Neutrino Factories: The Evolving Physics Case

Muon Collaboration

1. Introduction: What is known / not known
2. Beam properties, signal and background
3. The challenge: correlations & ambiguities
4. $\sin^2 2\theta_{13}$ sensitivity
5. CP Violation & the pattern of neutrino masses
6. What if LSND is confirmed ?
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Introduction

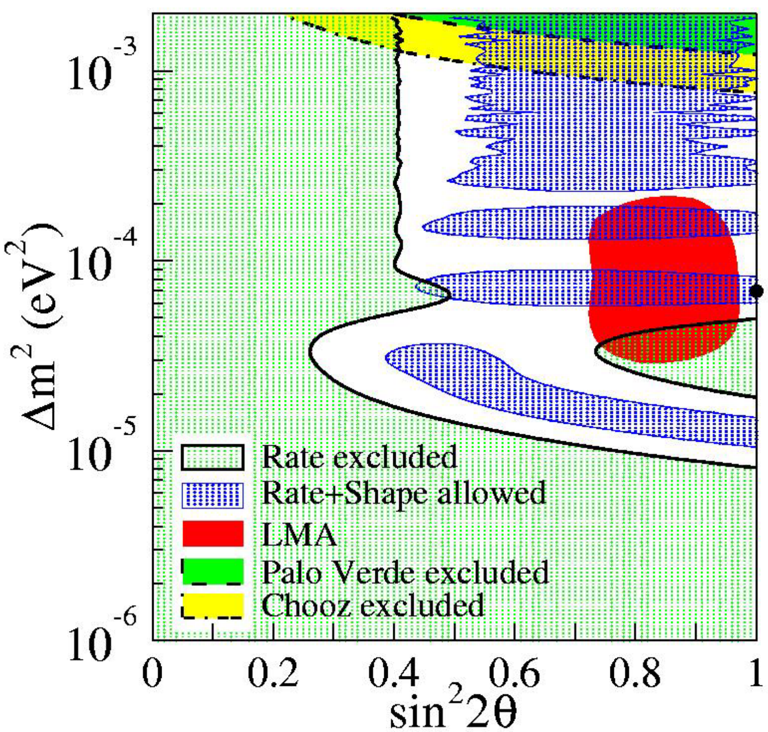
The focus of the Muon Collaboration on Neutrino Factories is driven by physics, & in particular by:

1. The exciting evidence for neutrino oscillations with oscillation parameters that are within reach of future accelerator-based experiments.

2. An understanding of the accelerator-based experiments that are needed to fully exploit the initial discovery.

News since the HEPAP Subpanel Presentations

KamLAND



1. SNO has confirmed that the solar neutrino deficit is due to neutrino flavor transitions: Electron neutrinos disappear and the LMA solution is preferred.

2. K2K has confirmed that the atmospheric neutrino deficit is due to flavor transitions: Muon neutrinos disappear.

3. KamLAND has confirmed the LMA solution to the solar neutrino problem !

IMPLICATIONS

1. CP violation in the lepton sector is within reach of experimental investigation provided θ_{13} is large enough …. but if θ_{13} is very small …

2. Probing tiny values of θ_{13} becomes important (discriminates between models)

What is known - 1

The solar- and atmospheric-neutrino measurements provide compelling evidence that neutrinos have mass, & neutrinos of one flavor can transform themselves into neutrinos of a different flavor → neutrino oscillations.

→ Lepton Flavor Violation
→ Physics beyond the Standard Model
→ A new handle on Grand Unification
→ A new handle on the physics of flavor

We also know that all three known flavors (ν_e, ν_μ, ν_τ) participate in neutrino oscillations. This implies an underlying 3 × 3 mixing matrix that can accommodate CP-Violation.

→ Baryogenesis ?

What is known - 2

Within the framework of three-flavor mixing neutrino oscillations are described by 3 mixing angles (θ_{12}, θ_{23}, θ_{13}), one complex phase (δ), and two independent mass splittings (Δm_{21}^2 , Δm_{32}^2).

We already know the approximate values of the parameters that describe the oscillations:

1. $\sin^2 2\theta_{23} \sim 1$ ($\geq$ 0.9 at 90% CL)
2. $|\Delta m_{32}^2| = | m_3^2 - m_2^2| \sim 2 \times 10^{-3}$ eV^2
3. $\Delta m_{21}^2 = m_2^2 - m_1^2 \sim (6 - 9) \times 10^{-5}$ eV^2 (at 2σ) (if LMA-1 confirmed)
4. $\sin^2 2\theta_{12} \sim 0.87$
5. $\sin^2 2\theta_{13} < 0.14$ (at 2σ)

… but there is a lot we don’t know ….

What is NOT Known

1. Does three-flavor mixing provide the right framework or are there contributions from: additional (sterile) neutrinos, neutrino decay, CPT-Violation, extra dimensions, …?
2. Is $\sin^2 2\theta_{13}$ small or tiny (or zero) ?
3. Is δ non-zero (Is there CP-violation in the lepton sector, and does it contribute significantly to Baryogenesis via Leptogenesis) ?
4. What is the sign of $\Delta m_{32}{}^2$ (pattern of neutrino masses) ?
5. Is $\sin^2 2\theta_{23}$ maximal (= 1) ?

The answers to these questions may lead us towards an understanding of the origin of flavor … but getting the answers will require the right tools.

Beam Properties at a Neutrino Factory

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \rightarrow 50\%\ \nu_e\ ,\ 50\%\ \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \rightarrow 50\%\ \bar{\nu}_e\ ,\ 50\%\ \nu_\mu$$

Decay kinematics well known → minimal systematic uncertainties in:

1. Spectrum
2. Flux
3. Comparison of neutrino with antineutrino results

… but, most important, there are ν_e as well as ν_μ in the initial beam.

Electron Neutrinos & Wrong-Sign Muons

The primary motivation for interest in neutrino factories is that they provide electron neutrinos (antineutrinos) in addition to muon anti-neutrinos (neutrinos). This enables a sensitive search for $\nu_e \rightarrow \nu_\mu$ oscillations.

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \overset{CC}{\Rightarrow} \mu^+$$
$$\nu_e \downarrow$$
$$\nu_\mu \underset{CC}{\Rightarrow} \mu^-$$

$\nu_e \rightarrow \nu_\mu$ oscillations at a neutrino factory result in the appearance of a "wrong-sign" muon … one with opposite charge to those stored in the ring:

Backgrounds to the detection of a wrong-sign muon are expected to be at the 10^{-4} level $\Rightarrow$ background-free $\nu_e \rightarrow \nu_\mu$ oscillations with amplitudes as small as $O(10^{-4})$ can be measured !

Signal Rates & Signal/Background

Note: backgrounds for $\nu_e \rightarrow \nu_\mu$ measurements (wrong-sign muon appearance) are much easier to suppress than backgrounds to $\nu_\mu \rightarrow \nu_e$ measurements (electron appearance).

Many groups have calculated signal & background rates. Recent example
Huber, Lindner & Winter; hep-ph/0204352

JHF-SK: Beam = 0.75 MW, M_{fid} = 22.5 kt, T = 5 yrs
JHF-HK: Beam = 4 MW, M_{fid} = 1000 kt, T = 8 yrs
Entry-Level NUFACT: Beam = 1×10^{19} decays/yr, M_{fid} = 100 kt, T = 5 yrs
High-Performance NUFACT: Beam = 2.6×10^{20} decays/yr, M_{fid} = 100 kt, T = 8 yrs

$\Delta m_{32}^2 = 0.003\ \mathrm{eV}^2$, $\Delta m_{21}^2 = 3.7\times10^{-5}\ \mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{12} = 0.8$, $\delta = 0$

	Superbeams		Neutrino Factories	
	JHF-SK	JHF-HK	Entry Level	High Performance
Signal	140	13000	1500	65000
Background	23	2200	4.2	180
S/B	6		360	

Correlations & Ambiguities

If the LMA solar solution is confirmed, extracting precise & unambiguous values for all of the three-flavor oscillation parameters (Δm_{32}^2, Δm_{21}^2 , $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{12}$, $\delta = 0$) will be challenging :

Look at expansion in powers of $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ **and** $\sin\theta_{13}$; $\Delta = \Delta m^2_{31} L/4E$; $V = 0$

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \quad \sin^2(\Delta) \\
& \pm \sin\delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin^3(\Delta) \\
& + \cos\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \sin^2(\Delta) \\
& + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \sin^2(\Delta)
\end{aligned}
$$

Method: Fit the measured energy-dependent probabilities to extract oscillation parameters.

Challenge: Additional false solutions & unwelcome correlations.

Solution: High statistics, low backgrounds, and redundant measurements … a Neutrino Factory !

Oscillation Measurements at a Neutrino Factory

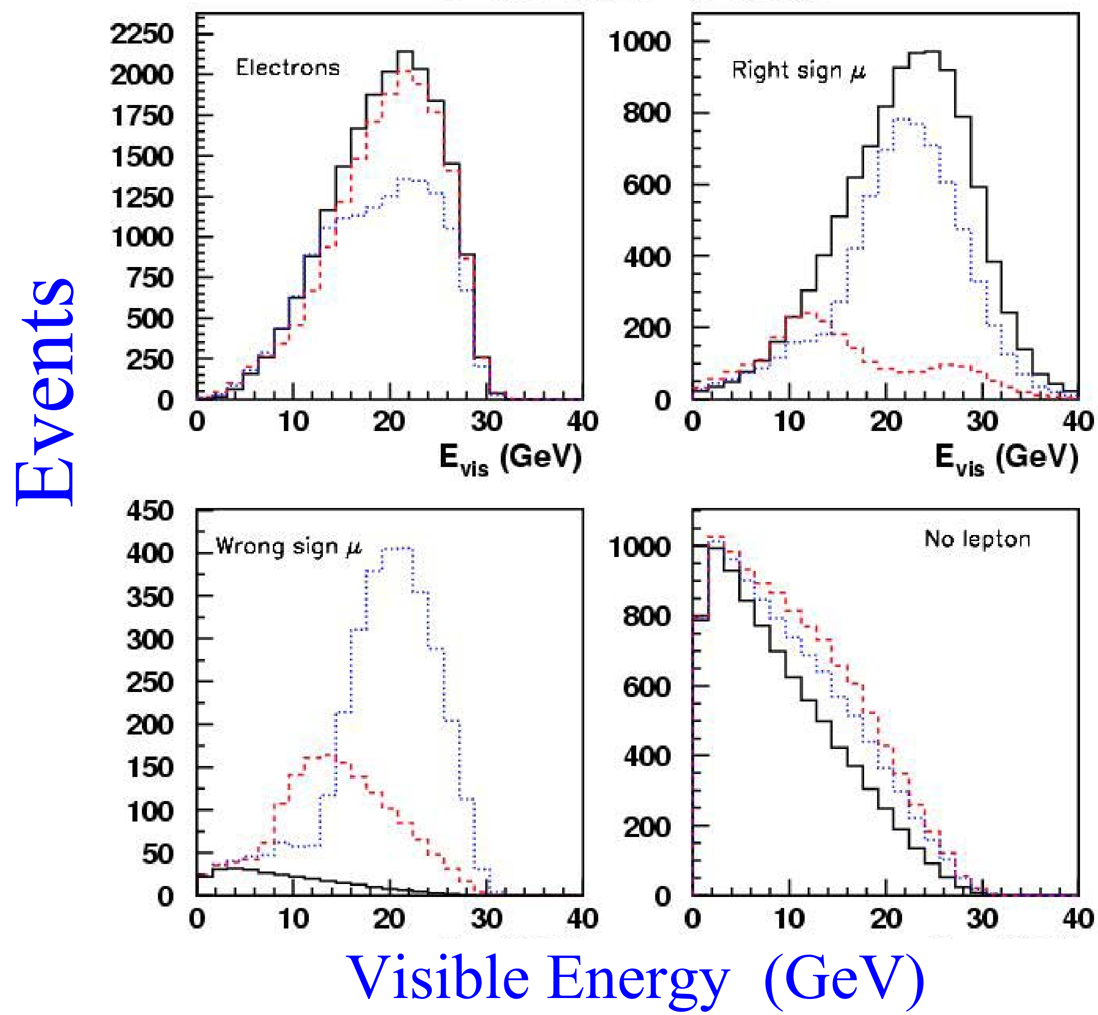
There is a wealth of information that can be used at a neutrino factory. Oscillation parameters can be extracted using events tagged by:

a) right-sign muons
b) wrong-sign muons
c) electrons/positrons
d) positive τ-leptons
e) negative τ -leptons
f) no leptons

×2 (μ^+ stored and μ^- stored)

Bueno, Campanelli, Rubbia; hep-ph/00050007

Simulated distributions for a 10kt LAr detector at L = 7400 km from a 30 GeV nu-factory with 10^{21} μ^+ decays.



$\mathrm{Sin}^2 2\theta_{13}$ Reach - 1

In a long baseline experiment the $\nu_e \leftrightarrow \nu_\mu$ oscillation probability is approximately proportional to the amplitude parameter $\sin^2 2\theta_{13}$:

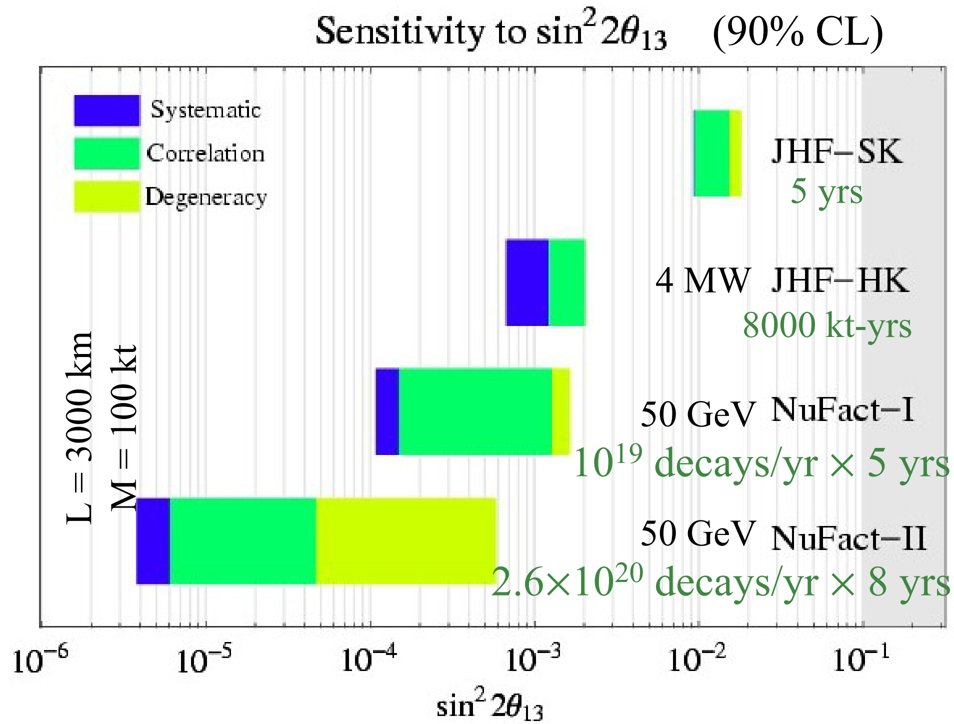
$$P(\nu_e \leftrightarrow \nu_\mu) \approx \underbrace{\sin^2 \theta_{23}}_{\sim 0.5} \sin^2 2\theta_{13} \ \sin^2(1.267\ \Delta m_{32}{}^2\ L / E)$$

From the CHOOZ reactor ν_e disappearance search we know that at 90% CL: $\sin^2 2\theta_{13} < O(0.1)$. Therefore we need to be able to measure very small oscillation probabilities.

Impact of correlations & ambiguities on the $\sin^2 2\theta_{13}$ sensitivity

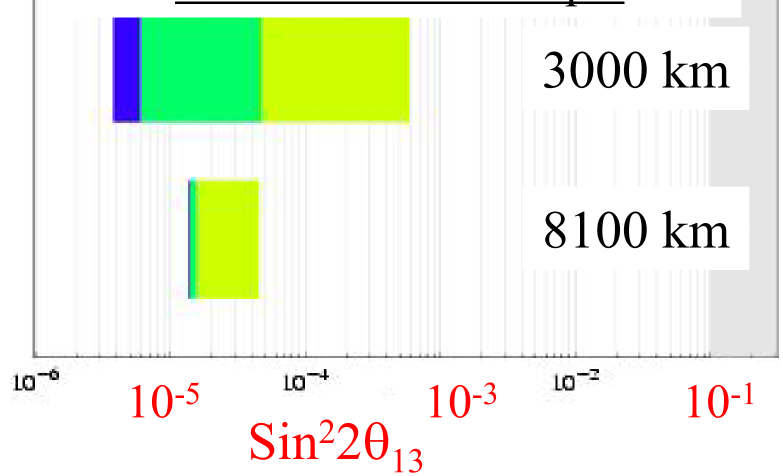
The impact of ambiguities & correlations has now been studied by several groups → can be overcome at a Neutrino Factory by exploiting two baselines or a very long baseline together with the $\nu_e \rightarrow \nu_\tau$ mode (unique for Neutrino Factories).

Will be able to see a signal for $\sin^2 2\theta_{13}$ as small as a few × 10^{-5} !



Huber, Lindner & Winter; hep-ph/0204352

Resolving the ambiguities with a Neutrino : An Example



$\mathrm{Sin}^2 2\theta_{13}$ "Predictions"

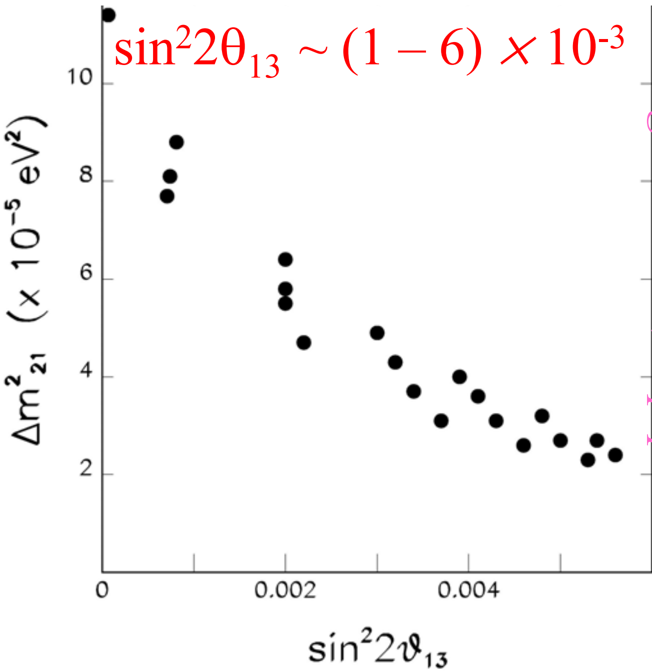
Lots of GUT models, but very few explicit predictions for parameter values that are consistent with the LMA solar neutrino solution

Prediction 1 : *Naturalness*

$\sin^2 2\theta_{13} > m_2 / m_3 \sim 0.01$ (will this suffer the same fate as small mixing angles ?)

Prediction 2: *SO(10) with $U(1) \times Z_2 \times Z_2$ flavor symmetry*

$\sin^2 2\theta_{13} \sim (1 - 6) \times 10^{-3}$



Albright & Geer, hep-ph/0108070

Prediction 3 : *Phenomenological Model for charged lepton mass matrix; Bi & Dai, hep-ph/0204317*

$\sin^2 2\theta_{13} \sim 10^{-4}$

Prediction 4 : *L_e-L_μ-L_τ symmetry broken by Planck-scale effects; Babu & Mohapatra, hep-ph/0201176*

$\sin^2 2\theta_{13} \sim 10^{-3}$

Conclude that predictions are all over the map → measurements/constraints can reject models !
Maybe if Superbeam experiments tell us that $\sin^2 2\theta_{13} < 10^{-2}$ - 10^{-3} we should keep on searching ?!

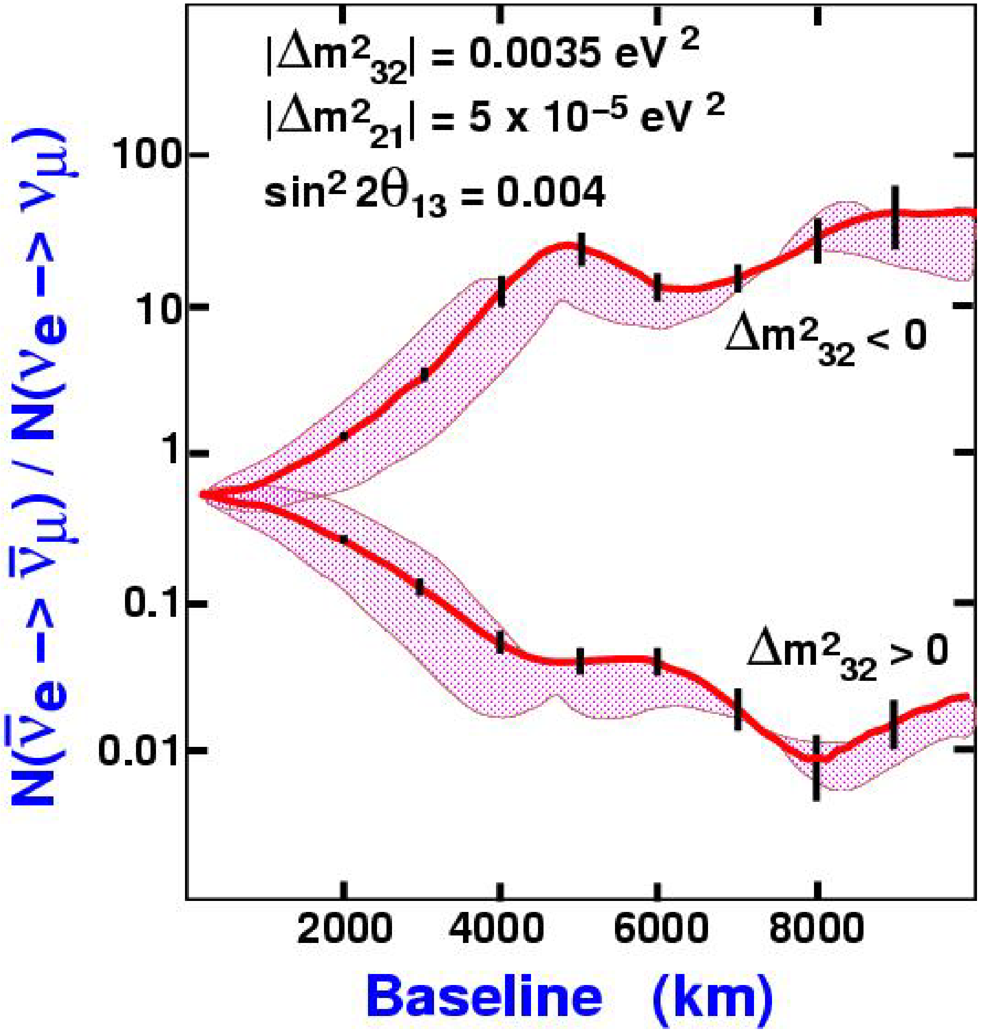
CP-Violation & the pattern on neutrino masses

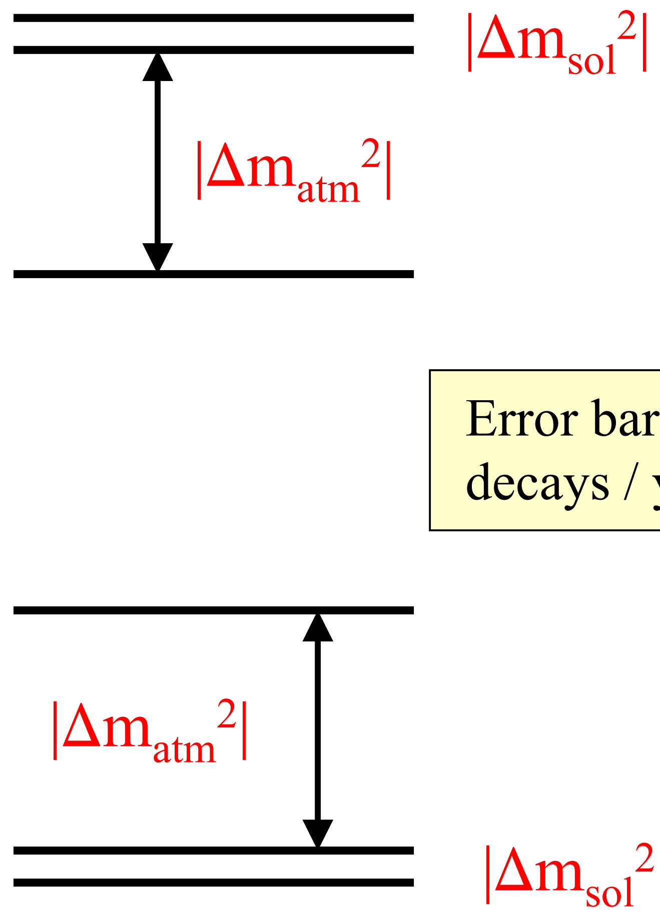
The signature for CP violation would be an inequality between $P(\nu_e \leftrightarrow \nu_\mu)$ and $P(\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu) \rightarrow$ Measure wrong-sign muon rates for μ^+ and μ^- running.

If the baseline is a few × 1000 km, matter effects can also produce an inequality between $\overline{P}(\nu_e \leftrightarrow \nu_\mu)$ and $P(\nu_e \leftrightarrow \nu_\mu)$ which depends upon the sign of $\Delta m_{32}^2 \rightarrow$ the pattern of neutrino masses.

CP-Violation & the pattern on neutrino masses

Barger, Geer, Raja, Whisnant, PRD 62, 073002
S. Geer, hep-ph/0008155





Error bars → 2×10^{20} decays / yr for 5 years

Sensitivity to the Neutrino Mass Hierarchy & CP Violation

Detailed studies that take account of the effects of correlations and ambiguities suggest that :

Neutrino Factory Experiments can determine the sign of Δm_{32}^2 and will be sensitive to maximal CP violation provided exceeds about 10^{-4}

Impact of Two Baselines on the $\sin^2 2\theta_{13}$, sign Δm^2_{32} & CPV Sensitivity

Huber & Winter, hep-ph/0301257

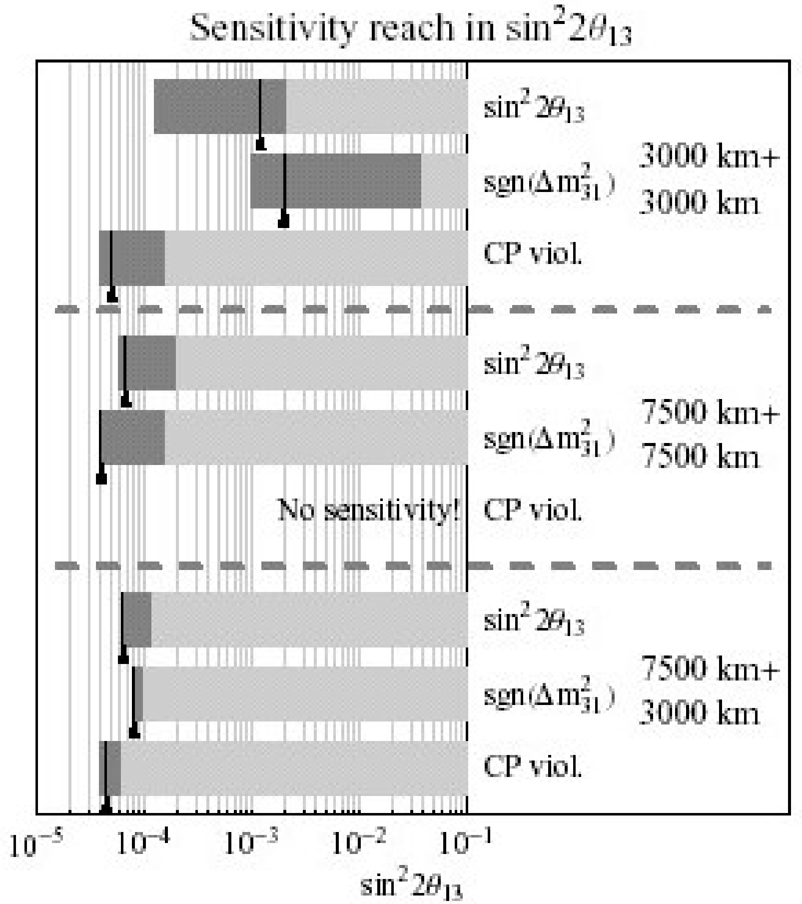


FIG. 3: The sensitivity reaches as functions of $\sin^2 2\theta_{13}$ for $\sin^2 2\theta_{13}$ itself, the sign of $\Delta m^2_{31} > 0$, and (maximal) CP violation $\delta_{CP} = \pi/2$ for each of the indicated baseline-combinations. The bars show the ranges in $\sin^2 2\theta_{13}$ where sensitivity to the corresponding quantity can be achieved at the 3σ confidence level. The dark bars mark the variations in the sensitivity limits by allowing the true value of Δm^2_{21} vary in the 3σ LMA-allowed range given in Ref. [19] and others ($\Delta m^2_{21} \sim 4 \cdot 10^{-5}\,\mathrm{eV}^2 - 3 \cdot 10^{-4}\,\mathrm{eV}^2$). The arrows/lines correspond to the LMA best-fit value.

With two carefully chosen baselines, the correlations & ambiguities can be overcome at a Neutrino Factory.

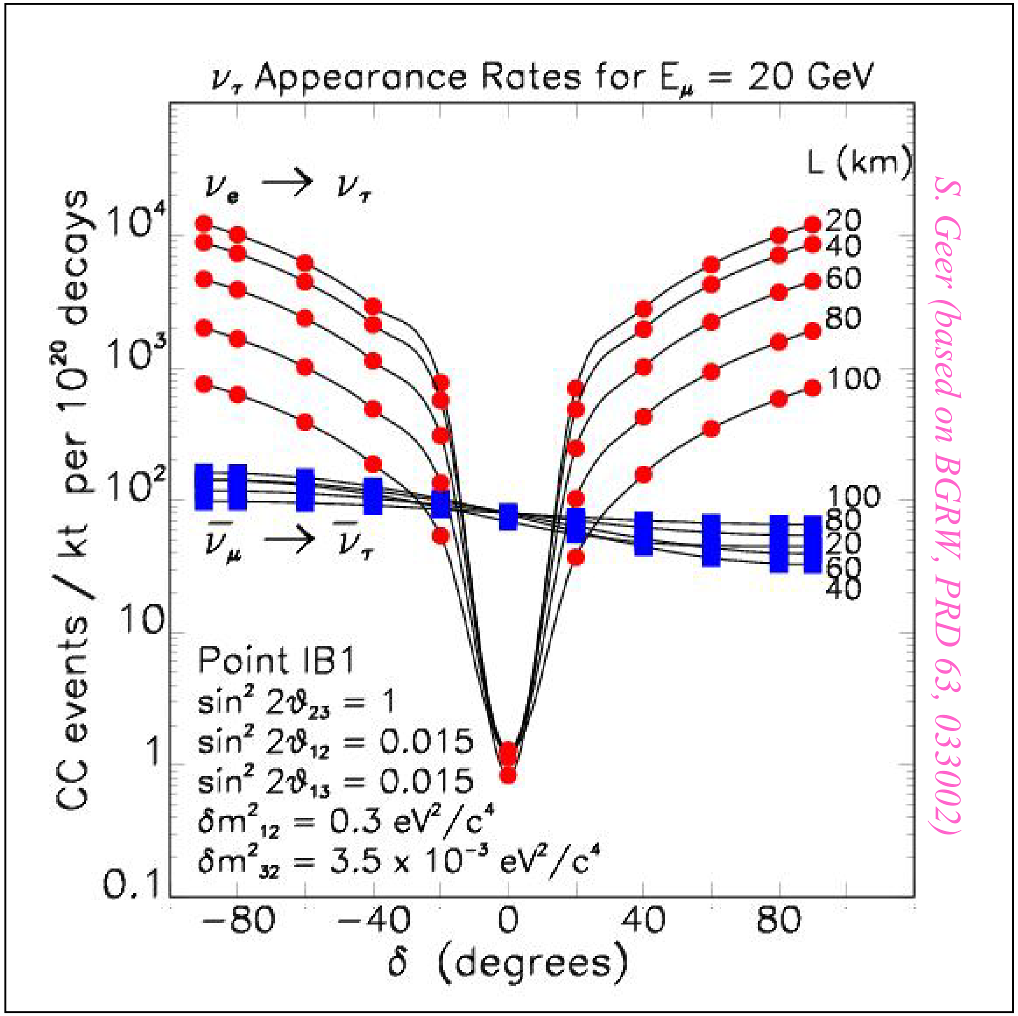
The calculated $\sin^2 2\theta_{13}$ reach (3σ) is below 10^{-4} for all three physics goals (measuring $\sin^2 2\theta_{13}$, determining the mass hierarchy, & observing maximal CPV) !!

For the right baseline choice, the physics reach is not sensitive to Δm^2_{21} (variation within dark grey bands).

The calculations are for a 50 GeV Neutrino Factory.

If Oscillations at the LSND Scale are Confirmed

We must be prepared to respond to surprises. If the LSND result is confirmed, then perhaps CPT is violated, or perhaps there are light sterile neutrinos:



Searching for $\nu_e \rightarrow \nu_\tau$ becomes important → Neutrino Factory

CP Violation might be observed with a low intensity Neutrino Factory … perhaps as low as 10^{18} decays / year !

In the LSND-confirmed scenario it might even be possible to motivate a learning Neutrino Factory with a limited physics program delivering only 10^{17} decays / year ???

Possibility	Accomplished by SuperBeam	Goals of Neutrino Factory
<u>Not 3-Flavor Mixing</u>	Establish not 3-Fl. &/or confusion	Establish framework Measure parameters Search for CPV
<u>3-Flavor Mixing</u>		
$\sin^2 2\theta_{13} < 0.01$, $\sin\delta_{CP} << 1$	θ_{13} limit only	Search for finite θ_{13}, sign of Δ, & CPV
$\sin^2 2\theta_{13} < 0.01$, $\sin\delta_{CP} \sim 1$	θ_{13} limit only	Search for finite θ_{13}, sign of Δ, & CPV
$\sin^2 2\theta_{13} > 0.01$, $\sin\delta_{CP} << 1$	θ_{13} & sign of Δ (may be ambiguous solutions)	Search for CPV
$\sin^2 2\theta_{13} > 0.01$, $\sin\delta_{CP} \sim 1$	First (3σ ?) evidence for CPV but no precise measurements	Precise measurement of all parameters including δ_{CP}

Neutrino Interaction Experiments

50 GeV ν-Fact: $10^6 - 10^7$ events/kg/year

Broad program – many experiments

1. Precise $\sigma(\nu)$ measurements
2. Structure Fus (no nuclear corrections) → individual quark flavor parton distributions
3. Precise α_s measurements (from non-singlet str. Fus.)
4. Study of nuclear effects (e.g. shadowing)for, separately, valence & sea quarks
5. Spin structure functions
6. Single tagged charm mesons & baryons(1 ton detector → 10^8 flavor tagged charm hadrons/year) → D^0-$\overline{D}^0$ mixing
7. Electroweak tests → $\sin^2\theta_W$ & $\sigma(\nu - e^-)$
8. Exotic interaction search (clean initial state)
9. Neutral heavy leptons (10-100 MeV/c^2)
10. Anomalous ν interactions in EM fields

Summary

1. Neutrino oscillations are exciting
   - Physics beyond the Standard Model
   - Physics of GUTs
   - Origin of flavor ?
   - CP violation and Baryogenesis

2. Now that the LMA solution is confirmed, we know that unambiguously determining all the oscillation parameters will be a challenge
   - LMA solution will enable us to learn more (CP- Violation ?), but also makes parameter extraction more complicated.

3. Neutrino Factories have the right characteristics to do the job:
   (i) high statistics
   (ii) low systematics (for neutrino-antineutrino comparisons in particular),
   (iii) low background rates,
   (iv) high energy neutrinos that permit very long baselines (seems to be important to resolve degenerate solutions)
   (v) both muon- and electron- neutrinos & antineutrinos → large variety of measurements to help fully determine all the oscillation parameters.

Support from the neutrino community

6 January, 2003

To: John O'Fallon

From: J. Conrad
W. Louis
D. Michael
M. Shaevitz
S. Wojcicki

Dear John,

We would like to encourage you to increase support for Neutrino Factory R&D in FY04.

Neutrino oscillation physics has entered a very exciting period. In the not-too-distant future we expect that results from MiniBooNE and MINOS will add to the excitement. No matter what the results are from these experiments it is already clear that more ambitious long-baseline experiments will be needed in the future. It also seems increasingly likely that we will ultimately need the full power of a Neutrino Factory to unambiguously determine all of the parameters that describe neutrino oscillations. This will be particularly true if the LMA solution to the solar neutrino problem is confirmed (which initial KamLAND results suggest is the case), or if MiniBooNE and/or MINOS make discoveries that indicate there is more going on than just three-flavor mixing.

The HEPAP subpanel recommended a funding level for Neutrino Factory R&D at the FY01 level of 8M$ per year. We understand that since that recommendation support for the all important R&D has been significantly reduced. We believe it is important to maintain an investment in the long-term future. Since the HEPAP subpanel presentations the R&D seems to have made good progress, and the physics case for an eventual Neutrino Factory has, if anything, grown stronger. We would therefore like to encourage a restoration of the support for Neutrino Factory R&D to the level that the subpanel recommended.

cc: Steve Geer
Bob Palmer