# Neutrino Factories

1. Introduction: What is known / not known
2. Beam properties, signal and background
3. $\sin^2 2\theta_{13}$ sensitivity
4. CP Violation & the pattern of neutrino masses
5. The challenge: correlations & ambiguities
6. Physics reach – fighting correlations & ambiguities
7. What if LSND is confirmed ?
8. Neutrino Interaction Experiments
9. Neutrino Factory R&D – The critical path
10. Brief summary

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Steve Geer Neutrinos: Data, Cosmos, and Planck Scale. Santa Barabara, 3-7 March 2003

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# Introduction

1. Neutrino Factory R&D is an international endeavor, with active groups in the US, Europe, and Japan

2. In the US the R&D is being pursued by the (Neutrino Factory and Muon Collider Collaboration (Muon Collaboration) which consists of 130 particle- and accelerator-physicists and engineers from 6 US Labs, 16 US Universities, and 11 foreign institutions.

3. The accelerator R&D is driven by physics … we are excited by neutrino oscillations !

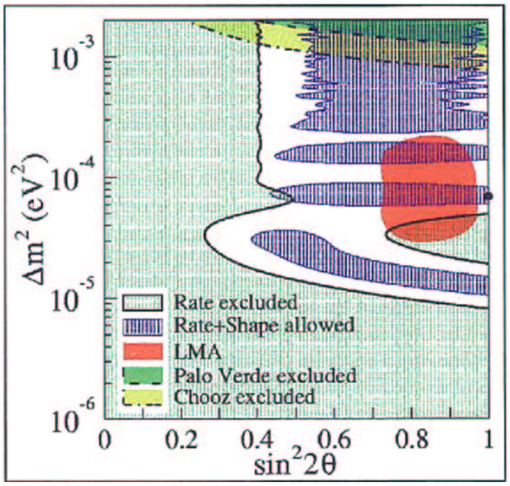
# What is Known

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

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 $2\sigma$) (if LMA-1 confirmed)
4. $\sin^2 2\theta_{12} \sim 0.87$
5. $\sin^2 2\theta_{13} < 0.14$ (at $2\sigma$)

KamLAND



… but there is a lot we don’t know ….

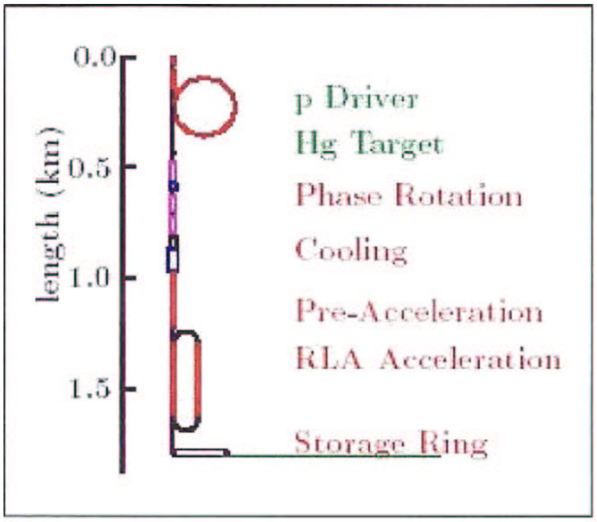
# What is NOT Known

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 $\delta$ non-zero (Is there CP-violation in the lepton sector) ?
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.

## Neutrino Factory Design

- Fall 1997: Neutrino Factory Idea
- 1999: Muon Collaboration shifted emphasis to Neutrino Factories
- Spring 2000: Completed Feasibility Study I – demonstrated feasibility of concepts and consolidated R&D plans, but failed intensity goal by a factor of 6.
- Spring 2001: Completed Feasibility Study II: Improved design & met intensity goal.



2 x $10^{20}$ muon decays / year in one straight section

Muon Energy: 20 – 50 GeV with 20 GeV preferred since acceleration is a cost-driver.

## 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 $\nu_e$ as well as $\nu_\mu$ 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.

$$\begin{tikzcd}
\mu^+ \arrow[r] & e^+ \nu_e \bar{\nu}_\mu \arrow[r, Rightarrow, "CC"] \arrow[d] & \mu^+ \\
& \nu_\mu \arrow[r, Rightarrow, "CC"'] & \mu^-
\end{tikzcd}$$

$\nu_e \rightarrow \nu_\mu$ 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 ⇒ 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
*Hubner, 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 = $1 \times 10^{19}$ decays/yr, $M_{fid} = 100$ kt, T = 5 yrs
High-Performance NUFACT: Beam = $2.6 \times 10^{20}$ decays/yr, $M_{fid} = 100$ kt, T = 8 yrs

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

| | 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 | |

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

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

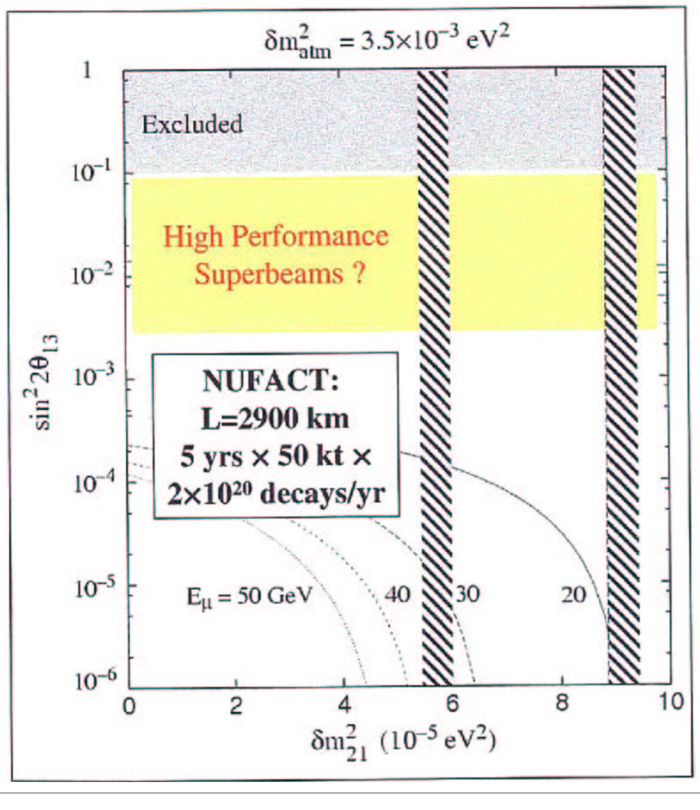
$$\boxed{P(\nu_e \leftrightarrow \nu_\mu) \approx \underbrace{\sin^2\theta_{23}}_{\sim 0.5} \sin^2 2\theta_{13}\ \sin^2(1.267\,\Delta m_{32}^2\, L / E)}$$

From the CHOOZ reactor $\nu_e$ 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.

In the absence of background and systematic uncertainties, to a first approximation the $\sin^2 2\theta_{13}$ reach improves linearly with the event statistics.

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

K. Whisnant (based on BGRW PRD 62, 073002)



Neutrino Factory experiments are so sensitive that the signal rates depend upon the sub-leading $|\Delta m_{21}^2|$ scale.

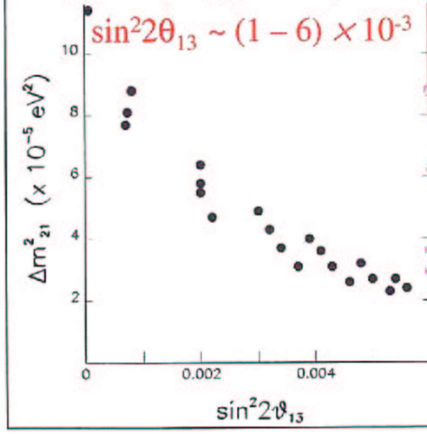
Sensitive to variations in $\sin^2 2\theta_{13}$ down to values as small as $O(10^{-4})$ !

## $\mathrm{Sin}^2 2\theta_{13}$ “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 : *$L_e$-$L_\mu$-$L_\tau$ symmetry broken by Planck-scale effects; Babu & Mohapatra, hep-ph/0201176*
$\sin^2 2\theta_{13} \sim 10^{-3}$

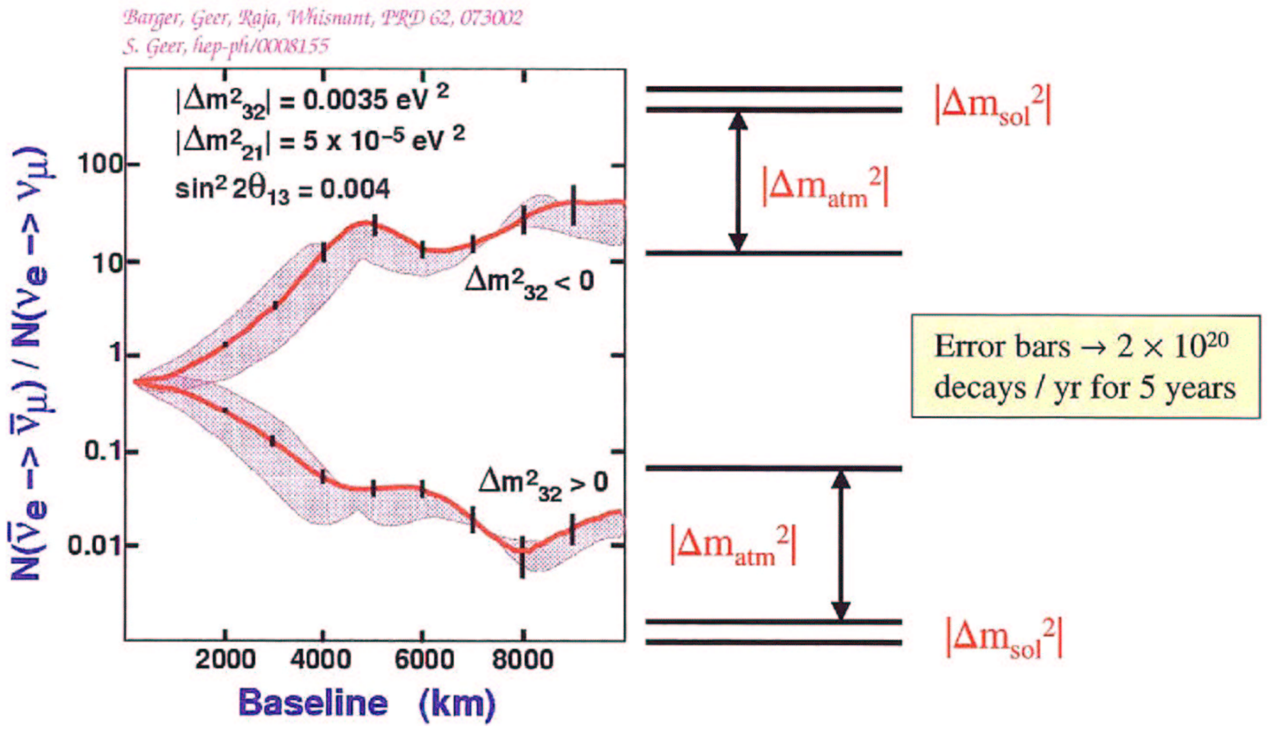
Conclude that predictions are all over the map →
measurements/constraints can reject models !
Maybe if Superbeam experiments tell us that
$\sin^2 2\theta_{13} < 10^{-2} - 10^{-3}$ we should keep on searching ?!

## CP-Violation & the pattern on neutrino masses

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

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

# CP-Violation & the pattern on neutrino masses



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

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# Correlations & Ambiguities

Exracting precise & unambiguous values for all of the three-flavor oscillation parameters ($\Delta m_{32}^2, \Delta m_{21}^2$ , $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{13}$ , $\sin^2 2\theta_{12}$ , $\delta = 0$) will be challenging :

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \;\approx\; & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
& \pm \sin\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
& + \cos\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
& + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

Fits prone to correlations between the parameters & to degenerate (false) solutions

$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ , $\Delta = \Delta m^2_{31}$ L/4E, $A = 2VE/\Delta m^2_{31}$ , $V = \sqrt{2} G_F n_e$

Note: (i) For $\nu \to \bar{\nu}$, A → -A, (ii) The sign of A depends on the sign of $\Delta m_{32}^2$

## Oscillation Measurements at a Neutrino Factory

There is a wealth of information that can be used to eliminate false solutions in parameter space & minimize correlations between fitted parameter values

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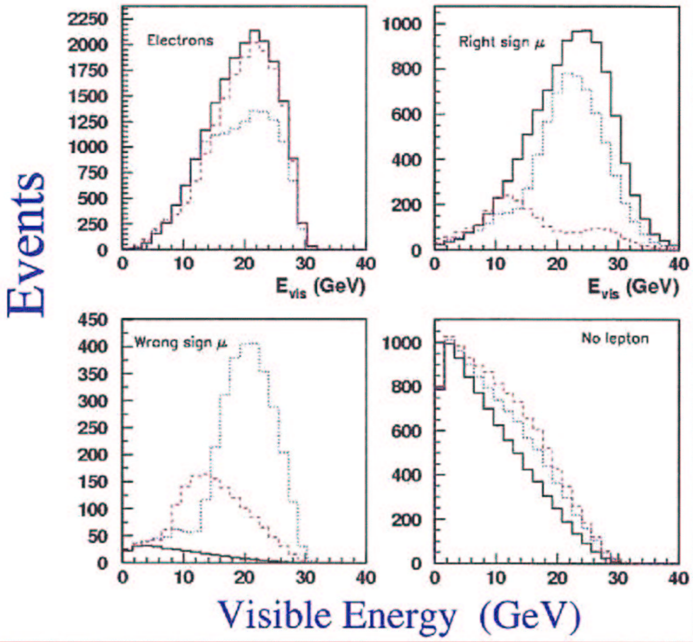
Oscillation parameters can be extracted using events tagged by:

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

×2 ($\mu^+$ stored and $\mu^-$ 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 $10^{21}$ $\mu^+$ decays.



## Fighting Correlations & Ambiguities

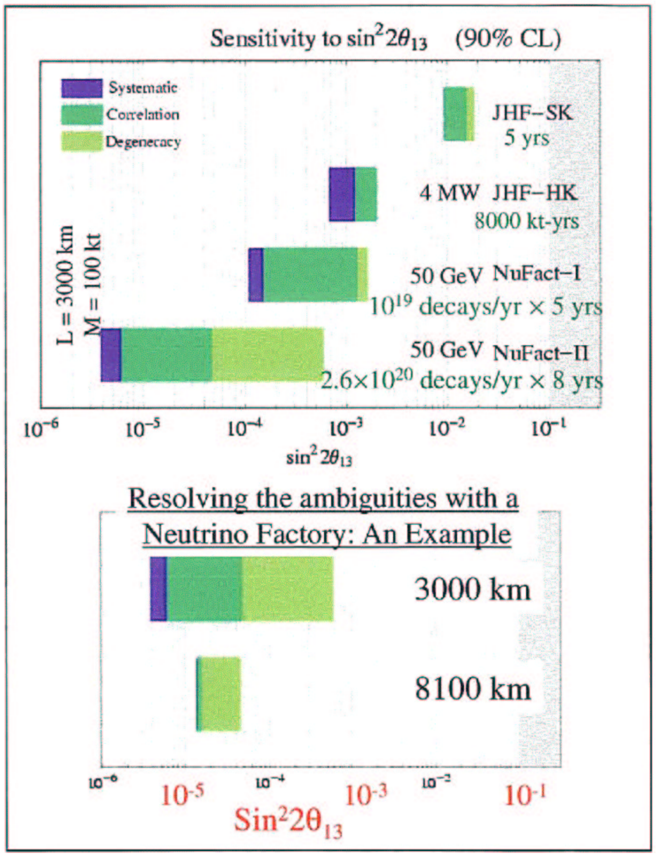
Winning Strategies:

1. Combine Neutrino Factory and high-performance Superbeam data.
2. Use two Neutrino Factory baselines (bowtie shaped ring) with at least one of the baselines very long.
3. Use all of the data from the Neutrino Factory (not just right-sign & wrong-sign muons, but all 12 distributions).
4. ALL of the above.

Several groups have studied how to fight correlations & ambiguities → encouraging results. Simultaneously fitting the 12 Neutrino Factory distributions × 2 baselines + combined Superbeam results has not yet been done … we don't yet know the bottom line.

# Impact on $\sin^2 2\theta_{13}$ sensitivity of choosing a very long baseline

*Hubner, Lindner & Winter; hep-ph/0204352*



With a 50 GeV Neutrino Factory, we may be able to see a signal for $\sin^2 2\theta_{13}$ as small as a few × $10^{-5}$ !

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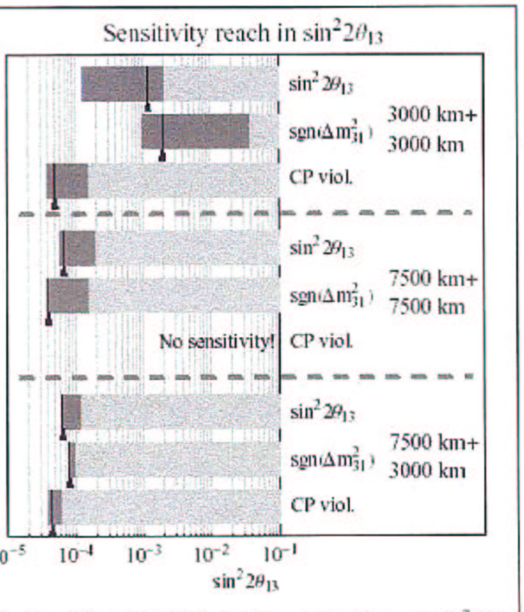


FIG. 3: The sensitivity reaches as functions of $\sin^2 2\theta_{13}$ for $\sin^2 2\theta_{13}$ itself, the sign of $\Delta m^2_{31} > 0$, and (maximal) CP violation $\delta_{CP} = \pi/2$ for each of the indicated baseline-combinations. The bars show the ranges in $\sin^2 2\theta_{13}$ where sensitivity to the corresponding quantity can be achieved at the $3\sigma$ confidence level. The dark bars mark the variations in the sensitivity limits by allowing the true value of $\Delta m^2_{21}$ vary in the $3\sigma$ 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.

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

*Huber & Winter, hep-ph/0301257*

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

The calculated $\sin^2 2\theta_{13}$ reach ($3\sigma$) 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 $\Delta m^2_{21}$ (variation within dark grey bands).

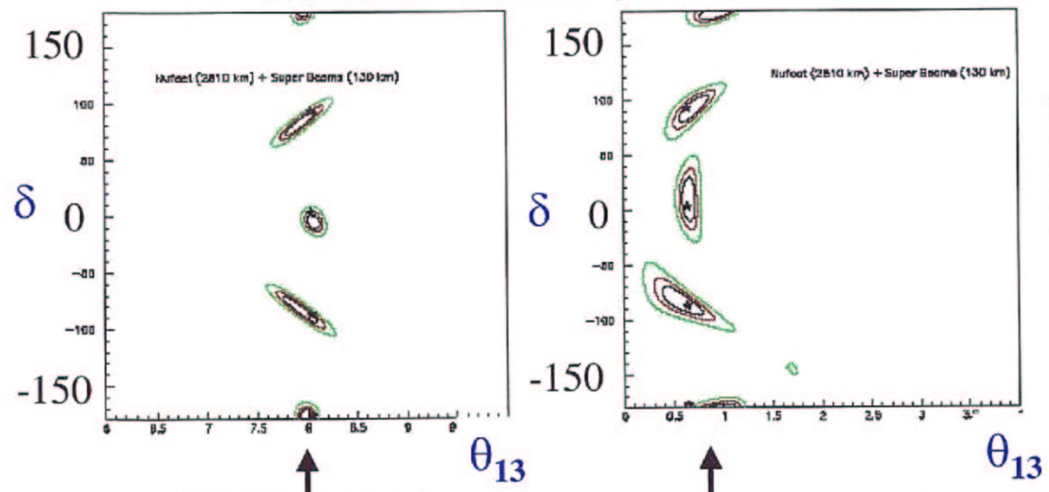
The calculations are for a 50 GeV Neutrino Factory.

19

# Impact of combing Superbeam & Neutrino Factory Data

*Burguet_castell, Gavela, Gomez-Cadenas, Hernandez, Mena; hep-ph/0207080*

NuFact: L = 2810 km, SB: L = 130 km



$\sin^2 2\theta_{13} = 0.076$

$\sigma_\delta \sim \pm 7°$

$\sin^2 2\theta_{13} = 4.4 \times 10^{-4}$

$\sigma_\delta \sim \pm 20°$

False solutions have disappeared.

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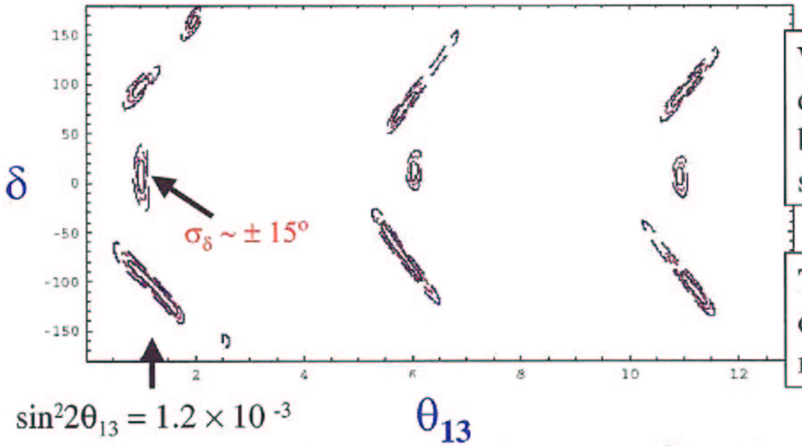
20

# Impact of using $\nu_e - \nu_\tau$ channel at a Neutrino Factory

*Donini, Meloni & Migliozzi, hep-ph/0206034*



$\sin^2 2\theta_{13} = 1.2 \times 10^{-3}$

With a 2kT emulsion detector, false solutions begin to appear for $\sin^2 2\theta_{13} < 0.001$

These false solutions disappear if the detector mass is increased to 4kT.

Figure 14: *68.5, 90 and 99 % C.L. contours resulting from a $\chi^2$ fit of $\theta_{13}$ and $\delta$, for $\bar{\theta}_{13} = 1°, 6°$ and $11°$, and $\bar{\delta} = -90°, 0°$ and $90°$, for the combination of an iron detector at $L = 3000$ Km (with "golden" muon events) and an emulsion detector at $L = 732$ Km (with "golden" and "silver" muon events). Realistic estimates for efficiencies and backgrounds at both the iron and the emulsion detector have been taken into account. Five years of data taking for both polarities in the distant detector and only five years in the $\mu^+$ polarity in the near detector have been considered.*

# Sensitivity to the Neutrino Mass Hierarchy & CP Violation

Tentative conclusions:

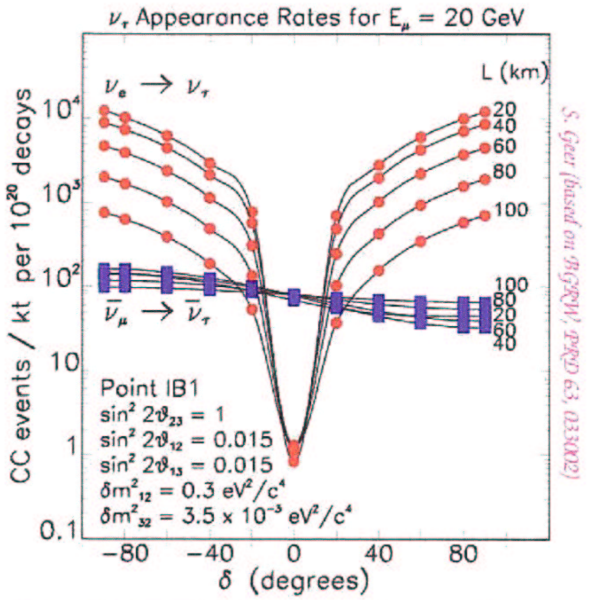
1. With a Neutrino Factory & Superbeam, using all of the available information, we should be able to determine the sign of $\Delta m_{32}^2$ and see maximal CP-Violation provided $\sin^2 2\theta_{13}$ exceeds $O(10^{-4})$.

2. If $\sin^2 2\theta_{13}$ is not far below the current bound & CPV is maximal, Neutrino Factories will enable a first observation of CPV (at a Superbeam) to be confirmed, the parameter values established with sufficient redundancy to check the phenomenological franework, & the precision of the CPV measurements to be improved by at least a factor of a few (perhaps much better than this if all the available information is used).

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

## 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:



S. Geer (based on BGRW, PRD 63, 033002)

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 ???

## Neutrino Interaction Experiments

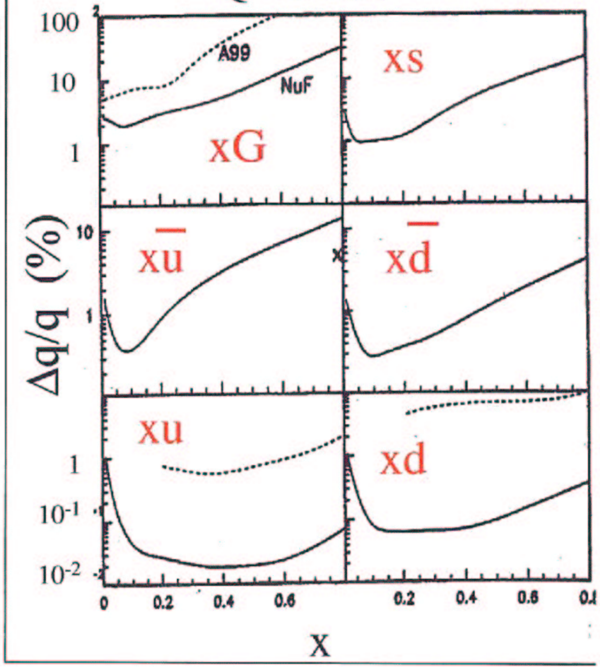
50 GeV ν-Fact: $10^6 - 10^7$ events/kg/year

Broad program – many experiments

1. Precise σ(ν) measurements
2. Structure Fus (no nuclear corrections) → individual quark flavor parton distributions
3. Precise $\alpha_s$ measurements (from non-singlet str. Fus.)
4. Study of nuclear effects (e.g. shaddowing) 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) → $D^0$-$\bar{D}^0$ 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

One Example

$Q = 9\ GeV^2$



## Neutrino Factory Community

Although difficult to estimate, we might expect a Neutrino Factory Facility to support a community of about 1000 scientists.

Example:

| | |
|---|---|
| Long baseline Osc. Expt. 1 | 250 |
| Long baseline Osc. Expt. 2 (possibly superbeam) | 250 |
| Neutrino Interaction Expt. 1 | 100 |
| Neutrino Interaction Expt. 2 | 100 |
| Neutrino Interaction Expt. 3 | 50 |
| Kaon/Muon/Neutron Beam Expt. 1 | 100 |
| Kaon/Muon/Neutron Beam Expt. 2 | 50 |
| Accelerator R&D (for Muon Collider ?) | 100 |
| TOTAL | 1000 |

## Neutrino Factory R&D – Critical Path

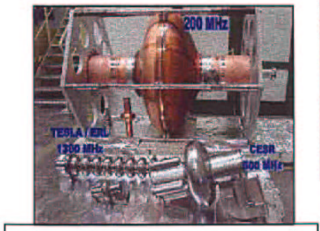
1. The technical R&D needed for a Neutrino Factory has been going well – the reports from the last two annual external technical reviews have been glowing.

2. There are two critical path things that have been identified that we need to accomplish in the next few years, before a Neutrino Factory could be proposed:

   i) A muon ionization cooling demonstration experiment.

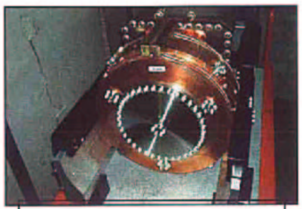
   ii) Feasibility Study III – focused on a cost effective Neutrino Factory design

# Neutrino Factory Hardware R&D – 1

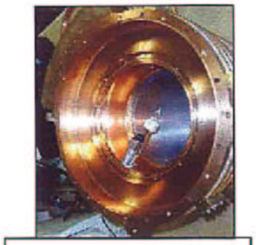


201 MHz SCRF
Cavity for Acceleration
– Cornell

Studied dark current &
X-rays from cavity with
various detectors

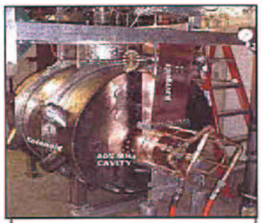


Single cell cavity with
Be windows - LBNL



Tested Be-Windows
for RF Cavities
– LBNL

High-Gradient RF Tests in
High Magnetic Field
– FNAL



5T Cooling Channel
Solenoid – LBNL
& Open Cell NCRF
Cavity operated at
Lab G – FNAL

High pressure seal
test for high-pressure
RF studies – Muons Inc

Dark current ring
measurements on
glass plate –
ANL/FNAL/IIT

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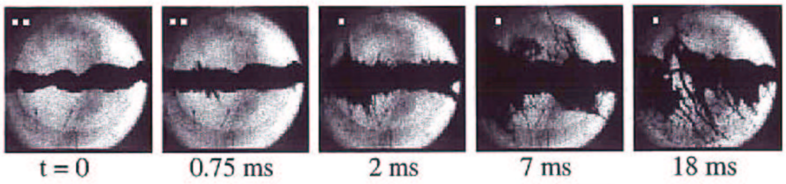
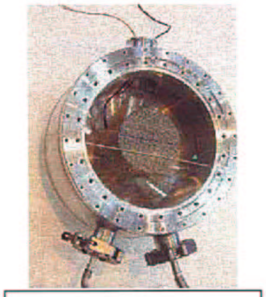
# Neutrino Factory Hardware R&D – 2



Hg jet beam tests – Target experiment

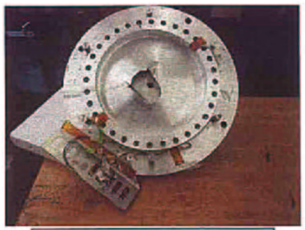
Bolometer detectors
for Window Beam
profile – cryogenic
setup– U. Chicago

Thin absorber windows
Tested – new technique
– ICAR Universities



Liq.H Absorber with
central heater– KEK

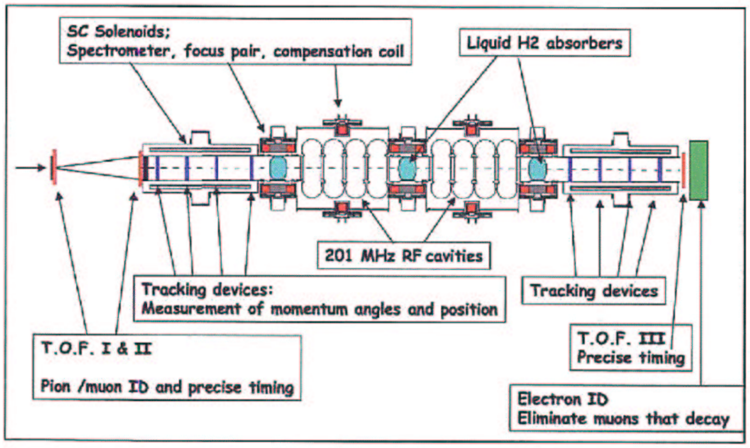
Liq.H Absorber
– KEK
To be tested
at FNAL



Window burst tests
– ICAR Universties

# Muon Ionization Cooling Experiment: MICE

Our external technical review committee said that: *"The cooling demonstration is the key systems test for a Neutrino Factory "*



Strong international collaboration has been assembled to propose a muon cooling experiment.

LoI submitted to RAL early 2002 had a favorable review. Full proposal submitted in February … under review.

RAL has assembled a project team to help.

We have a strong international team, a good experimental design, & a laboratory interested in hosting the experiment. Now is the time to move ahead.

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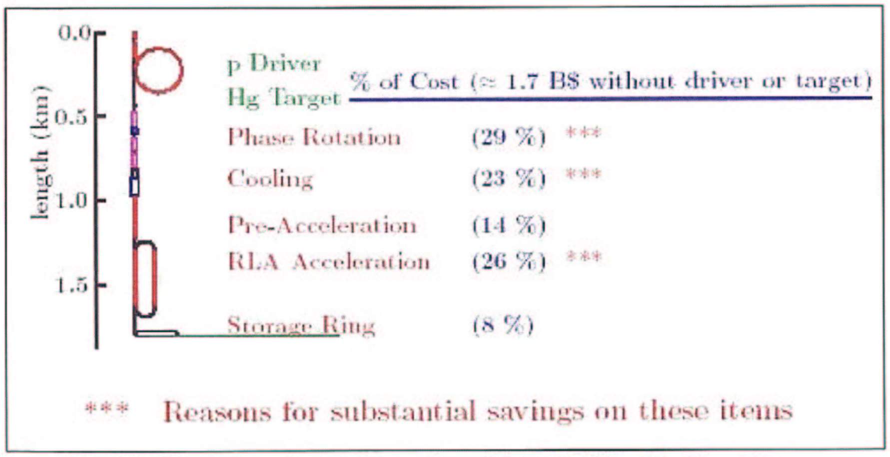
# Study III and Cost Reduction

Study II focused on achieving the desired Neutrino Factory performance with sufficient engineering for a serious cost estimate – but did not focus on cost reduction. Having achieved the desired performance the next step is to improve the design to reduce costs.



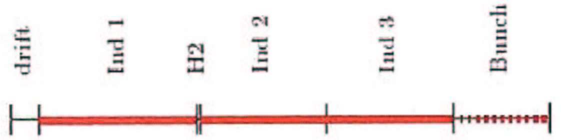
Detailed cost estimate based on Feasibility Studies II.
Direct costs (no overhead or contingency)

Since Study II we have developed concepts that look as if they might substantially reduce the costs of the three most expensive sub-systems (which account for ¾ of the total cost). We will not know the cost reduction until we have completed Feasibility Study III.

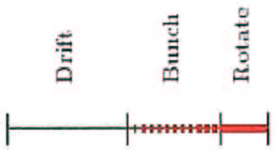
We think we will be ready for Study III in about 2 years, & it will probably be an international endeavor

# Phase Rotation – Progress towards Cost Reduction

- Study 2



- e.g. Bunch Beam Rotation



| | Study 2 | Now | Factor |
|---|---|---|---|
| Tot Length (m) | 328[1] | 166 | 51 % |
| Acc Length (m) | 269[2] | 35 | 13 % |
| Acc Type | Induction[3] | Warm RF | |

# Cooling Channel – Progress towards Cost Reduction

- Study 2 Cooling

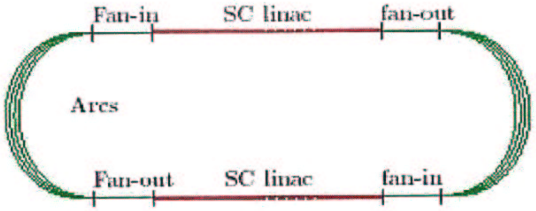
- e.g. RFOFO Cooling Ring

| | Study 2 | Now | Factor |
|---|---|---|---|
| Tot Length (m) | 108 | 33 | 30 % |
| Acc Length (m) | 54 | 37 | 21 % |
| Acc Grad | 16 MV/m | 12 MV/m | 66 % |

- Similar transmission
- Similar Trans emittance
- Less Long Emittance

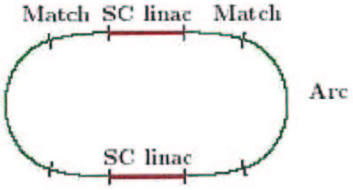
# Acceleration – Progress towards Cost Reduction

- Study 2 RLA



|  | Study 2 | Now | Factor |
|---|---|---|---|
| Vac Length[1] | 3261 | 1094 | 34 % |
| Tun Length[2] | 1494 | 1094 | 49 % |
| Acc Length[3] | 288 | 102 | 35 % |
| Acc Grad. | 16 | 8 | 50 % |
| Acc Type | SC RF | SC RF |  |

- e.g. Racetrack FFAG



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# Summary

1. 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
    (v) both muon- and electron- neutrinos & antineutrinos
2. Sensitive to a finite $\theta_{13}$, the sign of $\Delta m_{32}^2$ & CPV for $\sin^2 2\theta_{13}$ down to ~ $10^{-4}$
3. If $\theta_{13}$ just below current limit &if CPV maximal, would allow confirmation of the first observation of CPV at a Superbeam, a test of the phenomonological framework, unambiguous determination of all the parameters, and an improvement in the precision of the determination of $\delta_{CP}$ by at least a factor of a few.
4. Neutrino oscillation experiments, together with neutrino interaction experiments & experiments using intense kaon, muon, or neutron beams, and accelerator R&D (for a muon collider ?) would probably support a Neutrino Factory user community of about 1000 scientists – a broad & exciting scientific program.
5. The R&D is going well but we need adequate support to bring the required Neutrino Factory R&D to a successful conclusion.