Oscillation Physics at the Neutrino Factory

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Disclaimer

- Not comprehensive, surely biased, my view of what is going on in the field.
- (Almost) not discussing:
  - Oscillation physics with LA "ICARUS" like detectors (will be covered by André Rubbia)
  - Potential of Beta Beams (will be covered by Jacques Bouchez)
  - Super Beams proposals and potential (Dough Michael)

Outline

- Preliminaries
- Early research on neutrino oscilations at NuFact, as told by Spires (1998-2000)
- Degeneracies, Correlations, Systematic errors (2001,2002)
- Puzzling it out
  - Combining two facilities to solve degeneracies
  - Combining golden and silver channels
- Conclusions

Preliminaries

The source of the mixing

The Pontecorvo-Maki-Nakagawa-Sakata matrix:

$$\begin{pmatrix} \text{FlavourBasis} \\ |\nu_\alpha\rangle \end{pmatrix} = \sum_i U^{\alpha i}_{\text{PMNS}} \times \begin{pmatrix} \text{MassBasis} \\ |\nu_i\rangle \end{pmatrix}$$

and its space-evolution:

$$i\,\frac{d}{dx}\,|\nu_\alpha\rangle = \sum_\alpha \sum_\beta \left(U \left[\frac{\Delta m^2}{2E_\nu}\right] U^\dagger + [A] \right)_{\alpha\beta} |\nu_\beta\rangle$$

$$\left[\frac{\Delta m^2}{2E_\nu}\right] = \frac{1}{2E_\nu}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}$$

$$[A] = \begin{pmatrix} \sqrt{2}G_F N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Matter effects

The PMNS mixing matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \Leftarrow$$

Δm^2_{23} and θ_{23}:
SK, K2K;
MINOS, CNGS

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \Rightarrow$$

CHOOZ bound:
$\sin^2(2\theta_{13}) \leq 0.1$
NO HINTS on δ

$$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \Leftarrow$$

Δm^2_{12} and θ_{12}:
SNO, KamLand

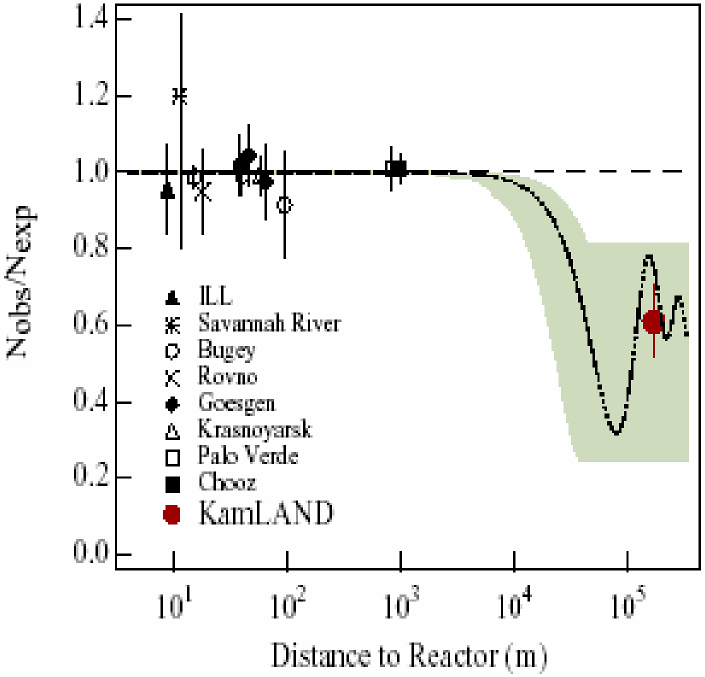
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\gamma_1} & 0 \\ 0 & 0 & e^{i\gamma_2} \end{pmatrix} \Rightarrow$$

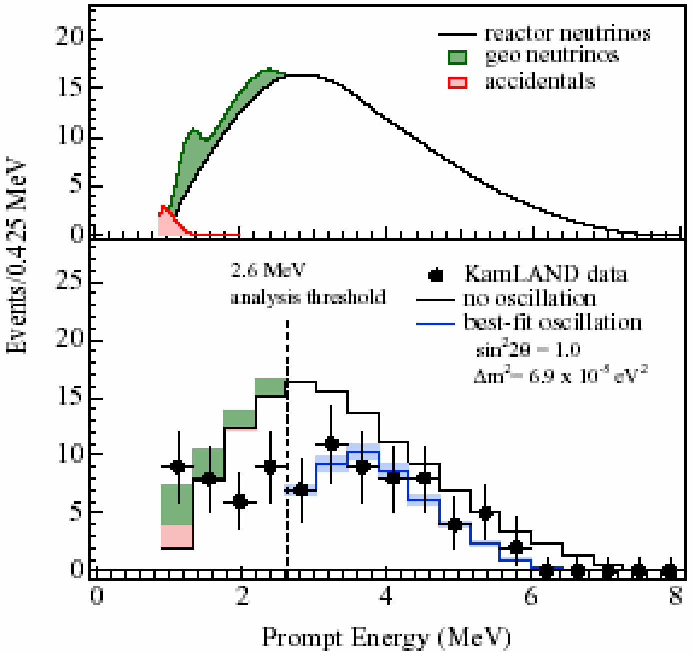
Majorana phases:
not in oscillations!

- **KamLAND (2002):**

Measures reactor neutrinos from a cluster of nuclear plants around Kamioka $\langle L \rangle = O(175)$km

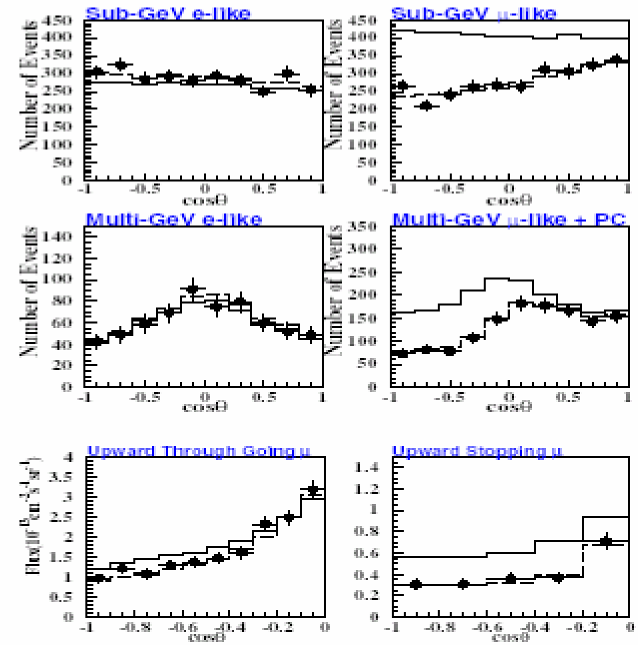
$\langle E_\nu(\text{MeV})\rangle / L(100km) \sim 10^{-5}\text{eV}^2$



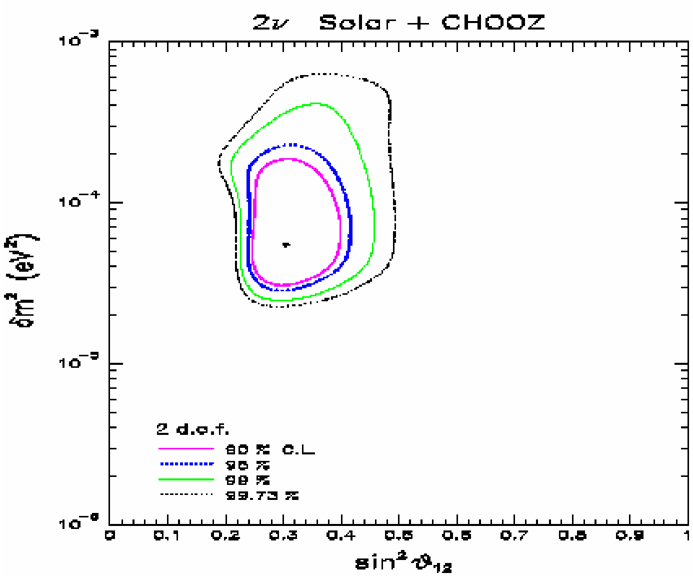


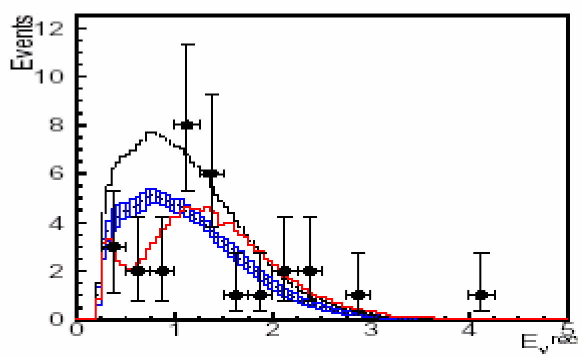
Reactor fluxes contain less $\bar{\nu}_e$ than expected and show the expected E/L dependence: if confirmed first direct proof of oscillations!

Evidence for oscillations



Global Fits 2003





Fogli et al

Early research on neutrino oscillations at Nufact, as told by Spires (1997-2000)

Neutrino Factory (re)invented

Neutrino Beams from Muon Storage Rings: Characte
and Physics Potential

S. Geer

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

High-intensity high-energy neutrino beams could be produced by expl
ing a very intense future muon source, and allowing the muons to decay i
storage ring containing a long straight section. Taking the parameters of m
source designs that are currently under study, the characteristics of the neut
beams that could be produced are discussed and some examples of their phy
potential given. It is shown that the neutrino and antineutrino beam intensi
may be sufficient to produce hundreds of charged current interactions per y
in a detector on the far side of the Earth.

PACS numbers: 14.60.Pq, 13.15.+g, 13.35.Bv, 07.77Ka

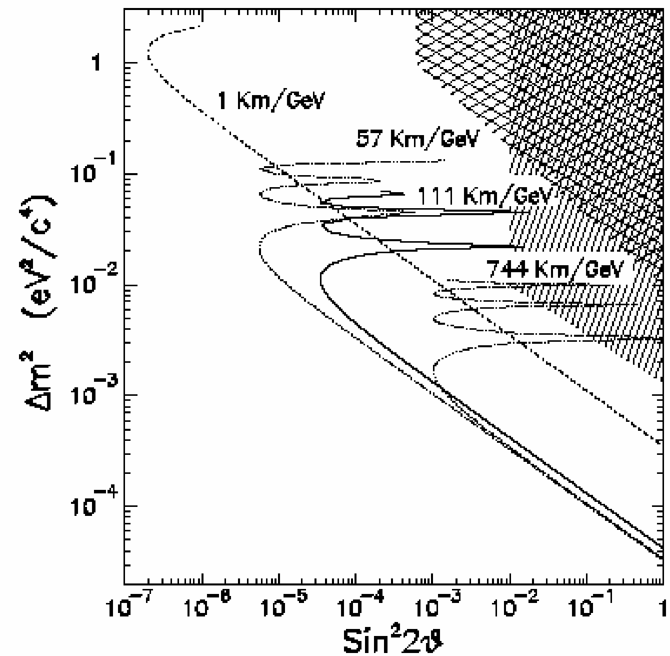


Figure 8: Contours of single–event sensitivity for ν_e–ν_μ oscillations for 1 year of running with the 4 values of L/E specified on the figure, which correspond to the 4 detector configurations summarized in Table 1. The hatched and cross-hatched areas show the expected regions that will be explored by respectively the MINOS experiment [10] after 2 years of running and the MiniBooNe experiment [11] after 1 year of running.

Wrong sign muons give access to full PNMS matrix including CP

CERN-TH/98-321
FTUAM-98-19

Neutrino oscillation physics with a neutrino factory

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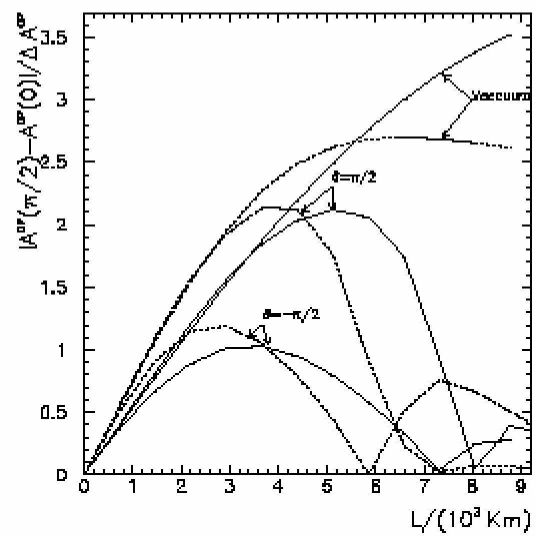
Abstract

Data from atmospheric and solar neutrinos indicate that there are at least three neutrino types involved in oscillation phenomena. Even if the corresponding neutrino mass scales are very different, the inevitable reference to mixing between more than two neutrino types has profound consequences on the planning of the accelerator experiments suggested by these results. We discuss the measurement of mixing angles and CP phases in the context of the neutrino beam emanating from a *neutrino factory*: the straight sections of a muon storage ring. We emphasize the importance of charge identification. The appearance of wrong sign muons in a long baseline experiment may provide a powerful test of neutrino oscillations in the mass-difference range indicated by atmospheric-neutrino observations.



Signal over statistical uncertainty in a measurement of CP asymmetries as a distance, with the continuous (dashed) lines corresponding to $E_\mu = 20\,(10)$ chosen CKM parameters are those of the last row of Table 1. The lower four ribe $|\overline{\mathcal{A}}_{e\mu}(\pm\pi/2)|$ over its statistical error. The upper two curves are vacuum the same CP phase(s).

Matter effects

FERMILAB-Pub-99-187-T
MADPH-99-1122
AMES-HET-99-0
hep-ph/9906487

Long Baseline Neutrino Physics with a Muon Storage Ring Neutrino Sou

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We examine the physics capabilities of known flavor neutrino beams from intense muon sources. We find that long-baseline neutrino experiments based on such beams can provide precise measurements of neutrino oscillation mass and mixing parameters. Furthermore, they can test whether the dominant atmospheric neutrino oscillations are $\nu_\mu \to \nu_\tau$ and/or $\nu_\mu \to \nu_s$, determine the $\nu_\mu \to \nu_e$ content of atmospheric neutrino oscillations, and measure $\nu_e \to \nu_\tau$ appearance. Depending on the oscillation parameters, they may be able to detect Earth matter and CP violation effects and to determine the ordering of some of the mass eigenstates.

14.60.Pq, 13.15.+g, 13.35.Bv, 07.77Ka

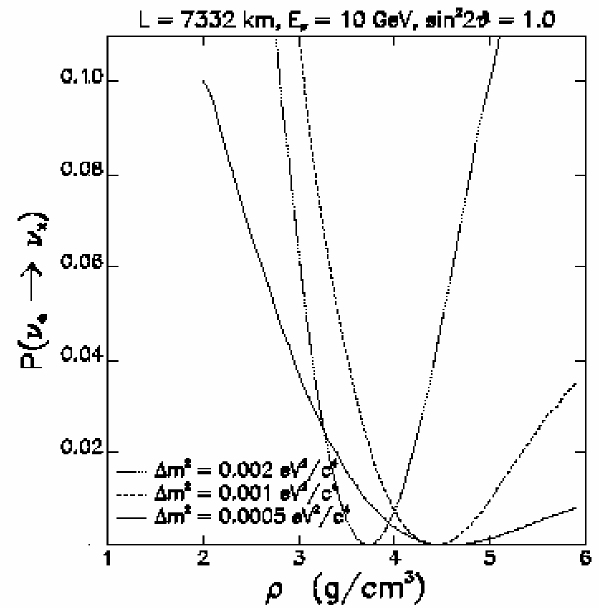

FIG. 11. Electron neutrino disappearance probability $P(\nu_e \to \nu_x)$ for $x = \mu$ or τ, shown as a function of the assumed matter density for 10 GeV electron neutrinos propagating 7332 km through the Earth. The curves correspond to the oscillation parameters $\sin^2 2\theta = 1$ and Δm^2 as indicated.

CP violation in 3 and 4 families

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CERN-TH/99-252
FTUAM-99-25
FTUV/99-59
IFIC/99-62

Neutrino mixing and CP-violation

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Abstract

The prospects of measuring the leptonic angles and CP-odd phases at a neutrino factory are discussed in two scenarios: 1) three active neutrinos as indicated by the present ensemble of atmospheric plus solar data; 2) three active plus one sterile neutrino when the LSND signal is also taken into account. For the latter we develop one and two mass dominance approximations. The appearance of wrong sign muons in long baseline experiments and tau leptons in short baseline ones provides the best tests of CP-violation in scenarios 1) and 2), respectively.

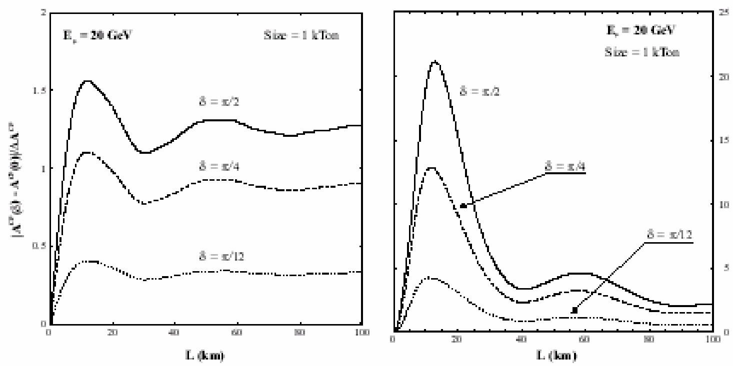

Figure 10: *CP violation asymmetry in the* $\nu_e \to \nu_\mu$ *(left) and* $\nu_\mu \to \nu_\tau$ *(right) channel for* $E_\mu = 20$ *GeV, angles and mass differences as in Set 2 and for different choice of the CP phases:* $\delta_1 = \delta_2 = \delta_3 = \pi/2$ *(full line),* $\pi/4$ *(dashed line) and* $\pi/12$ *(dotted line). We consider a 1 kTon detector from the source of a* 2×10^{20} *muon/year beam.*

CP Violation in 3 and 4 families. Depencency with θ_{13}

TUM–HEP–345/99
SFB 375–334
MPI–PhT/9907
OUTP–99–15P
April 1999

CP-Violation in Neutrino Oscillations*

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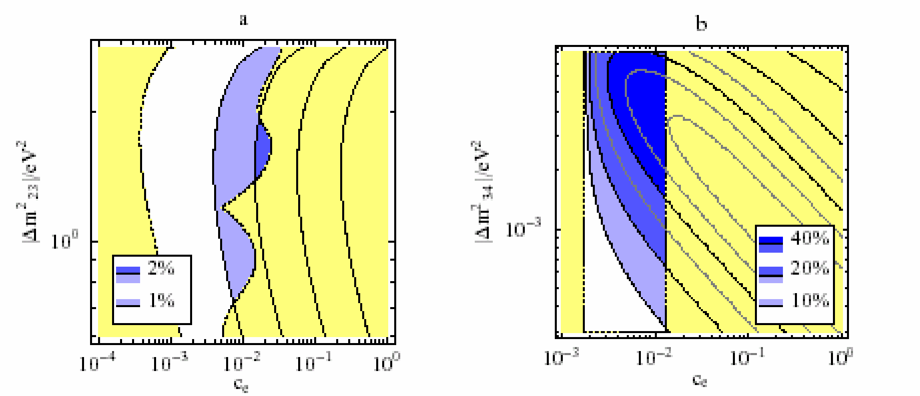
Abstract

We study in a quantitative way CP-violating effects in neutrino oscillation experiments in the light of current and future data. Different scenarios with three and four neutrinos are worked out in detail including matter effects in long baseline experiments and it is shown that in some cases CP-violating effects could affect the analysis of a possible measurement. In particular in the three neutrino case we find that the effects can be larger than expected, at least in long-baseline $\nu_\mu \to \nu_e$. Moreover, measuring these effects could give useful information on the solar oscillation frequency. In four neutrino scenarios large effects are possible both in the $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ channels of long-baseline experiments, whereas short-baseline experiments are affected only marginally.



igure 5: *Contour lines for* $|a^{CP}_{\nu_\mu\nu_e}/\sin\delta_{\mu e}|$ *in a four neutrino scenario plotted in the* c_e–
$m^2_{23}|$ *parameter space of a short-baseline experiment for* $|\Delta m^2_{34}| = 8\cdot 10^{-3}\,\mathrm{eV}^2$ *(a) and in*
e c_e–$|\Delta m^2_{34}|$ *plane of a long-baseline experiment for* $|\Delta m^2_{23}| = 1\,\mathrm{eV}^2$ *(b). Only the allowed*
$m^2|$ *ranges are shown. The shadowed regions are excluded by the constraints (29).*

Sign of Δm^2, precision measurement of atmospheric parameters

MADPH-99-1145
Fermilab-PUB 99-341-T
AMES-HET 99-12
hep-ph/9911524
November 1999

Long-Baseline Study of the Leading Neutrino Oscillation at a Neutrino Factory

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Abstract

Within the framework of three-flavor neutrino oscillations, we consider the physics potential of $\nu_e \to \nu_\mu$ appearance and $\nu_\mu \to \nu_\mu$ survival measurements at a neutrino factory for a leading oscillation scale $\delta m^2 \sim 3.5 \times 10^{-3}$ eV^2. Event rates are evaluated versus baseline and stored muon energy, and optimal values discussed. Over a sizeable region of oscillation parameter space, matter effects would enable the sign of δm^2 to be determined from a comparison of $\nu_e \to \nu_\mu$ with $\bar{\nu}_e \to \bar{\nu}_\mu$ event rates and energy distributions. It is important, therefore, that both positive and negative muons can be stored in the ring. Measurements of the $\nu_\mu \to \nu_\mu$ survival spectrum could determine the magnitude of δm^2 and the leading oscillation amplitude with a precision of $\mathcal{O}$(1%–2%).

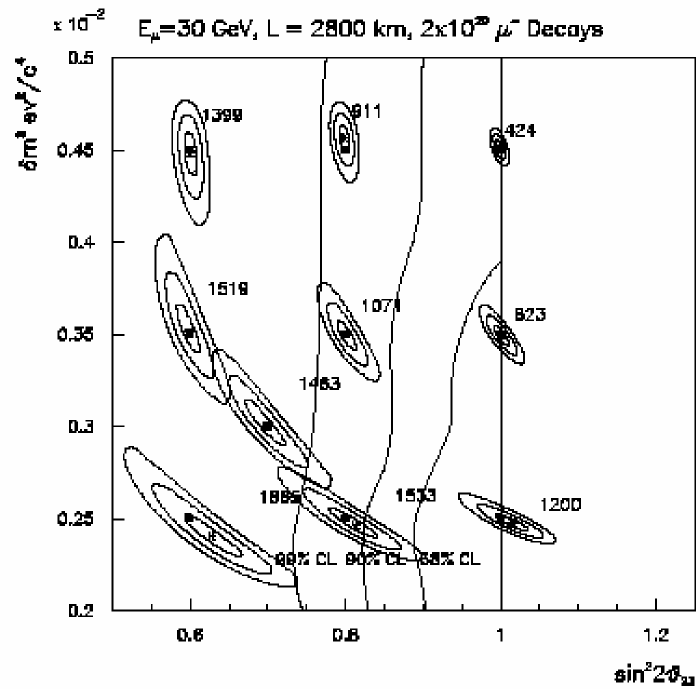

FIG. 13. Fit to muon neutrino survival distribution for $E_\mu = 30$ GeV and $L = 2800$ km for 10 pairs of $\sin^2 2\theta$, δm^2 values. For each fit, the 1σ, 2σ and 3σ contours are shown. The generated points are indicated by the dark rectangles and the fitted values by stars. The SuperK 68%, 90%, and 95% confidence levels are superimposed. Each point is labelled by the predicted number of signal events for that point.

Simultaneous Measurement of θ_{13} and δ through wrong sign muons

hep-ph/0002108
CERN-TH/2000-40
FTUAM-00-03
IFT-UAM/CSIC-00-04
FTUV/00-12
IFIC/00-13

Golden measurements at a neutrino factory

A. Cervera[a,1], A. Donini[b,2], M.B. Gavela[b,3], J.J. Gomez Cádenas[a,4], P. Hernández[c,5], O. Mena[b,6] and S. Rigolin[d,7]

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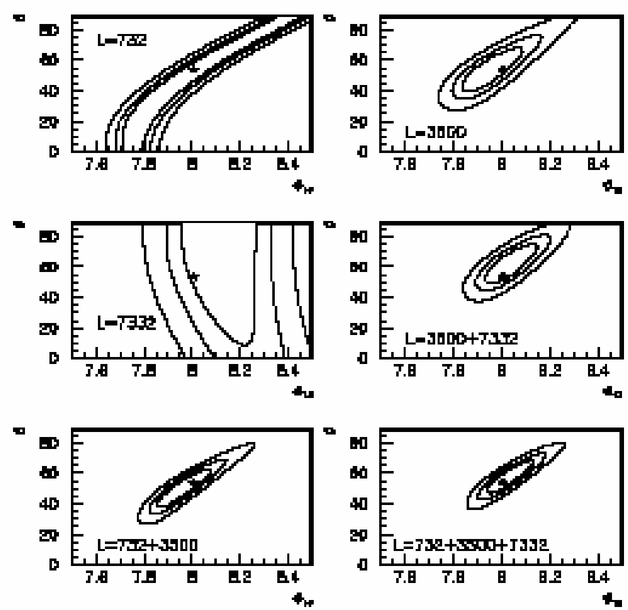
Abstract

The precision and discovery potential of a neutrino factory based on muon storage rings is studied. For three-family neutrino oscillations, we analyse how to measure or severely constraint the angle θ_{13}, CP violation, MSW effects and the sign of the atmospheric mass difference Δm^2_{23}. We present a simple analytical formula for the oscillation probabilities in matter, with all neutrino mass differences non-vanishing, which clarifies the subtleties involved in disentangling the unknown parameters. The appearance of "wrong-sign muons" at three reference baselines is considered: 732 km, 3500 km, and 7332 km. We exploit the dependence of the signal on the neutrino energy, and include as well realistic background estimations and detection efficiencies. The optimal baseline turns out to be $\mathcal{O}(3000$ km). Analyses combining the information from different baselines are also presented.



Physics potential

FERMILAB-FN-692
December 11, 2001

Physics at a Neutrino Factory

C. Albright,[8,22] G. Anderson,[14] V. Barger,[21] R. Bernstein,[8]
G. Blazey,[8] A. Bodek,[20] E. Buckley–Geer,[8] A. Bueno,[7]
M. Campanelli,[7] D. Carey,[8] D. Casper,[18] A. Cervera,[6] C. Crisan,[8]
F. DeJongh,[8] S. Eichblatt,[14] A. Erner,[14] R. Fernow,[3] D. Finley,[8]
J. Formaggio,[5] J. Gallardo,[3] S. Geer,[8] M. Goodman,[1] D. Harris,[8]
E. Hawker,[11] J. Hill,[16] R. Johnson,[9] D. Kaplan,[9] S. Kahn,[3]
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D. Krop,[14] Z. Ligeti,[8] J. Lykken,[8] K. McDonald,[15]
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J. Nelson,[19] D. Neuffer,[8] P. Nienaber,[12] R. Palmer,[3] S. Parke,[8]
Z. Parsa,[3] R. Plunkett,[8] E. Prebys,[15] C. Quigg,[8] R. Raja,[8]
S. Rigolin,[4] A. Rubbia,[7] H. Schellman,[14,8] M. Shaevitz,[8]
P. Shanahan,[8] R. Shrock,[3,16] P. Spentzouris,[8] R. Stefanski,[8]
J. Stone,[2] L. Sulak,[2] G. Unel,[14] M. Velasco,[14] K. Whisnant[10],
J. Yu[8], E.D. Zimmerman[5]

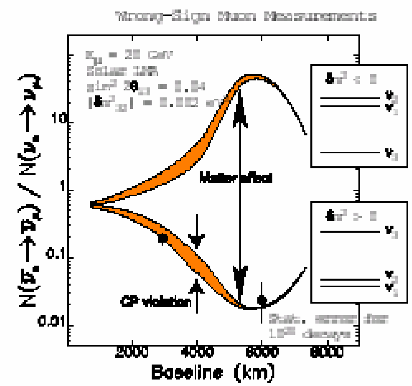

Figure I: Predicted ratios of $\bar{\nu}_e \to \bar{\nu}_\mu$ to $\nu_e \to \nu_\mu$ rates at a 20 GeV neutrino factory. The upper (lower) band is for $\delta m^2_{32} < 0$ ($\delta m^2_{32} > 0$). The range of possible CP violation determines the widths of the bands. The statistical error shown corresponds to 10^{20} muon decays of each sign and a 50 kt detector. Results are from Ref. 51.

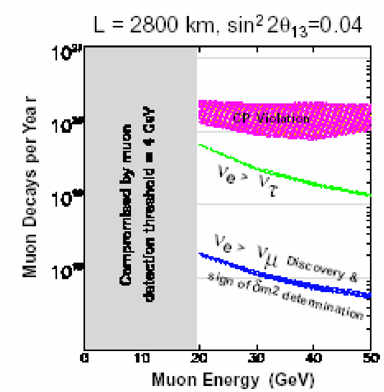

Figure II: The required number of muon decays needed in a neutrino factory to observe $\nu_e \to \nu_\mu$ oscillations in a 50 kt detector and determine the sign of δm^2, and the number of decays needed to observe $\nu_e \to \nu_\tau$ oscillations in a few kt detector, and ultimately put stringent limits on (or observe) CP violation in the lepton sector with a 50 kt detector. Results are from Ref. 51.

Degeneracies, correlations, systematic errors. Super Beams vs Nufact (2001,2002)

Oscillation Probability

Golden measurements at a neutrino factory

A. Cervera[a,1], A. Donini[b,2], M.B. Gavela[b,3], J.J. Gomez Cádenas[a,4], P. Hernández[c,5], O. Mena[b,6] and S. Rigolin[d,7]

$$P_{e\mu}^{\pm} = X_{\pm} \sin^2(2\,\theta_{13})$$
$$+Y_{\pm} \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13})$$
$$+Z + \ldots$$

$$\mu^+ \rightarrow \begin{cases} e^+ \\ \bar{\nu}_\mu \\ \nu_e \rightarrow \nu_\mu \rightarrow \mu^- \end{cases}$$

(+ neutrinos, − antineutrinos)

$$\begin{cases} X_\pm = \Delta_{atm}^2 \times f_X^{\pm}(\theta_{23}, A, L) \\ Y_\pm = \Delta_{sun} \times \Delta_{atm} \times f_Y^{\pm}(\theta_{12}, \theta_{23}, A, L) \\ Z = \Delta_{sun}^2 \times f_Z(\theta_{12}, \theta_{23}, A, L) \end{cases}$$

(θ_{13}', δ') are fake solutions of:

$$\left.\begin{array}{l} P_{\nu_e\nu_\mu}(\theta_{13}', \delta') = P_{\nu_e\nu_\mu}(\theta_{13}, \delta) \\ P_{\bar{\nu}_e\bar{\nu}_\mu}(\theta_{13}', \delta') = P_{\bar{\nu}_e\bar{\nu}_\mu}(\theta_{13}, \delta) \end{array}\right\} \text{at fixed } E_\nu \text{ and } L.$$

They appear when the full parameter is considered and the energy dependence of the signal (including realistic backgrounds and efficiencies) is not strong enough.

In fact, 3 sources of degeneracies

Intrinsic $\rightarrow \; P(\theta_{13}', \delta') = P(\theta_{13}, \delta)$

(J. Burguet-Castell, *et al*, Nucl. Phys. **B608**, (2001))

θ_{23}- Octant $\rightarrow \; P(\theta_{13}', \delta', \frac{\pi}{2} - \theta_{23}) = P(\theta_{13}, \delta)$

(G.L. Fogli and E. Lisi, Phys. Rev. **D54** (1996); V. Barger *et al*, Phys. Rev. **D65** (2002).)

Sign-Δm^2_{13} $\rightarrow \; P(\theta_{13}', \delta', -\Delta m^2_{13}) = P(\theta_{13}, \delta)$

(H. Minakata and H. Nunokawa, JHEP **0110** (2001); V. Barger *et al*, Phys. Rev. **D65** (2002).)

Intrinsic Degeneracy

On the measurement of leptonic CP violation

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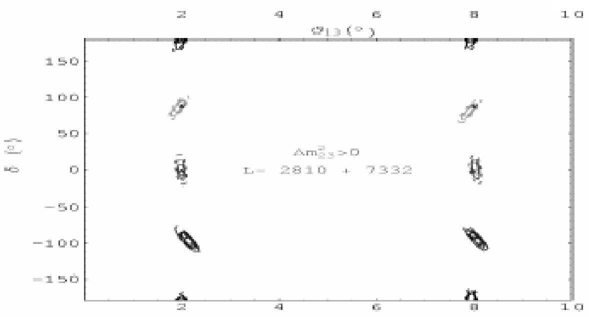
Abstract

We show that the simultaneous determination of the leptonic CP-odd phase δ and the angle θ_{13} from the subleading transitions $\nu_e \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\mu$ results generically, at fixed neutrino energy and baseline, in two degenerate solutions. In light of this, we refine a previous analysis of the sensitivity to leptonic CP violation at a neutrino factory, in the LMA-MSW scenario, by exploring the full range of δ and θ_{13}. Furthermore, we take into account the expected uncertainties on the solar and atmospheric oscillation parameters and in the average Earth matter density along the neutrino path. An intermediate baseline of $O(3000)$ km is still the best option to tackle CP violation, although a combination of two baselines turns out to be very important in resolving degeneracies.

Combining two baselines



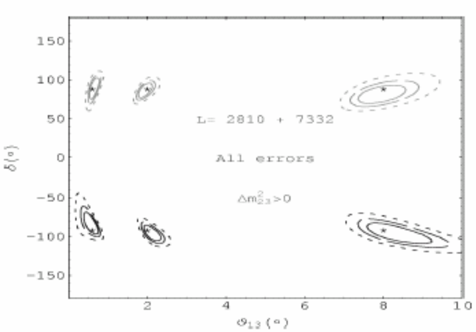


Figure 10: *Fits of δ and θ_{13} combining the two baselines: 2810 km and 7332 km, for various central values of δ and θ_{13} including all the errors on the remaining parameters with $\Delta A/A = 1\%$.*

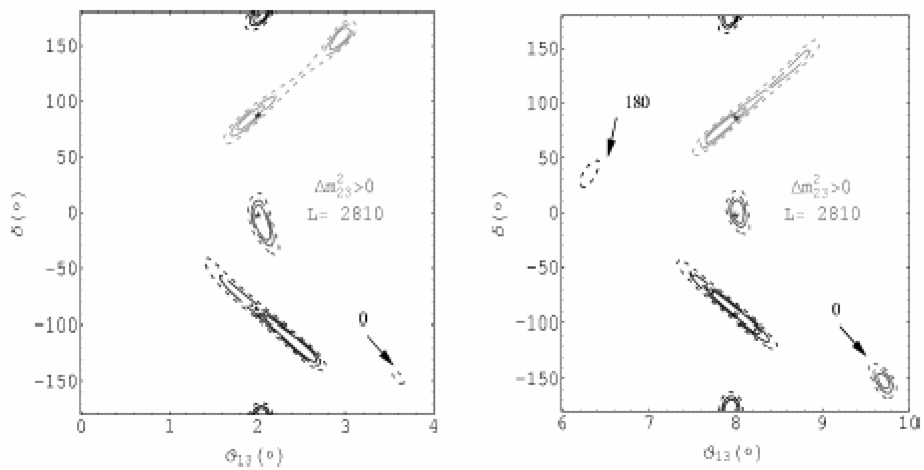


Figure 4: *Simultaneous fits of δ and θ_{13} at $L = 2810$ km for different central values (indicated by the stars) of $\bar{\delta} = -90°, 0°, 90°, 180°$ and $\bar{\theta}_{13} = 2°$ (left), $8°$ (right). The value of δ for the degenerate solutions is also indicated.*

Exploring Neutrino Mixing with Low Energy Superbeams

Sign degeneracy

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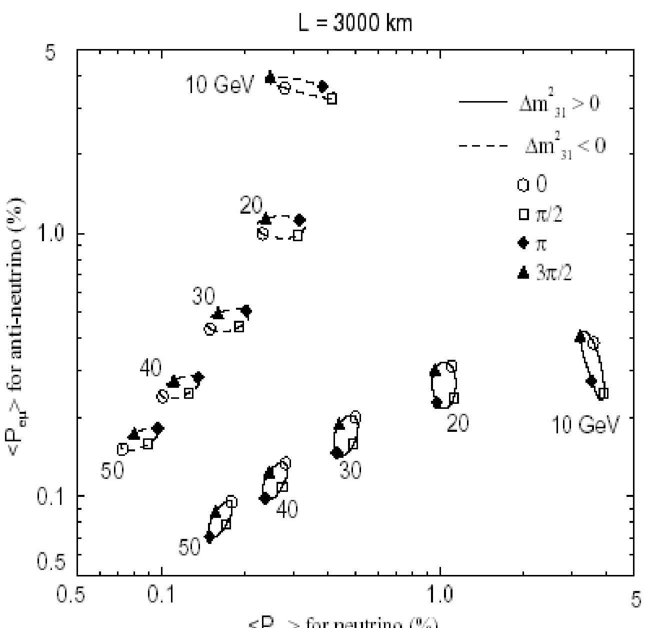

Figure 8: The CP trajectory diagram in bi-probability plane for $L = 3000$ km and much higher neutrino energies $E = 10-50$ GeV which correspond to so called "Neutrino Factory" situation. The mixing parameters are fixed to be the same as in Fig. 1 except that we take $\rho Y_e = 2.0$ g/cm^3.

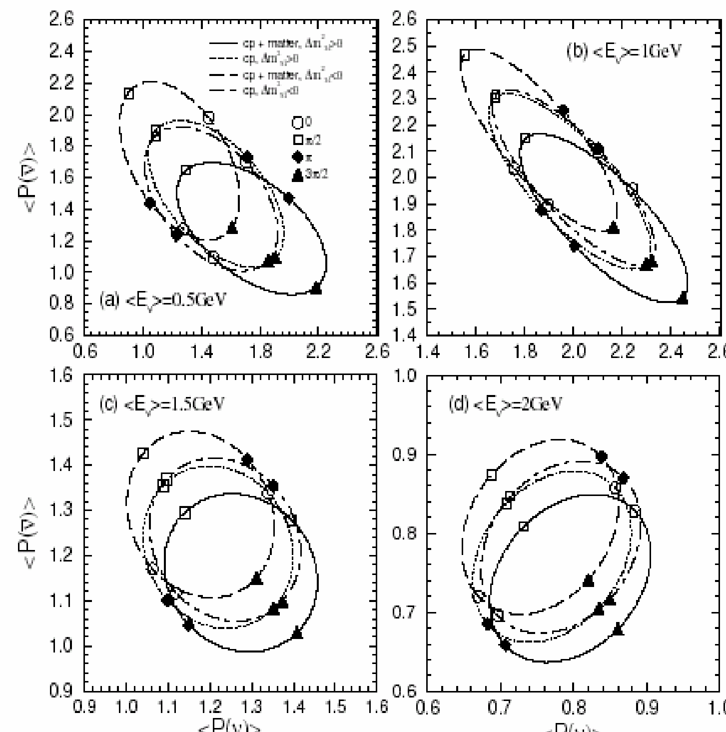

Figure 1: CP trajectory in the bi-probability (given in %) plane for the baseline $L = 295$ km. As indicated in the figures, the solid and the dashed lines are for $\Delta m^2_{13} > 0$ and $\Delta m^2_{13} < 0$ cases, respectively, and the dotted and the dash-dotted lines correspond to the same signs of Δm^2_{13} as above but with matter effect switched off. The mixing parameters are fixed as $\Delta m^2_{13} = \pm 3 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{12} = 5 \times 10^{-5}$ eV^2, $\sin^2 2\theta_{12} = 0.8$, $\sin^2 2\theta_{13} = 0.05$. We take $\rho Y_e = 1.4$ g/cm^3 where ρ is the matter density and Y_e is the electron fraction.

θ_{23} degeneracy and limitations on physics potential of superbeams

Breaking Eight–fold Degeneracies in Neutrino CP Violation, Mixing, and Mass Hierarchy

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Abstract

We identify three independent two-fold parameter degeneracies $(\delta\,,\theta_{13})$, $\mathrm{sgn}(\delta m^2_{31})$ and $(\theta_{23}\,,\pi/2-\theta_{23})$ inherent in the usual three–neutrino analysis of long–baseline neutrino experiments, which can lead to as much as an eight–fold degeneracy in the determination of the oscillation parameters. We discuss the implications these degeneracies have for detecting CP violation and present criteria for breaking them. A superbeam facility with a baseline at least as long as the distance between Fermilab and Homestake (1290 km) and a narrow band beam with energy tuned so that the measurements are performed at the first oscillation peak can resolve all the ambiguities other than the $(\theta_{23}\,,\pi/2-\theta_{23})$ ambiguity (which can be resolved at a neutrino factory) and a residual $(\delta\,,\pi-\delta)$ ambiguity. However, whether or not CP violation occurs in the neutrino sector can be ascertained independently of the latter two ambiguities. The $(\delta\,,\pi-\delta)$ ambiguity can be eliminated by performing a second measurement to which only the $\cos\delta$ terms contribute. The hierarchy of mass eigenstates can be determined at other oscillation peaks only in the most optimistic conditions, making it necessary to use the first oscillation maximum. We show that the degeneracies may severely compromise the ability of the proposed SuperJHF–HyperKamiokande experiment to establish CP violation. In our calculations we use approximate analytic expressions for oscillation probabilitites that agree with numerical solutions with a realistic Earth density profile.

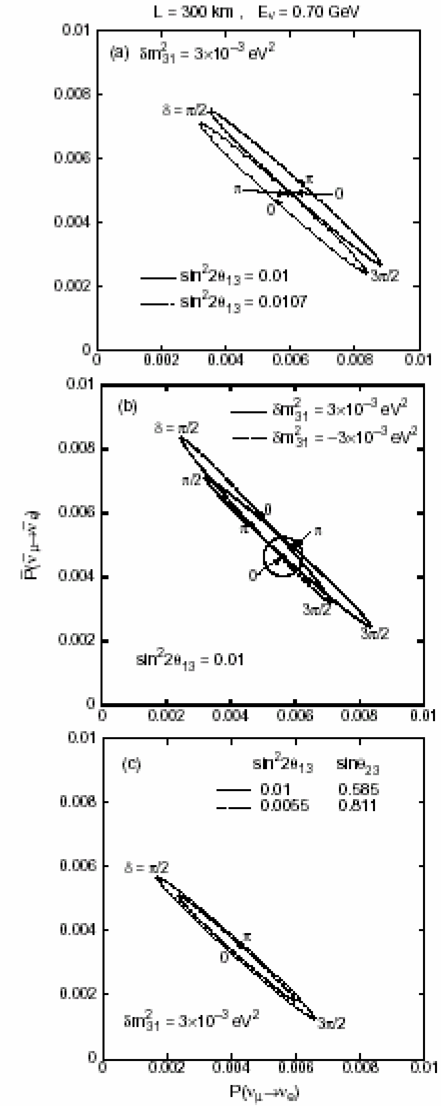

FIG. 10. Examples of the three types of ambiguities for the proposed SuperJHF–HyperK experiment [16] with $L=300$ km and $E_\nu = 0.7$ GeV: (a) (δ,θ_{13}) ambiguity, (b) $\mathrm{sgn}(\delta m^2_{31})$ ambiguity, and (c) $(\theta_{23},\pi/2-\theta_{23})$ ambiguity. In each case $\delta m^2_{21} = 5\times10^{-5}$ eV^2, $\sin^2 2\theta_{23}=1$, and $\sin^2 2\theta_{12} = 0.8$, unless otherwise stated in the figure. The circle in (b) indicates the size of the expected experimental uncertainties [16].

Super Beams vs Neutrino Factories

Superbeams versus Neutrino Factories*

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arXiv:hep-ph/0204352 v2 30 Jul 2002

Abstract

We compare the physics potential of planned superbeams with the one of neutrino factories. Therefore, the experimental setups as well as the most relevant uncertainties and errors are considered on the same footing as much as possible. We use an improved analysis including the full parameter correlations, as well as statistical, systematical, and degeneracy errors. Especially, degeneracies have so far not been taken into account in a numerical analysis. We furthermore include external input, such as improved knowledge of the solar oscillation parameters from the KamLAND experiment. This allows us to determine the limiting uncertainties in all cases. For a specific comparison, we choose two representatives of each class: For the superbeam, we take the first conceivable setup, namely the JHF to SuperKamiokande experiment, as well as, on a longer time scale, the JHF to Hyper-Kamiokande experiment. For the neutrino factory, we choose an initially conceivable setup and an advanced machine. We determine the potential to measure the small mixing angle $\sin^2 2\theta_{13}$, the sign of Δm^2_{31}, and the leptonic CP phase δ_{CP}, which also implies that we compare the limitations of the different setups. We find interesting results, such as the complete loss of the sensitivity to the sign of Δm^2_{31} due to degeneracies in many cases.

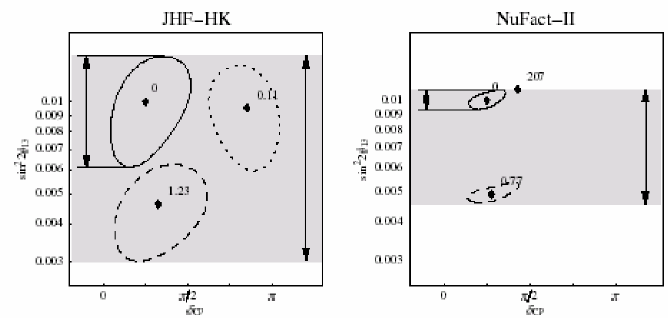

Figure 7: *The 3σ contours of the χ^2–function, which is plotted as function of δ_{CP} and $\sin^2 2\theta_{13}$ for the JHF-HK (left–hand plot) and NuFact-II (right–hand plot) experiments. The solid curves refer to the original solution at the best–fit point, the dashed curves to the degeneracy in $(\theta_{23}, \pi/2 - \theta_{23})$, and the the dotted curve to the degeneracy in $\mathrm{sgn}(\Delta m^2_{31})$. The diamonds mark the local minima with the respective χ^2–values. The arrows on the left–hand sides of the plots illustrate the measurement error in $\sin^2 2\theta_{13}$ from statistical, systematical, external, and correlational sources, as we had it at the end of Section 3. The arrows on the right–hand sides of the plots mark the overall error, as we would have it for taking the whole range covered by degeneracies, given by the gray–shaded region. For the oscillation parameters, we choose the LMA solution with $\Delta m^2_{21} = 4.5 \cdot 10^{-5}$ eV, $\sin^2 2\theta_{12} = 1.0$, $\sin^2 2\theta_{13} = 0.01$, $\delta_{CP} = \pi/4$, and $\sin^2 2\theta_{23} = \pi/4 - 0.2$.*

August 15, 2002

Parameter Degeneracies in Neutrino Oscillation Measurement of Leptonic CP and T Violation

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Abstract

The measurement of the mixing angle θ_{13}, sign of Δm^2_{13} and the CP or T violating phase δ is fraught with ambiguities in neutrino oscillation. In this paper we give an analytic treatment of the paramater degeneracies associated with measuring the $\nu_\mu \to \nu_e$ probability and its CP and/or T conjugates. For CP violation, we give explicit solutions to allow us to obtain the regions where there exist two-fold and four-fold degeneracies. We calculate the fractional differences, $(\Delta\theta/\bar{\theta})$, between the allowed solutions which may be used to compare with the expected sensitivities of the experiments. For T violation we show that there is always a complete degeneracy between solutions with positive and negative Δm^2_{13} which arises due to a symmetry and cannot be removed by observing one neutrino oscillation probabilityand its T conjugate.

FIGURES

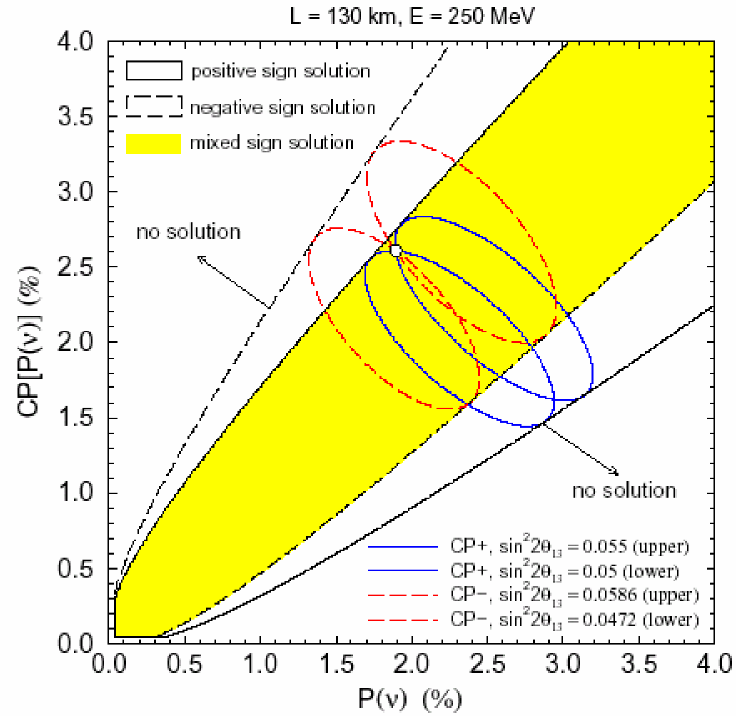

FIG. 1. An example of the degenerate solutions for the CERN-Frejius project in the $P(\nu) \equiv P(\nu_\mu \to \nu_e)$ verses $CP[P(\nu)] \equiv P(\bar{\nu}_\mu \to \bar{\nu}_e)$ plane. Between the solid (dashed) lines is the allowed region for positive (negative) Δm^2_{13} and the shaded region is where solution for both signs are allowed. The solid (dashed) ellipses are for positive (negative) Δm^2_{13} and they all meet at a single point. This is the CP parameter degeneracy problem. We have used a fixed neutrino energy of 250 MeV and a baseline of 130 km. The mixing parameters are fixed to be $|\Delta m^2_{13}| = 3 \times 10^{-3} eV^2$, $\sin^2 2\theta_{23} = 1.0$, $\Delta m^2_{12} = +5 \times 10^{-5} eV^2$, $\sin^2 2\theta_{12} = 0.8$ and $Y_e\rho = 1.5$ g cm^{-3}.

hep-ph/0105087

Correlations of errors in measurements of CP violation at neutrino factories

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(May, 2001)

Abstract

Using $\Delta\chi^2$ which is defined by the difference of the number of events with the CP phase δ and the hypothetical one with $\delta = 0$, we discuss correlations of errors of the CP phase and other oscillation parameters as well as the matter effect in measurements at neutrino factories. By varying the oscillation parameters and the normalization of the matter effect, we evaluated the data size required to reject a hypothesis with $\delta = 0$ at 3σCL. The optimum muon energy and the baseline depends on the magnitude of θ_{13}, the background fraction, the uncertainty of the normalization of the matter effect, but in general lie in the ranges 20GeV $\lesssim E_\mu \lesssim$ 50GeV, 1000km$\lesssim L \lesssim$3000km. If we assume that the uncertainty of the matter effect is as large as 20% then the optimum values may be modified to $E_\mu \lesssim$ 10GeV, $L \lesssim$1000km due to the strong correlation of δ and the matter effect. We show analytically that sensitivity to CP violation is lost for $E_\mu \ll$ 10GeV or for $E_\mu \gg$ 50GeV. We also discuss the possibility of measuring CP violation at the upgraded JHF experiment by taking all the error correlations into account, and show that it is possible to demonstrate $\delta \neq 0$ at 3σCL for $\theta_{13} \gtrsim 3°$.

13.15.+g, 14.60.Pq, 23.40.Bw, 26.65.+t

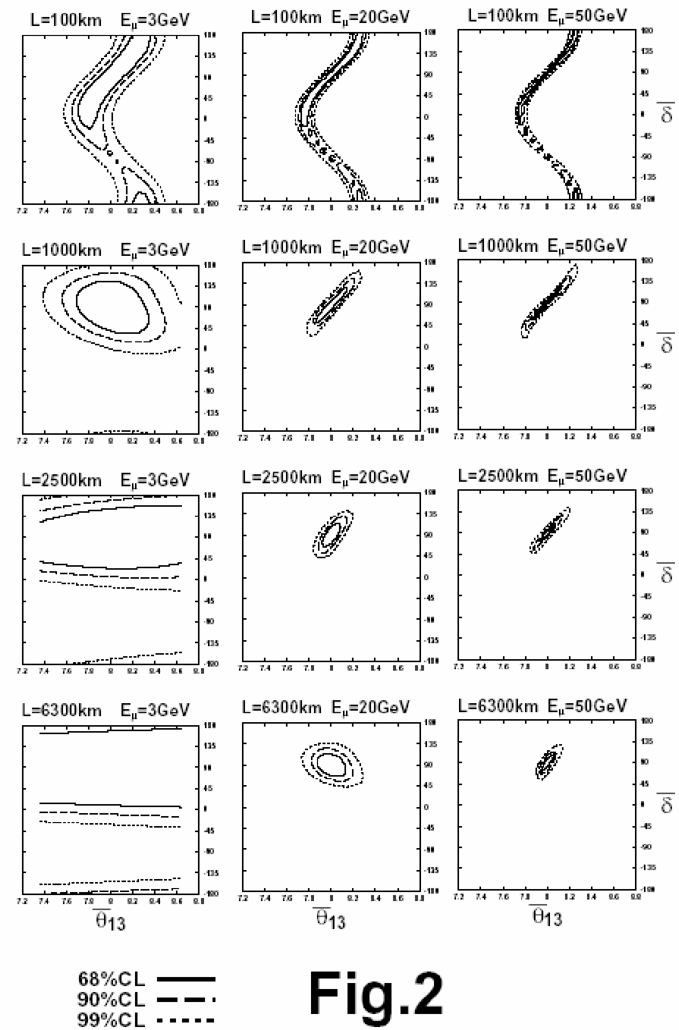
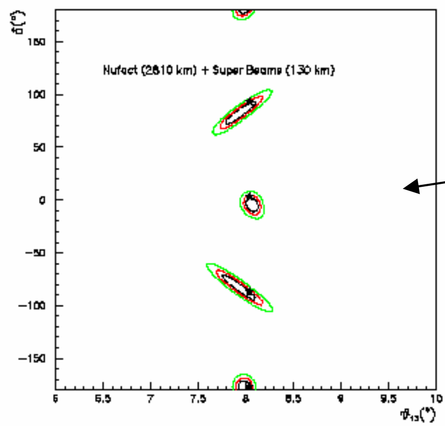


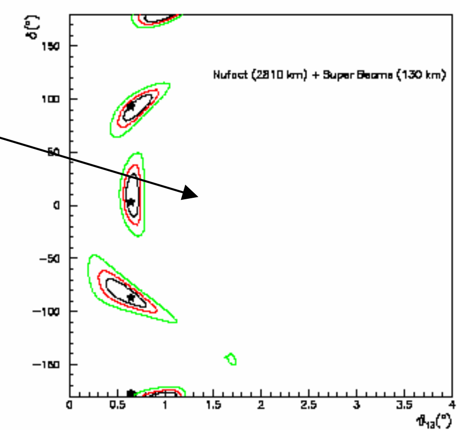
Fig.2

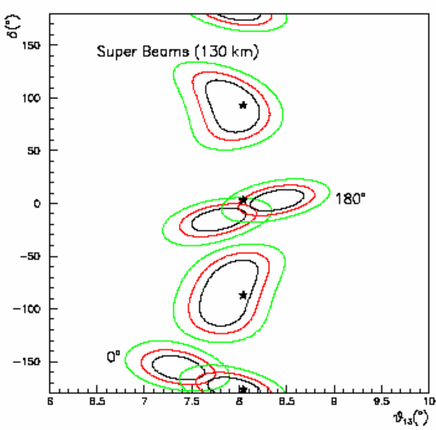
Puzzling it out

Solving intrinsic degeneracy combining two facilities



Combination of SB + NF





Intrinsic degeneracy

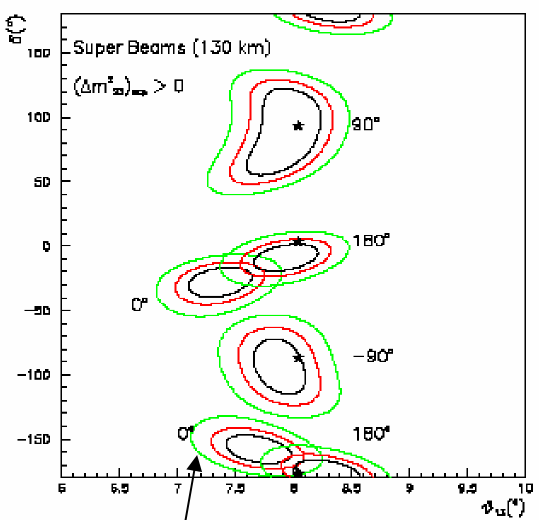
SB alone

4 Jul 2002

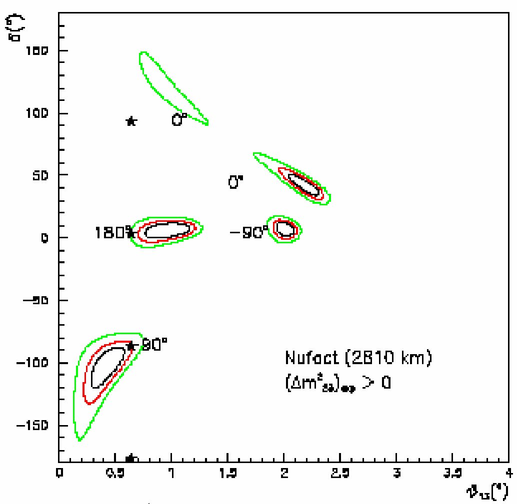
Superbeams plus Neutrino Factory: the golden path to leptonic CP violation

J. Burguet-Castell[a], M.B. Gavela[b,1], J.J. Gómez-Cadenas[a,c2], P. Hernández[c,3], O. Mena[b,4]

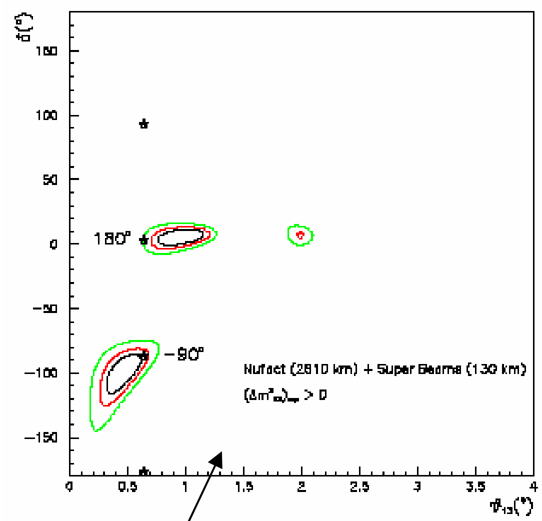
Solving sign Degeneracy combining two facilities



Super Beam

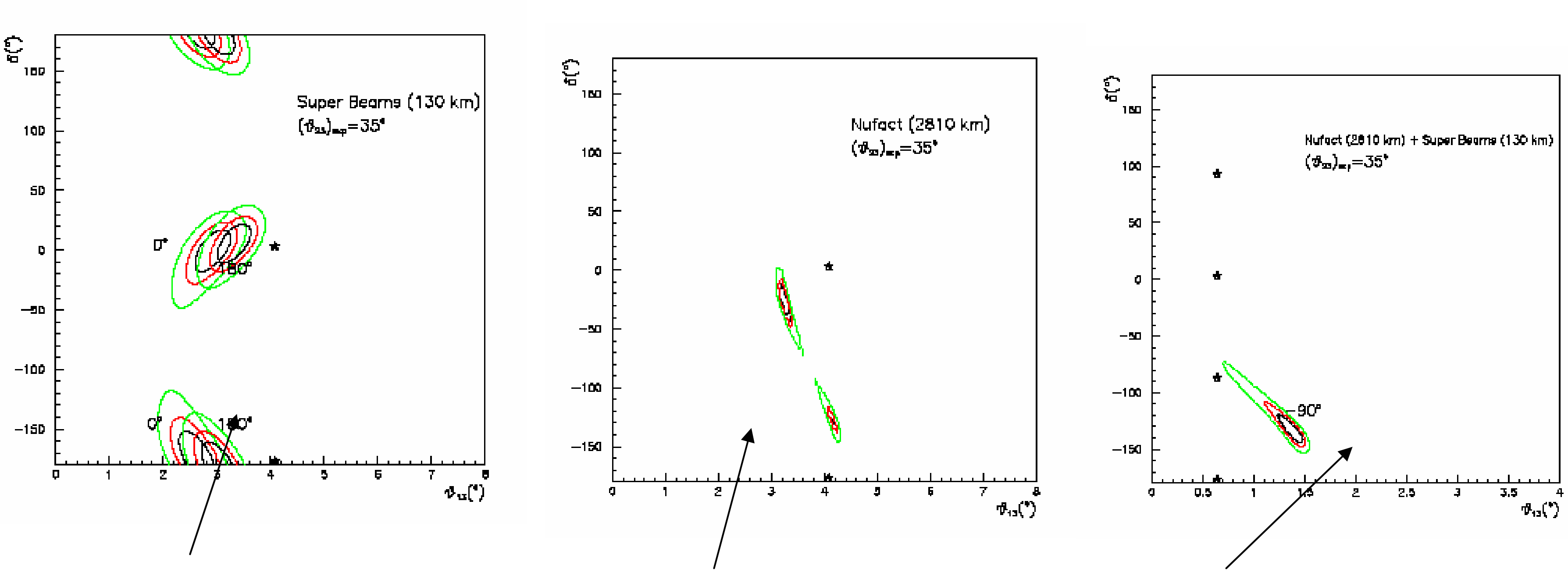


Nufact



Combination

Solving θ_{23} Degeneracy combining two facilities



Super Beam

NuFact

Combination

Solving Degeneracies at Nufact combining golden and silver channels

4 v1 4 Jun 2002

The silver channel at the Neutrino Factory

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[b] Dip. Fisica, Università di Roma "La Sapienza" and I.N.F.N., Sezione di Roma I, P.le A. Moro 2, I-00185, Rome, Italy
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16 May 2003

The synergy of the golden and silver channels at the Neutrino Factory

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[a] IPN Lyon, F-69622, Villeurbanne (Lyon), France

The Golden Channel at the Neutrino Factory

$$\boxed{\mu^+} \to \begin{cases} e^+ \\ \bar{\nu}_\mu \\ \boxed{\nu_e \to \nu_\mu \to \mu^-} \end{cases}$$

The oscillation probability is

$$\begin{aligned} P^{\pm}_{e\mu} = & \; X_\pm \sin^2(2\,\theta_{13}) \\ & + Y_\pm \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13}) \\ & + Z + \ldots \end{aligned}$$

with

$$\begin{cases} X_\pm & = & \Delta^2_{atm} \times f^{\pm}_X\,(\theta_{23}, A, L) \\ Y_\pm & = & \Delta_{sun} \times \Delta_{atm} \times f^{\pm}_Y\,(\theta_{12}, \theta_{23}, A, L) \\ Z & = & \Delta^2_{sun} \times f_Z\,(\theta_{12}, \theta_{23}, A, L) \end{cases}$$

(+ neutrinos, − antineutrinos)

The Silver Channel at the Neutrino Factory

$$\boxed{\mu^+} \to \begin{cases} e^+ \\ \bar{\nu}_\mu \\ \boxed{\nu_e \to \nu_\tau \to \tau^- \to \mu^-} \end{cases}$$

The oscillation probability is

$$\begin{aligned} P^{\pm}_{e\tau} = & \; X^{\tau}_\pm \sin^2(2\,\theta_{13}) \\ & - Y_\pm \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13}) \\ & + Z^\tau + \ldots \end{aligned}$$

with

$$\begin{cases} X^\tau_\pm & = & \Delta^2_{atm} \times (c^2_{23}/s^2_{23}) f^{\pm}_X\,(\theta_{23}, A, L) \\ Y_\pm & = & \Delta_{sun} \times \Delta_{atm} \times f^{\pm}_Y\,(\theta_{12}, \theta_{23}, A, L) \\ Z^\tau & = & \Delta^2_{sun} \times (s^2_{23}/c^2_{23}) f_Z\,(\theta_{12}, \theta_{23}, A, L) \end{cases}$$

(+ neutrinos, − antineutrinos)

Equal-Number-of-Events Curves

The number of GOLDEN muon events is:

$$N^i_{\mu^-}(\bar\theta_{13},\bar\delta) = \left\{\sigma_{\nu_\mu} \otimes P^+_{e\mu}(\bar\theta_{13},\bar\delta) \otimes \Phi_{\nu_e}\right\}^{E_i+\Delta E}_{E_i}$$

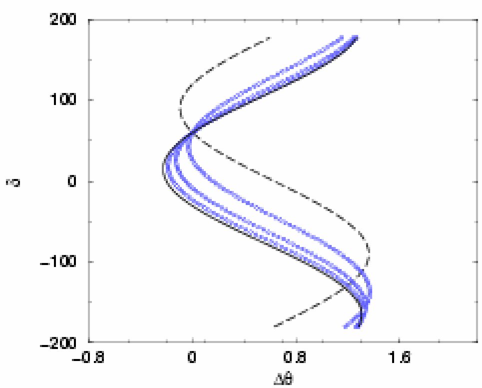
with i a given energy bin.

By changing (θ_{13},δ) accordingly,
we draw ENE curves in the (θ_{13},δ) plane:

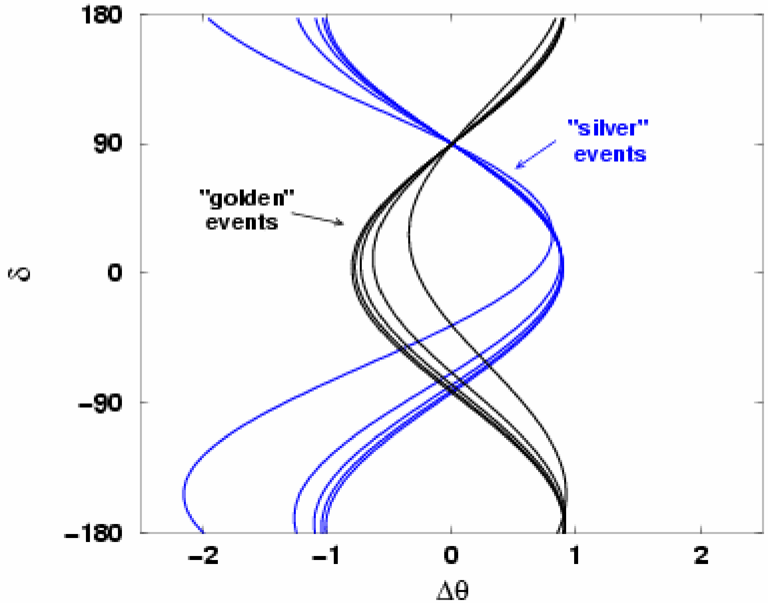
$$N^i_\pm(\bar\theta_{13},\bar\delta) = N^i_\pm(\theta_{13},\delta)$$

$L = 3000$ Km

$$\begin{cases} \bar\theta_{13} & = & 5^\circ \\ \bar\delta & = & 90^\circ \end{cases}$$



Comparison of ENE curves

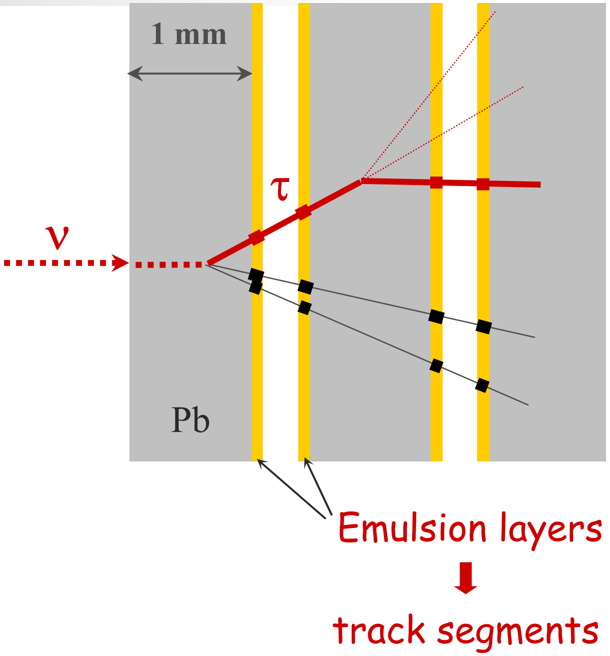


Baseline: $L = 732$ Km

$$\begin{cases} \bar\theta_{13} & = & 1^\circ \\ \bar\delta & = & 90^\circ \end{cases}$$

The Emulsion Cloud Chamber (ECC)

- Emulsions for tracking, passive material as target
  ↳ < μm space res. ↳ mass

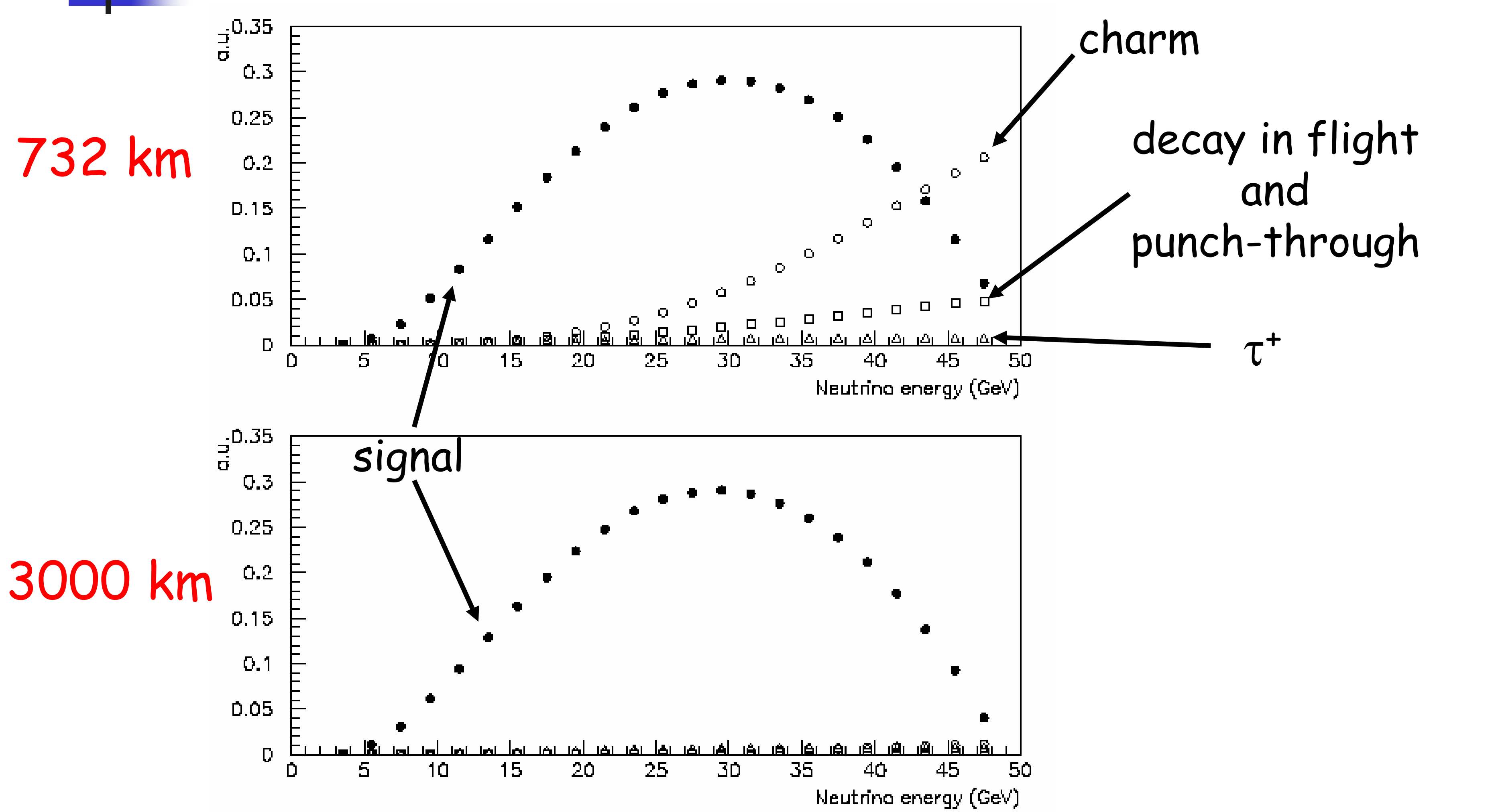


- Established technique
  - charmed "X-particle" first observed in cosmic rays (1971)
  - DONUT/FNAL beam-dump experiment: 7ν_τ observed (2000)

$\Delta m^2 = O\ (10^{-3}\ eV^2) \rightarrow M_{target} \sim 2$ kton

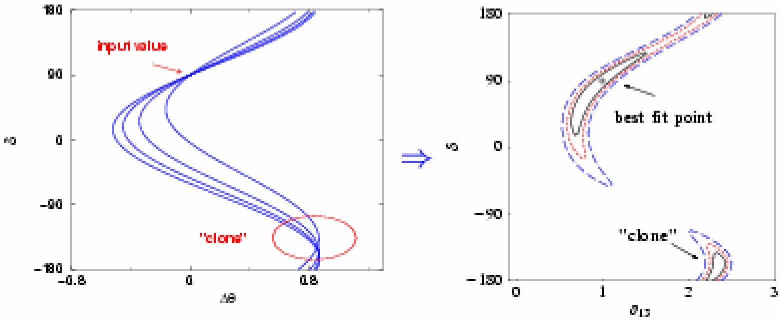
modular structure ("bricks"): basic performance is preserved
large detector → sensitivity, complexity
required: "industrial" emulsions, fast automatic scanning

Signal & background vs E_ν

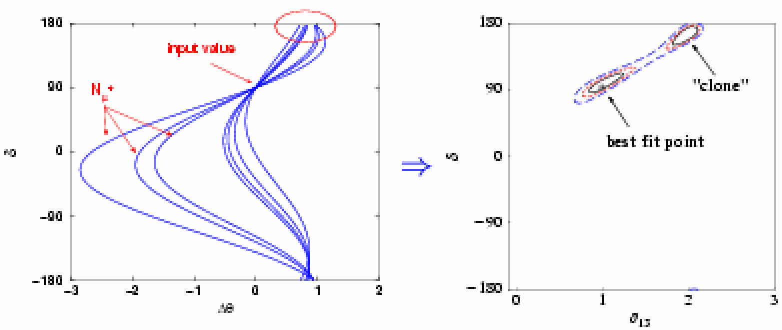


Results for golden muons at $L = 3000$ Km

Five years of data taking: one polarity only
(μ^+ in the storage ring)



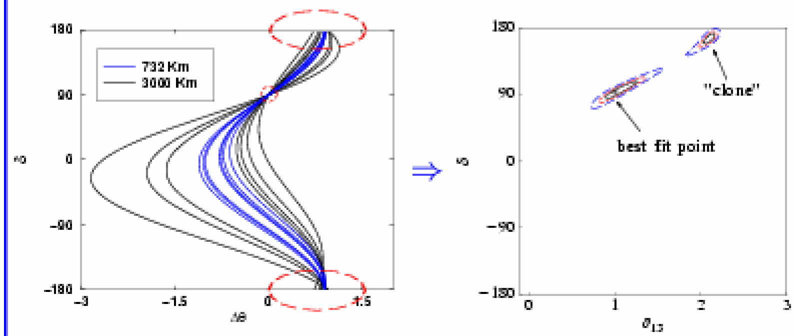
Ten years of data taking: two polarities
(μ^+ and μ^- in the storage ring)



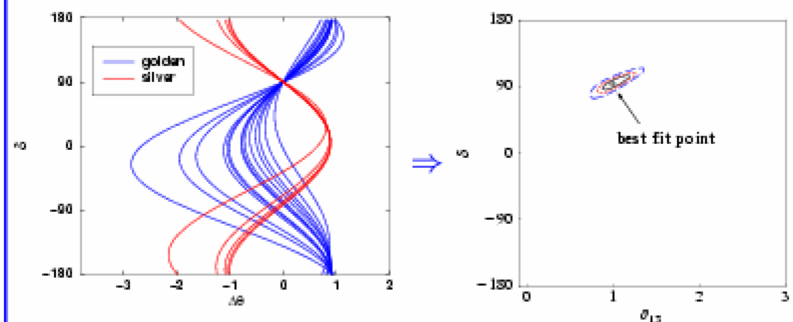
Input parameters: $\bar{\theta}_{13} = 1°, \bar{\delta} = 90°$

Using golden and silver muons

Setup A: two iron detectors and two baselines
(golden muons only)



Setup B: one iron and one emulsion detectors
(golden and silver muons; IDEAL emulsion detector)

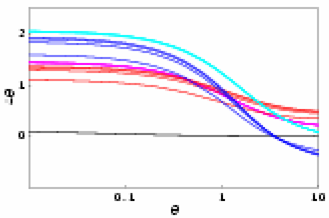


Input parameters: $\bar{\theta}_{13} = 1°, \bar{\delta} = 90°$

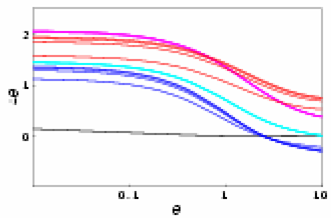
Solving the $[\theta_{23}, \pi/2 - \theta_{23}]$ ambiguity

We can analytically compute the location of the intrinsic clones.

Shift in $\Delta\theta$ for golden, silver and superbeam.

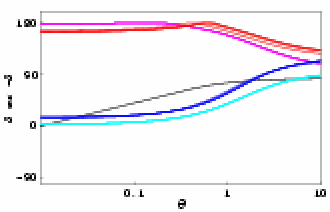


$\Rightarrow$

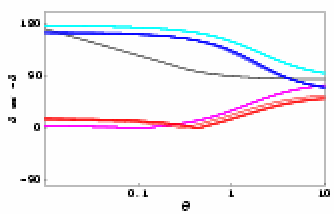


$\theta_{23} = 40°$ $\theta_{23} = 50°$

Shift in δ for golden, silver and superbeam.



$\Rightarrow$



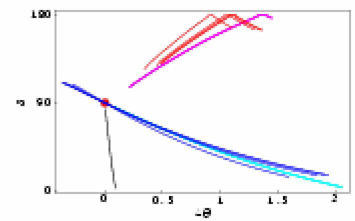
$\theta_{23} = 40°$ $\theta_{23} = 50°$

Input parameters: $\bar{\theta}_{13} \in [0.01°, 10°], \bar{\delta} = 90°$

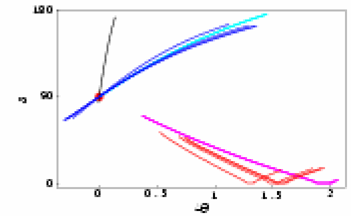
Solving the $[\theta_{23}, \pi/2 - \theta_{23}]$ ambiguity (2)

We can plot how the intrinsic clones moves for changing θ_{13} in the $\Delta\theta, \delta$ plane

(input,golden, silver and superbeam)



$\Rightarrow$



$\theta_{23} = 40°$ $\theta_{23} = 50°$

Input parameters: $\bar{\theta}_{13} \in [0.01°, 10°], \bar{\delta} = 90°$

Notice that for $\theta_{23} \to \pi/2 - \theta_{23}$ golden and silver clone trajectories interchange: they have opposite δ.

$\Downarrow$

For large enough statistics (i.e. not too small θ_{13}) we can solve the ambiguity combining golden and silver signals.

Conclusions

- The Good News: God has chosen LMA. Clearly she means us to measure the PMNS matrix parameters.
- The Bad News: Those measurement are difficult both intrinsically (correlations, degeneracies) and experimentally (powerful new facilities needed).

Conclusions (II)

- The Bad News: Technological and economical restrictions may delay the neutrino factory more than we would like.
- The Good News: Super-Beam and Beta Beam facilities may be operational earlier. They are SYNERGETIC to NUFACT.
- The combination of two or more facilities, two baselines, and precious (golden & silver) sub leading transitions will eventually unlock Pandora's box for us. Then, loo and behold!