). The calculations are performed for a factory with a beam energy of 20 GeV and a muon decay yeild of 10^{21} decays per year. For this plot a value of $sin\theta_{13} = 0.1$ ($sin^2 2\theta_{13} = 0.04$) has been assumed, along with a run of 1 year each of either sign of stored muon, and a detector mass of 32 kT has been used. The dashed curves are for $\delta = \pm\pi/2$ and the data points show the values (along with statistical errors) for $\delta = 0$ at the Beijing (1952 km), RAMAM (4865 km) and PUSHEP (6591 km) respectively. The two sets of curves (upper and lower) correspond to opposite signs of Δm^2_{32}, which reflect the effects of matter. We note that CP effects tend to cancel (i.e are small) for this configuration at PUSHEP, hence the measurements there afford an opportunity to effectively isolate and measure the matter effects. Such measurements can be used in conjunction with measurements at a baseline where CP effects are relatively large and afford a cleaner discrimination between $\delta = 0$ and a non-zero value of this parameter. This is exemplified in Figure 5(b) which uses the same parameters as 5(a) but assumes a beam energy of 50 GeV and a slightly more massive detector of 50 kT. One notes here (as in Fig 5(a)) that the RAMMAM baseline offers an opportunity to detect the presence of a δ which is different from zero, especially as exposure (in kT-yr) and statistics improve.

Figures 5(c) and 5(d) show the CP capabilities for the same 2 configurations as the ones in Fig 5(a) and Fig 5(b) respectively, but for a lower value of $sin\theta_{13}$, namely 0.03. Note that both our chosen values of this parameter are well below the current CHOOZ bound. The conclusions for both RAMMAM and PUSHEP are similar to the ones above. The former provides us with an opportunity to measure the presence of a non-zero CP violation, while the latter provides us an opportunity to seperate matter effects from the CP violation contributions in conjunction with another long-baseline experiment.

4 Conclusions

We have presented sample calculations to exemplify the physics possible with a large Iron Calorimeter based at RAMMAM and PUSHEP, two proposed locations in India, when such a detector is used as an end detector for a neutrino factory at JHF. We conclude that such a set-up offers rich possibilities for measurements related to $\nu_e \rightarrow \nu_\mu$ oscillations, $sin^2 2\theta_{13}$, the detection of matter effects, the determination of the sign of Δm^2_{32}, and finally the CP violation phase δ. We stress that although these prelimnary studies are encouraging, further work is called for to precisely determine the full physics potential offered by this combination of an intense source, a very long baseline and a large detector with very good charge-discrimination capabilities.

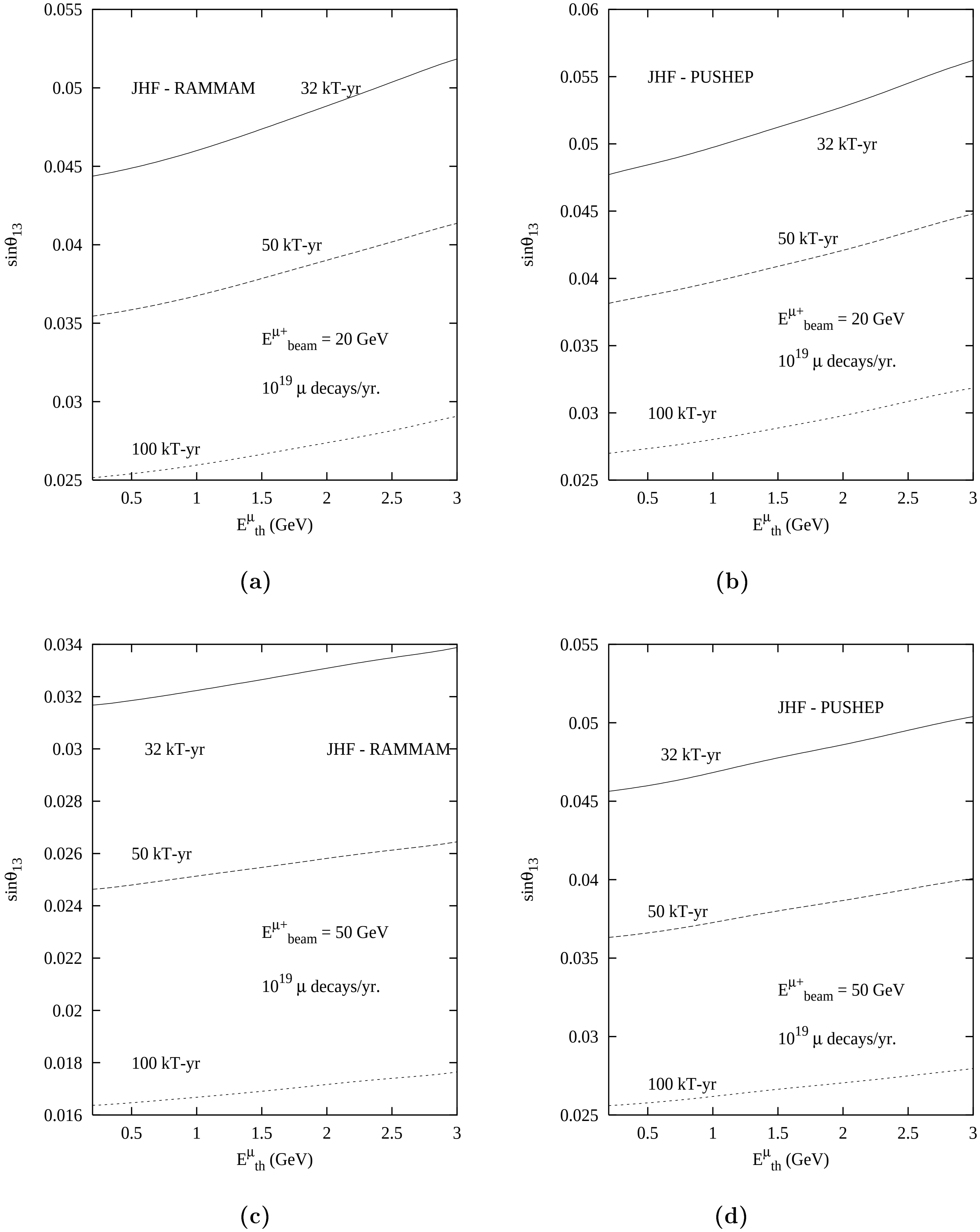

Figure 1: *The $sin\theta_{13}$ reach for detector exposures of 32 kT-yr, 50 kT-yr and 100 kT-yr for an entry-level neutrino factory configuration with $E_\mu = 20$ GeV for the (a) JHF-RAMAM baseline, the JHF-PUSHEP baseline (b). In (c) and (d) we show the improvement in reach if the storage muon energy is increased to 50 GeV, keeping the number of decays per year the same, i.e, 10^{19}/yr.*

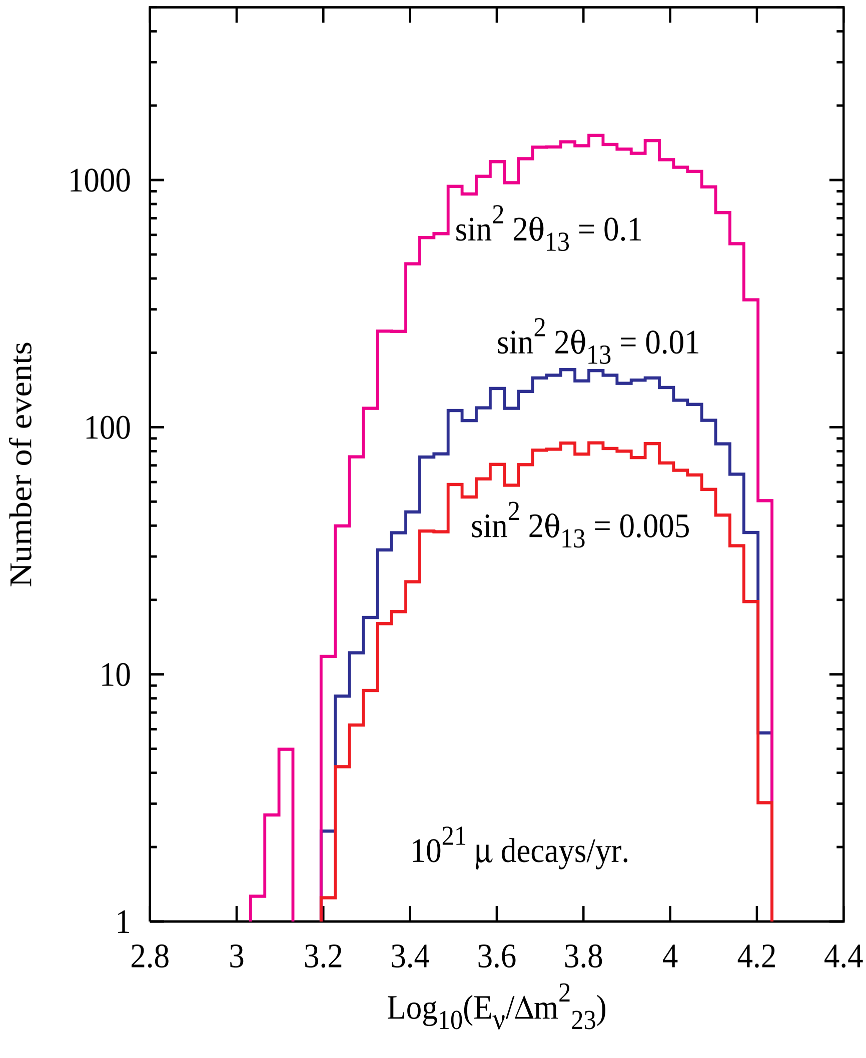

Figure 2: The number of right-sign muon events as a function of $E_\nu/\Delta m^2_{32}$ for the JHF-PUSHEP baseline. The dip to the left of the distribution is due to a minimum of the oscillation probability.

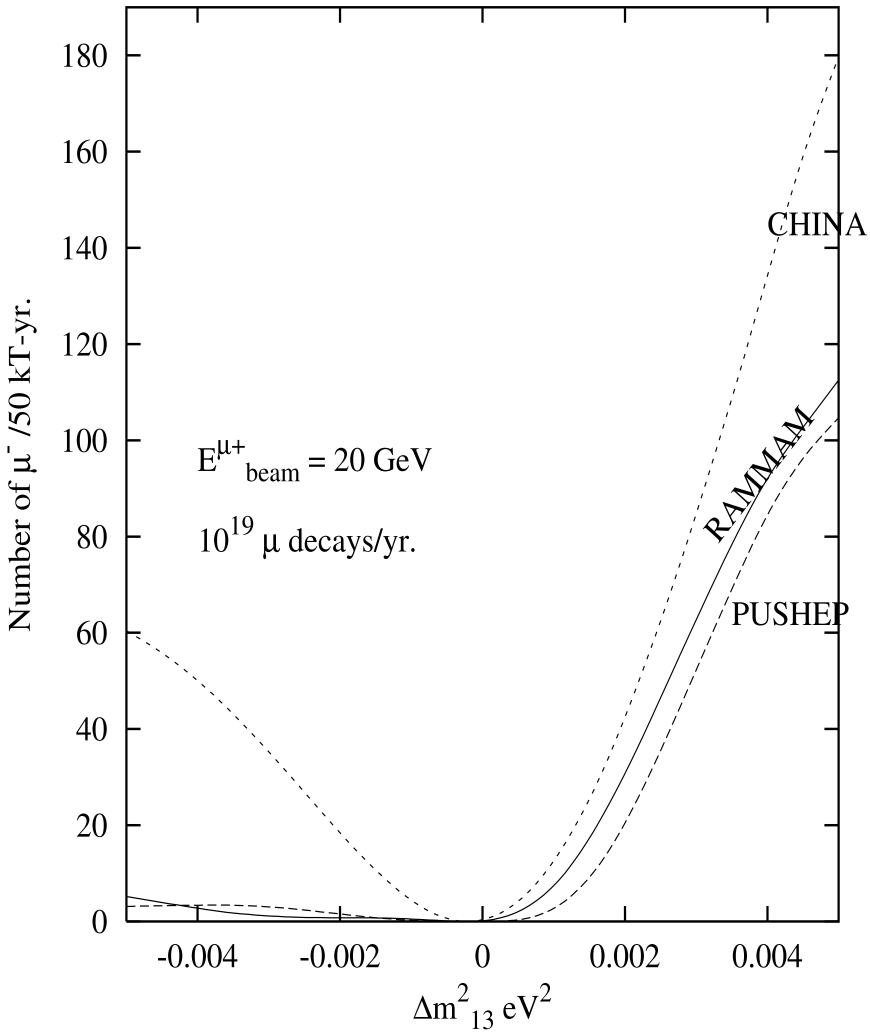

Figure 3: The number of wrong-sign muon events as a function of Δm^2_{32} for the three baselines from JHF, demonstrating the sign discriminating capability which arises as a result of matter effects. Event rates are computed for an entry-level configuration with a 50 kT-yr exposure.

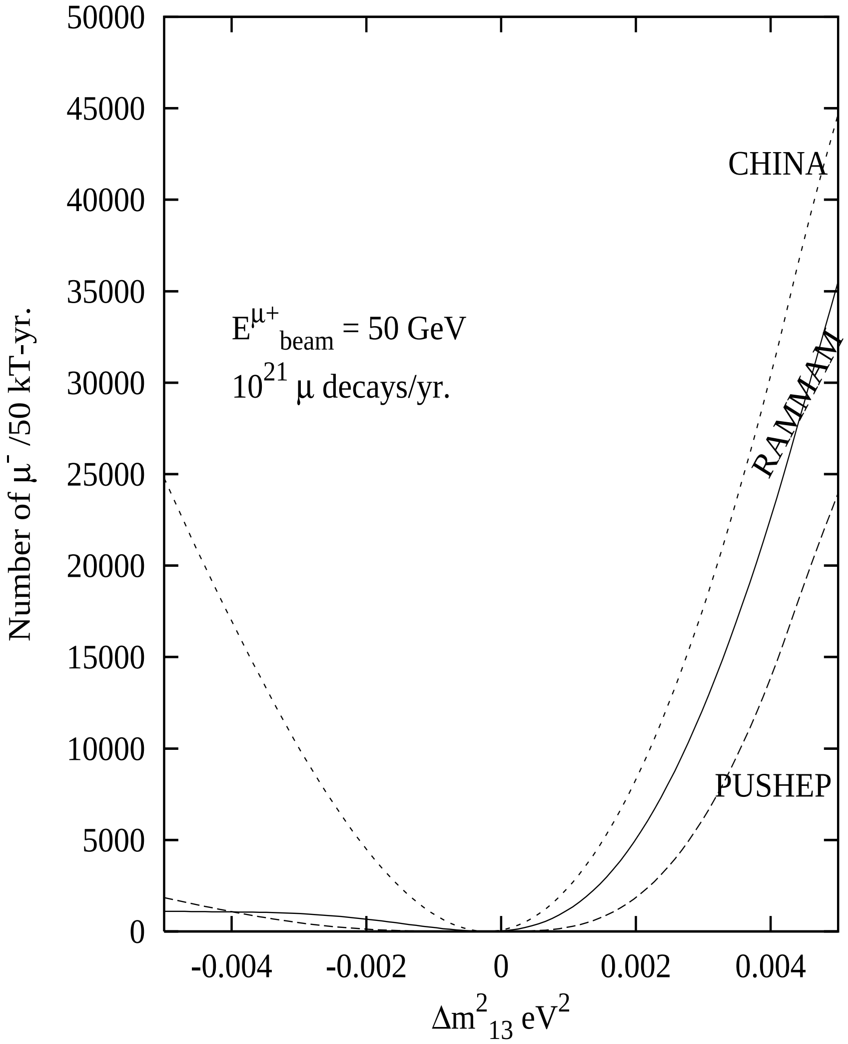

Figure 4: The same as Figure 3, but for a upgraded neutrino factory configuration with a 50 kT-yr exposure.

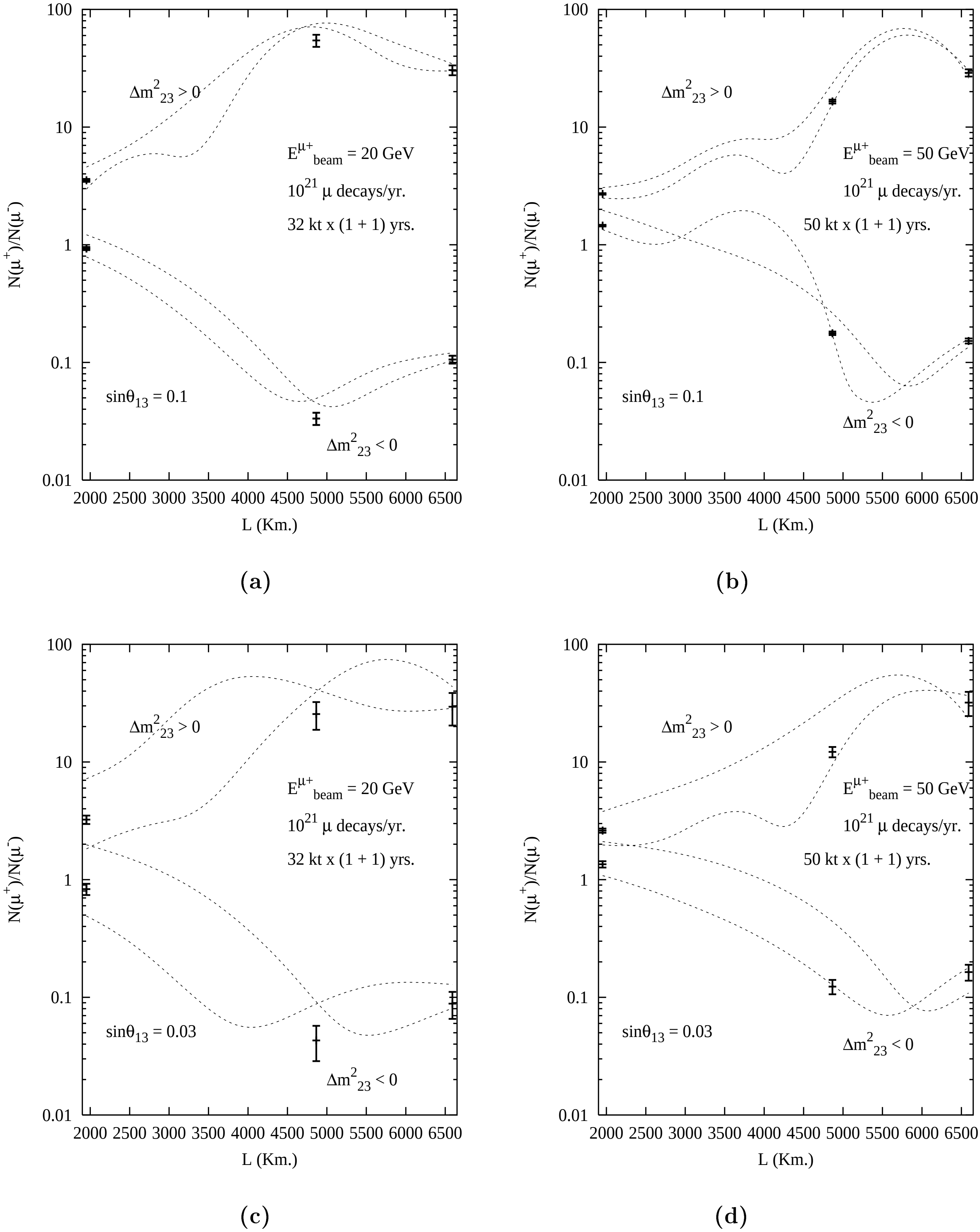

Figure 5: *The $sin\theta_{13}$ reach for detector exposures of 32 kT-yr, 50 kT-yr and 100 kT-yr for an entry-level neutrino factory configuration with $E_\mu = 20$ GeV for the (a) JHF-RAMAM baseline, the JHF-PUSHEP baseline (b). In (c) and (d) we show the improvement in reach if the storage muon energy is increased to 50 GeV, keeping the number of decays per year the same, i.e, 10^{19}/yr.*