Neutrino Oscillation Physics & Neutrino Factories

1. Atmospheric- and Solar-Neutrino Results
2. Framework – 3 flavor mixing
3. What is Known / Unknown
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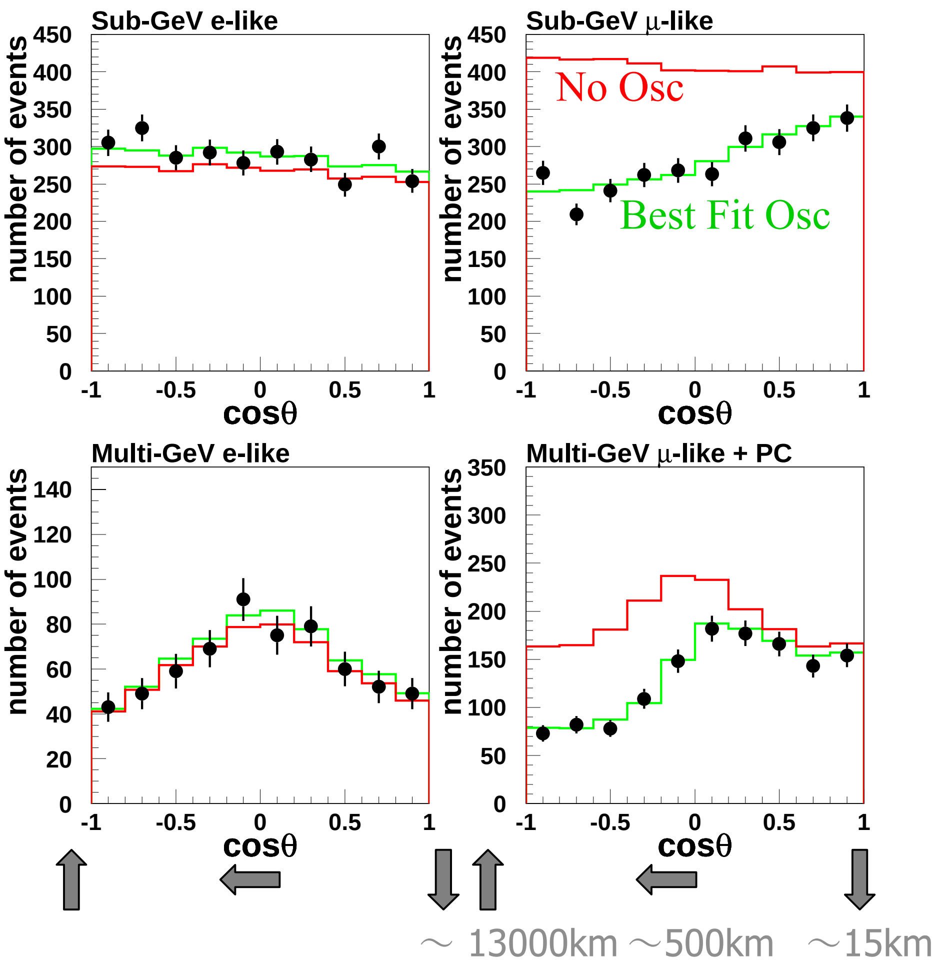
5. $\sin^2 2\theta_{13}$ reach
6. CP Violation & the Pattern of Neutrino Masses
7. LSND & the potential for surprises
8. Brief Summary

Introduction

There is now compelling evidence that neutrinos have mass, and neutrinos of one flavor can transform themselves into neutrinos of a different flavor → neutrino oscillations.

Atmospheric Neutrino Results from SuperK



Solar Neutrino Results from SNO

$$\phi_{CC} = \phi_e$$
$$\phi_{ES} = \phi_e + \varepsilon\, \phi_{\mu,\tau}$$
$$\phi_{NC} = \phi_e + \phi_\mu + \phi_\tau$$

$$\phi^{SNO}{}_{CC} = 1.75 \pm 0.13$$
$$\phi^{SK}{}_{ES} = 2.32 \pm 0.09$$
$$\phi^{SNO}{}_{NC} = 5.09 \pm 0.64$$

$$\phi_e = (1.76 \pm 0.10) \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$
$$\phi_{\mu,\tau} = (3.41 \pm 0.64) \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Two-Flavor Mixing

1. Atmospheric & Solar neutrino results are usually presented within the framework of two-flavor mixing:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

2. Flavor transition probability for neutrinos with energy E (GeV) traversing a baseline L (km) :

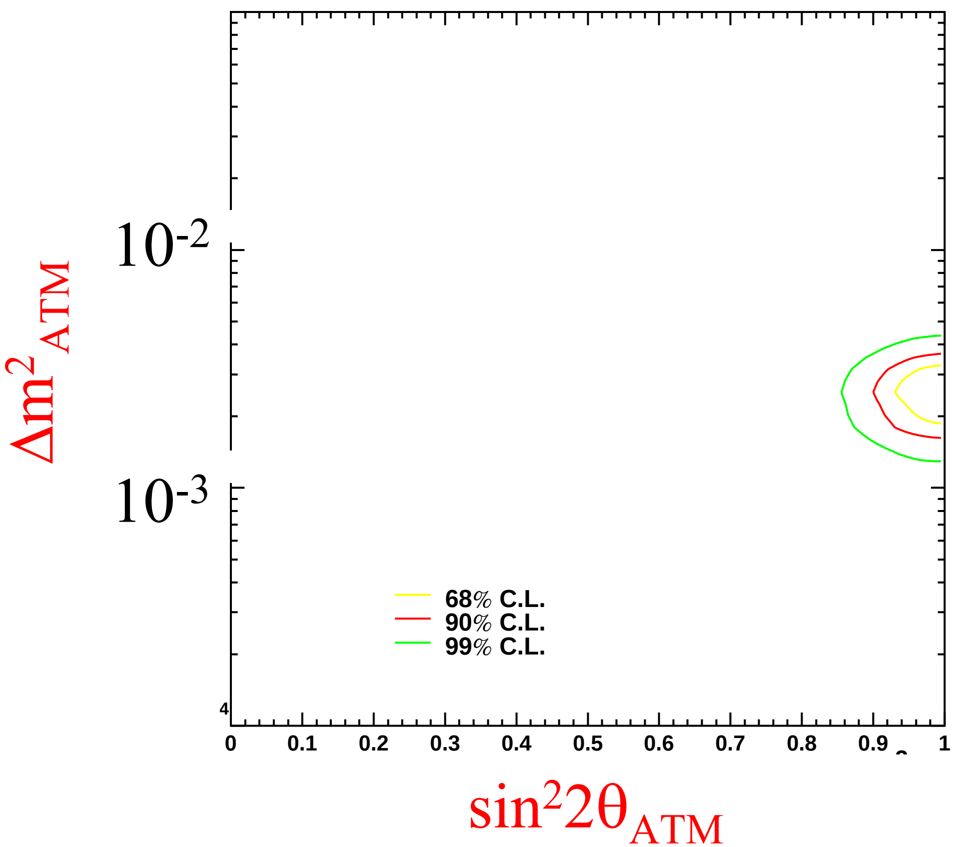
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$$

Oscillation amplitude: $\sin^2 2\theta$

Oscillation frequency determined by $\Delta m^2 = m_1^2 - m_2^2$

Atmospheric Neutrinos

Super-Kamiokande Fit Results

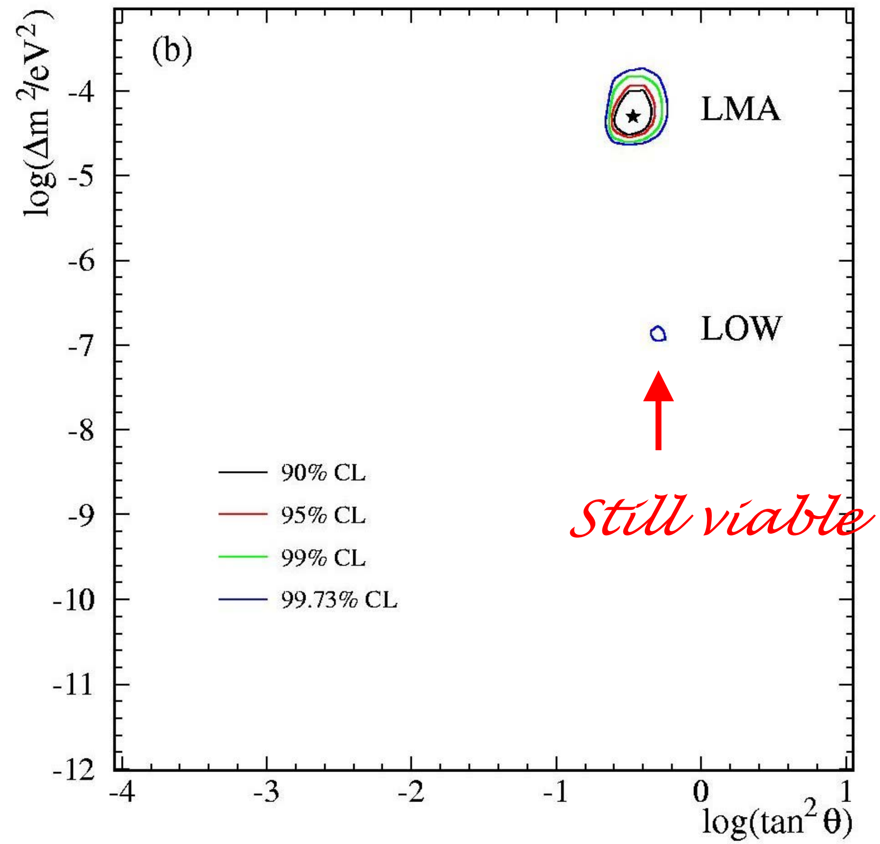


$\Delta m^2_{ATM} = (1.6 - 3.6) \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2 2\theta_{ATM} > 0.9$ (90% C.L.)

Solar Neutrinos

SNO Global Fit Results



$\Delta m^2_{SOL} \sim 5 \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2 2\theta_{SOL} \sim 0.87$

Three – Flavor Mixing - 1

If the Solar & Atmospheric neutrino results are both due to neutrino oscillations there must be at least 3 mass eigenstates …. Otherwise there cannot be two different mass splittings.

Within the framework of 3-flavor mixing, the 3 known flavor eigenstates (ν_e, ν_μ, ν_τ) are related to 3 neutrino mass eigenstates (ν_1, ν_2, ν_3) :

$$\boxed{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\big(3\times 3\big)}_{U_{MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}$$

Three – Flavor Mixing - 2

Within the framework of 3-flavor mixing ALL of the physics is encapsulated within the 3 × 3 mixing matrix U_{MNS} , and two independent Δm_{ij}^2

In analogy with the CKM matrix, U_{MNS} can be parameterized using 3 mixing angles (θ_{12} , θ_{23} , θ_{13}) and one complex phase (δ) :

$$\begin{pmatrix} C_{12}C_{23} & S_{12}C_{13} & S_{13}\, e^{-i\delta} \\ \begin{matrix} -S_{12}C_{23} \\ -C_{12}S_{23}\, S_{13}\, e^{i\delta} \end{matrix} & \begin{matrix} C_{12}C_{23} \\ -S_{12}C_{23}\, S_{13}\, e^{i\delta} \end{matrix} & S_{23}C_{13} \\ \begin{matrix} S_{12}S_{23} \\ -C_{12}C_{23}\, S_{13}\, e^{i\delta} \end{matrix} & \begin{matrix} -C_{12}S_{23} \\ -S_{12}C_{23}\, S_{13}\, e^{i\delta} \end{matrix} & C_{23}C_{13} \end{pmatrix}$$

Three – Flavor Mixing – Quarks vs Leptons

The first theorist guess was that the U_{MNS} matrix should be similar to the CKM matrix. However $\sin^2 2\theta_{ATM} > 0.9$ and $\sin^2 2\theta_{SOL} \sim 0.87$. Therefore :

$$U_{MNS} = \begin{pmatrix} \text{large} & \text{large} & \text{small/tiny ?} \\ \text{large} & \text{large} & \text{large} \\ \text{large} & \text{large} & \text{large} \end{pmatrix} \qquad V_{CKM} = \begin{pmatrix} \sim 1 & \text{small} & \text{tiny} \\ \text{small} & \sim 1 & \text{tiny} \\ \text{tiny} & \text{tiny} & \sim 1 \end{pmatrix}$$

Note that the size of the small/tiny U_{e3} element is governed by θ_{13}. We think we know that $\sin^2 2\theta_{13} < 0.1$ (CHOOZ reactor ν_e disappearance limit)

Establishing the size $\sin^2 2\theta_{13}$ a vital goal for future accelerator-based neutrino oscillation experiments … this will determine the size of the one completely unknown element of the mixing matrix.

From Three – Flavor Mixing to Oscillations

We take as the two independent Δm_{ij}^2 :

$$\Delta m_{atm}^2 \equiv \Delta m_{32}^2 \text{ and } \Delta m_{sol}^2 \equiv \Delta m_{21}^2$$

We know that :

$$\boxed{|\Delta m_{sol}^2| \leq O(10^{-4})\ \mathrm{eV}^2 \quad \ll \quad |\Delta m_{atm}^2| > 10^{-3}\ \mathrm{eV}^2}$$

The full expressions for the flavor transition probabilities are messy but, since $|\Delta m_{32}^2| >> |\Delta m_{21}^2|$ we can gain some insight by neglecting terms driven by Δm_{21}^2.

For neutrinos of energy E propagating a distance L in vacuum :

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

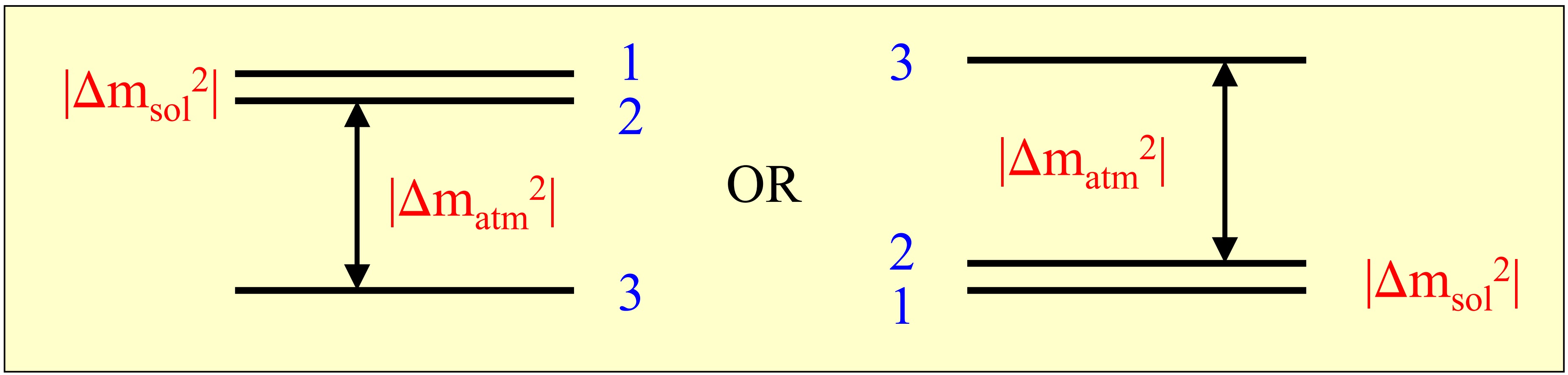
$$P(\nu_e \leftrightarrow \nu_\tau) \approx \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.267\, \Delta m_{32}^2 L / E)$$

$$P(\nu_\mu \leftrightarrow \nu_\tau) \approx \sin^2 2\theta_{23} \cos^4\theta_{13} \sin^2(1.267\, \Delta m_{32}^2 L / E)$$

Matter Effects

In vacuum the oscillation probabilities depend on $|\Delta m_{32}^2|$ but not on the sign of Δm_{32}^2 .

In matter electron neutrinos can forward-elastic scatter off the electrons, an additional interaction that modifies the transition probabilities for transitions involving a ν_e . The modification depends on the sign of Δm_{32}^2 and can be exploited to determine the pattern of neutrino masses:



What is Known

1. There are at least three flavors participating in neutrino oscillations.

2. $\sin^2 2\theta_{23} \sim 1$ ($\geq$ 0.9 at 90% CL)

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

4. $\Delta m_{21}{}^2 \sim 5 \times 10^{-5}\ \mathrm{eV}^2$ (if LMA confirmed)

5. $\sin^2 2\theta_{12} \sim 0.87$ (if LMA confirmed)

6. $\sin^2 2\theta_{13} < O(0.1)$

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 Δm_{32}^2 (pattern of neutrino masses) ?

5. Is $\sin^2 2\theta_{23}$ maximal (= 1) ?

Beam Properties at a Neutrino Factory

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

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

If $x = 2E_\nu/m_\mu$, θ is the angle between the neutrino & muon spin, and P is the muon polarization, in the muon rest-frame :

$$\nu_\mu : \quad \frac{d^2N}{dx\, d\cos\theta} \sim \frac{1}{4\pi}\left[2x^2(3-2x) \mp 2x^2(1-2x)\, P \cos\theta\right]$$

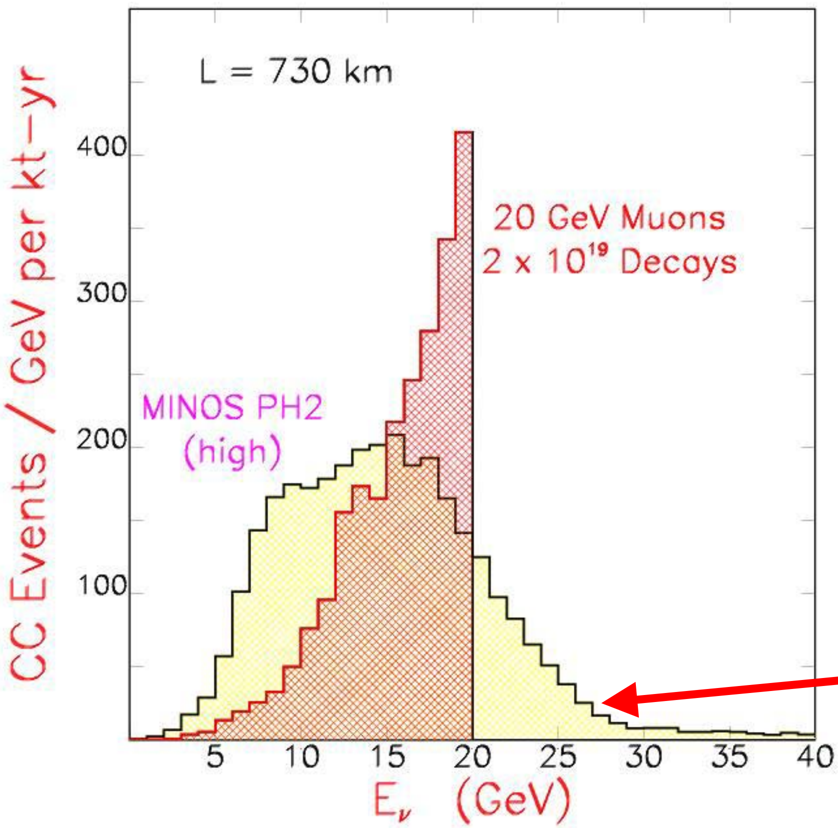
$$\nu_e : \quad \frac{d^2N}{dx\, d\cos\theta} \sim \frac{1}{4\pi}\left[12x^2(1-x) \mp 12x^2(1-x)\, P \cos\theta\right]$$

C. Albright et al., Physics Study Report, hep-ex/0008064

Muon Neutrinos at a Neutrino Factory

1.6 MW SNuMI WBB			NuFact		
Beam	E_ν (GeV)	CC Events (per kt-yr)	E_μ (GeV)	E_ν (GeV)	CC Events (per kt-yr)
LE	3	1800			
ME	6	5800	10	7.5	1400
HE	12	13000	20	15	12000
			30	38	180000

MW-scale proton driver can produce Neutrino Superbeams (e.g. SNuMI = 4 x NuMI) or a Neutrino Factory providing ~10^{20} decays/year.



Muon neutrino flux at a 20 GeV NuFact comparable to Superbeam flux. At higher energies NuFact event rates ~E^3.

The neutrino energy spectrum has NO HIGH ENERGY TAIL at a NuFact … a crucial advantage since neutral current backgrounds to $\nu_e \rightarrow \nu_\mu$ oscillations come from this tail which limits the sensitivity of Superbeams.

Electron Neutrinos at a Neutrino Factory

The real reason we want a Neutrino Factory is that we need a clean source of electron-neutrinos. These are only present in a Superbeam as a small (annoying) contamination.

We will see for $\nu_e \rightarrow \nu_\mu$ oscillations that (i) to fully exploit matter effects ($\rightarrow$ baseline of several $\times$ 1000 km, and (ii) to suppress back-grounds to wrong-sign muon signal events, we want electron neutrinos with energies O(10 GeV).

To search for $\nu_e \rightarrow \nu_\tau$ oscillations we also want electron neutrinos with energies of at least O(10 GeV) so we are well above the ν_τ CC threshold.

This leads us to consider Neutrino Factories with energies of 20 GeV or more.

Oscillation Measurements at a Neutrino Factory

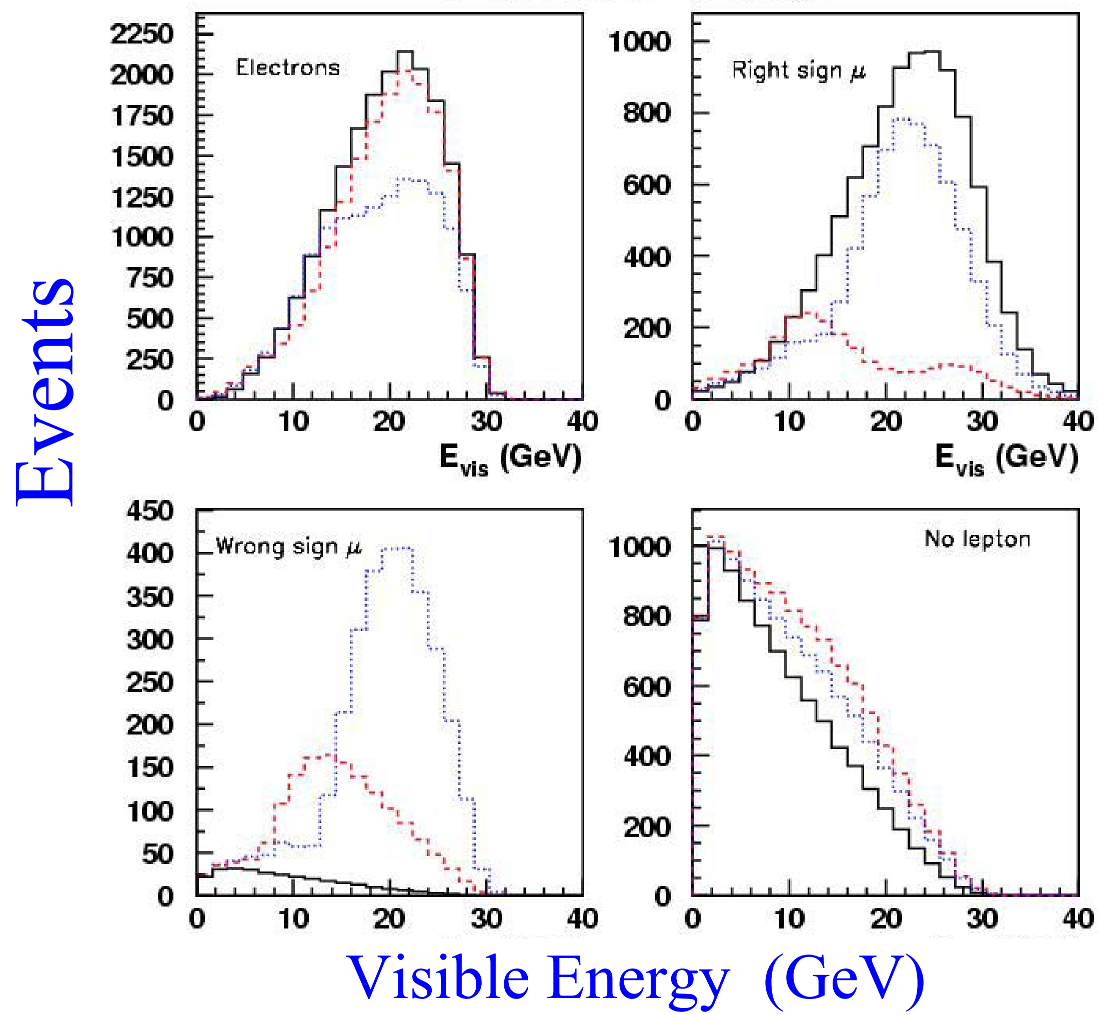
There is a wealth of information that can be used at a neutrino factory. Oscillation parameters can be extracted using events tagged by:

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.



Wrong-Sign Muons

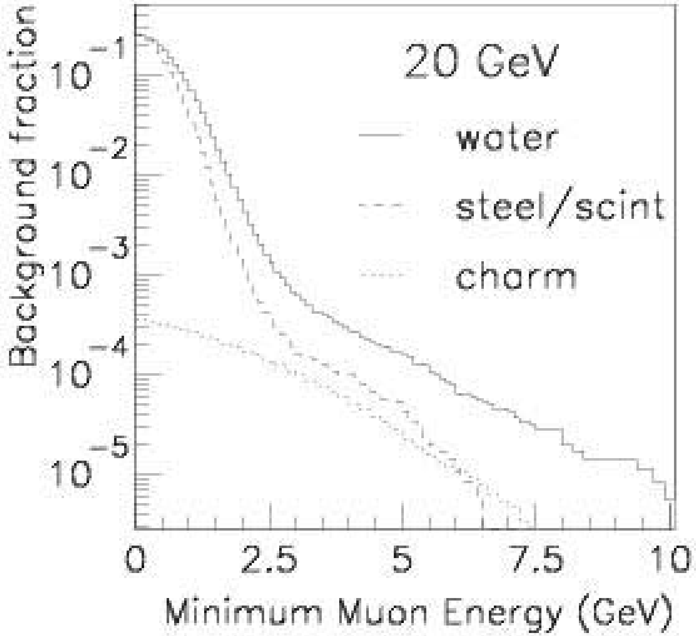
$\nu_e \to \nu_\mu$ oscillations at a neutrino factory result in the appearance of a "wrong-sign" muon … one with opposite charge to those stored in the ring:

$$\begin{array}{l} \mu^+ \to e^+ \, \nu_e \, \bar{\nu}_\mu \;\overset{CC}{\Rightarrow}\; \mu^+ \\ \qquad\qquad\quad\;\; \downarrow \\ \qquad\qquad\quad\;\; \nu_\mu \;\underset{CC}{\Rightarrow}\; \mu^- \end{array}$$

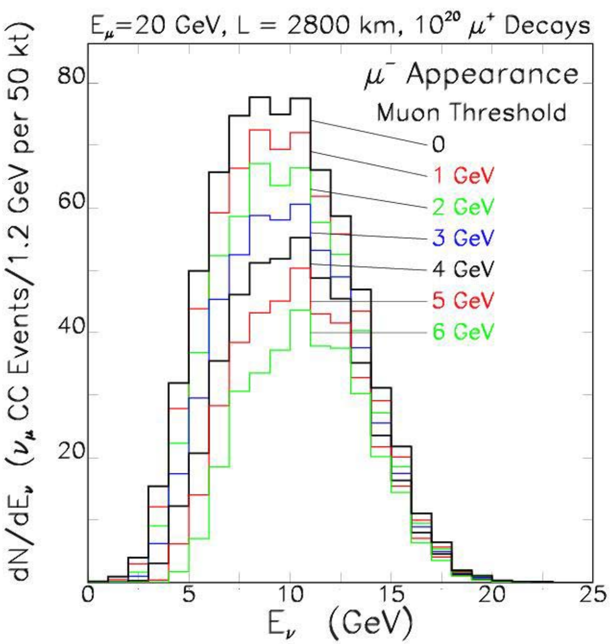
Backgrounds to the detection of a wrong-sign muon are expected to be at the 10^{-4} level $\Rightarrow$ $\nu_e \to \nu_\mu$ oscillations with amplitudes as small as $O(10^{-4})$ can be measured !

Muon Threshold

D. Harris & K. McFarland;



Barger, Geer, Raja, Whisnant, PRD 62, 073002



To measure wrong-sign muons with background fractions as low as $O(10^{-4})$ we need to impose a threshold on the muon energy which depends on detector technology. For a magnetized iron/scintillator detector $E_{min} \sim 4$ GeV.

With this threshold, to obtain reasonable muon detection efficiency we need neutrinos with energies ≥10 GeV

In practice this means the stored muons must have energies of at least ~20 GeV.

It is worth exploring reducing the Neutrino Factory energy by a couple of GeV, but we are losing ground fast !

$\sin^2 2\theta_{13}$ Reach - 1

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

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

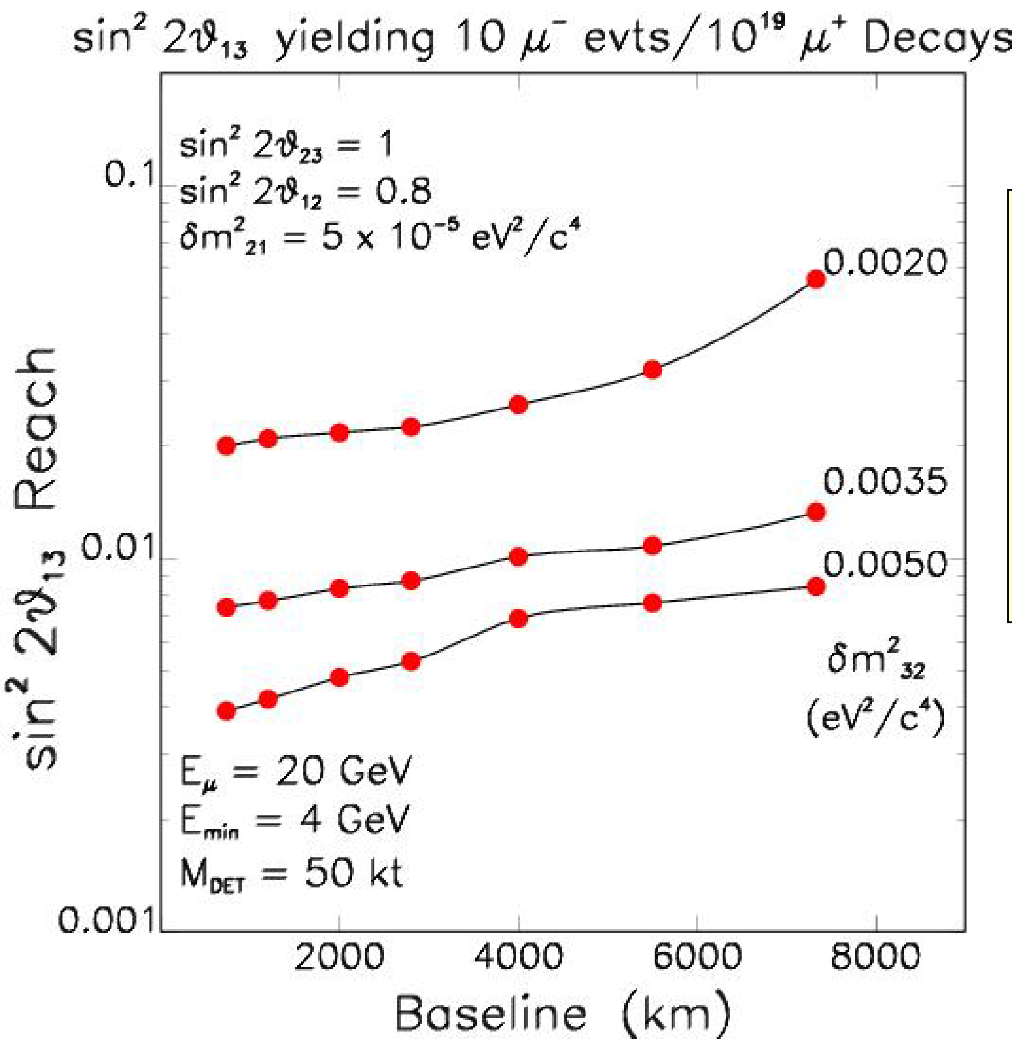
It is useful to define the $\sin^2 2\theta_{13}$ reach for a given experiment as the value of $\sin^2 2\theta_{13}$ for which a $\nu_e \leftrightarrow \nu_\mu$ signal would be observed 3σ above background. If the expected background is less than one event, we define the reach as the value of $\sin^2 2\theta_{13}$ that yields 10 signal events.

From the CHOOZ reactor ν_e disappearance search we know that at 90% CL: $\sin^2 2\theta_{13} < O(0.1)$

In the next 10 years Superbeam experiments are expected to achieve a $\sin^2 2\theta_{13}$ reach $\sim O(0.01)$

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

Barger, Geer, Raja, Whisnant, PRD 62, 073002



At a Nu Factory 10^{19} decays yields comparable reach to 5 yrs running at the 0.77 MW JHF Superbeam. With 2×10^{20} decays/yr, a Nu-Factory does almost $\times$ 100 better.

When do Superbeams Run Out of Steam ?

There are various first-generation superbeam ideas (JHF, NuMI off-axis, BNL study, …) all of which seem to yield similar $\sin^2 2\theta_{13}$ sensitivities.

To improve further we must increase N = beam flux × detector mass.
We are background limited … so sensitivity improves $\sqrt{N}$.

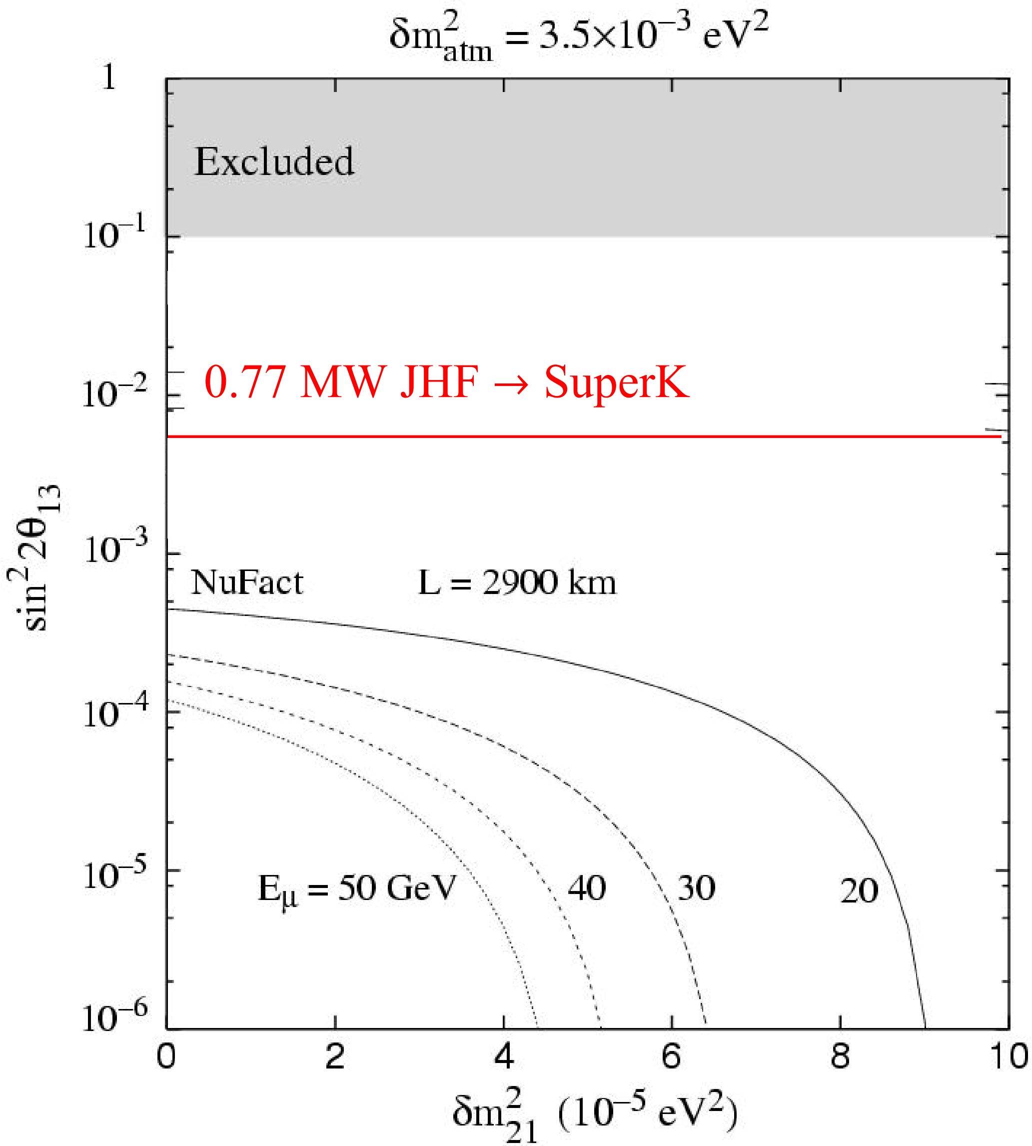
How much does it cost to improve a modest × 5 beyond JHF → SK ?

	With P-Driver Upgrade		Without P-Driver Upgrade	
Detector	Mass	Cost	Mass	Cost
Plastic/RPC	100 Mt	200 M$	500 Mt	1.0 B$
4.5mm steel/sc	75 Mt	325 M$	375 Mt	1.6 B$
Liq. Argon	25 Mt	500 M$	125 Mt	2.5 B$
Water C	500 Mt	425 M$	2500 Mt	2.1 B$
Liq. Sc	100 Mt	150 M$	750 Mt	0.8 B$

None of these costs should be taken very seriously … & should not be used to compare detector choices (yet). The Liq. Argon case could be much cheaper if new detector technology was successfully developed.

$\mathrm{Sin}^2 2\theta_{13}$ Reach - 3

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.

At large $|\Delta m_{21}{}^2|$ and very small $\sin^2 2\theta_{13}$ the sub-leading scale begins to dominate !

CP-Violation & the pattern on neutrino masses - 1

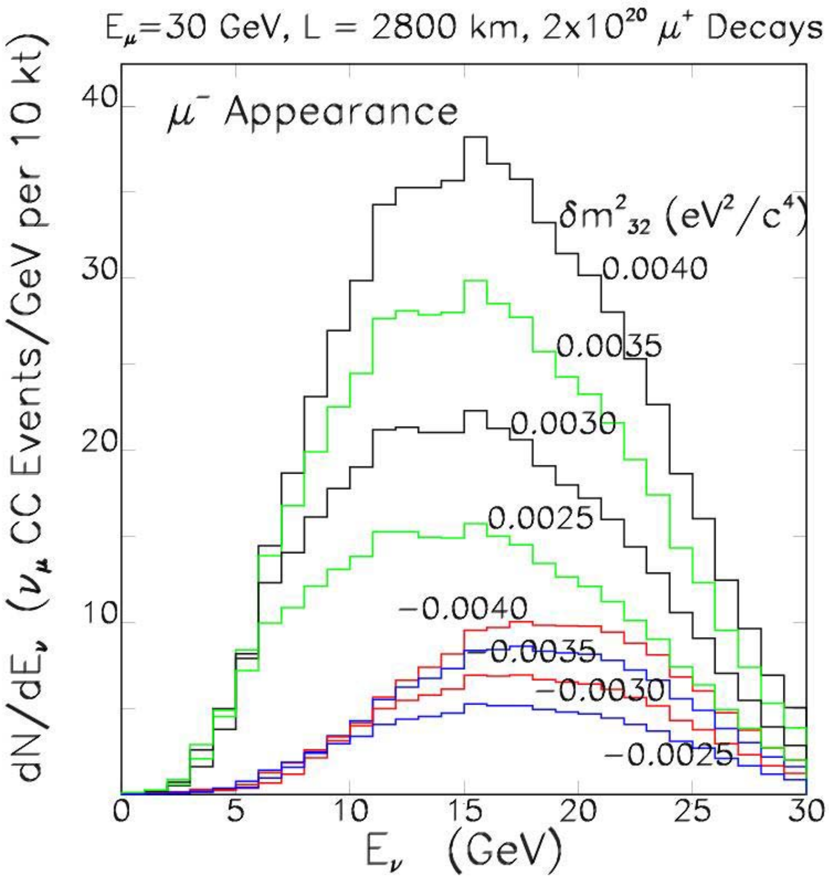
CP Violation requires contributions from both leading & sub-leading Δm^2 scales.

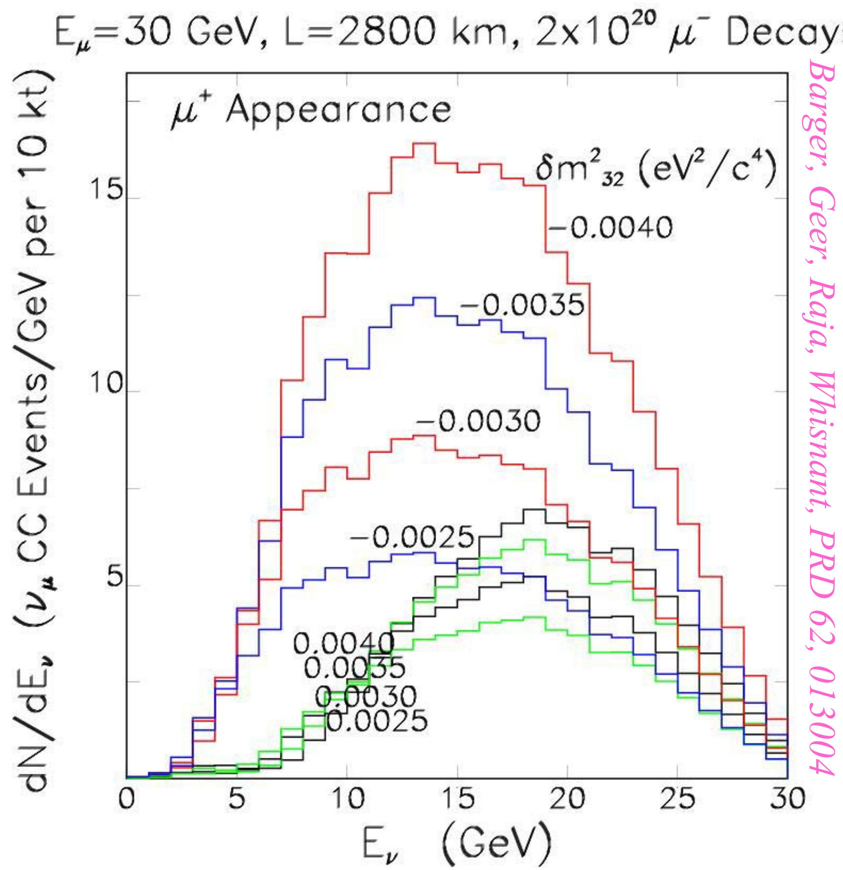
If the sub-leading scale ($\Delta m_{21}{}^2$) & the associated oscillation amplitude are large enough ($\rightarrow$ LMA) then CP violation might be observable in long-baseline experiments !

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

If the baseline is a few $\times 1000$ 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 $\Delta m_{32}{}^2$ $\rightarrow$ the pattern of neutrino masses.

The pattern on neutrino masses





μ^- Appearance

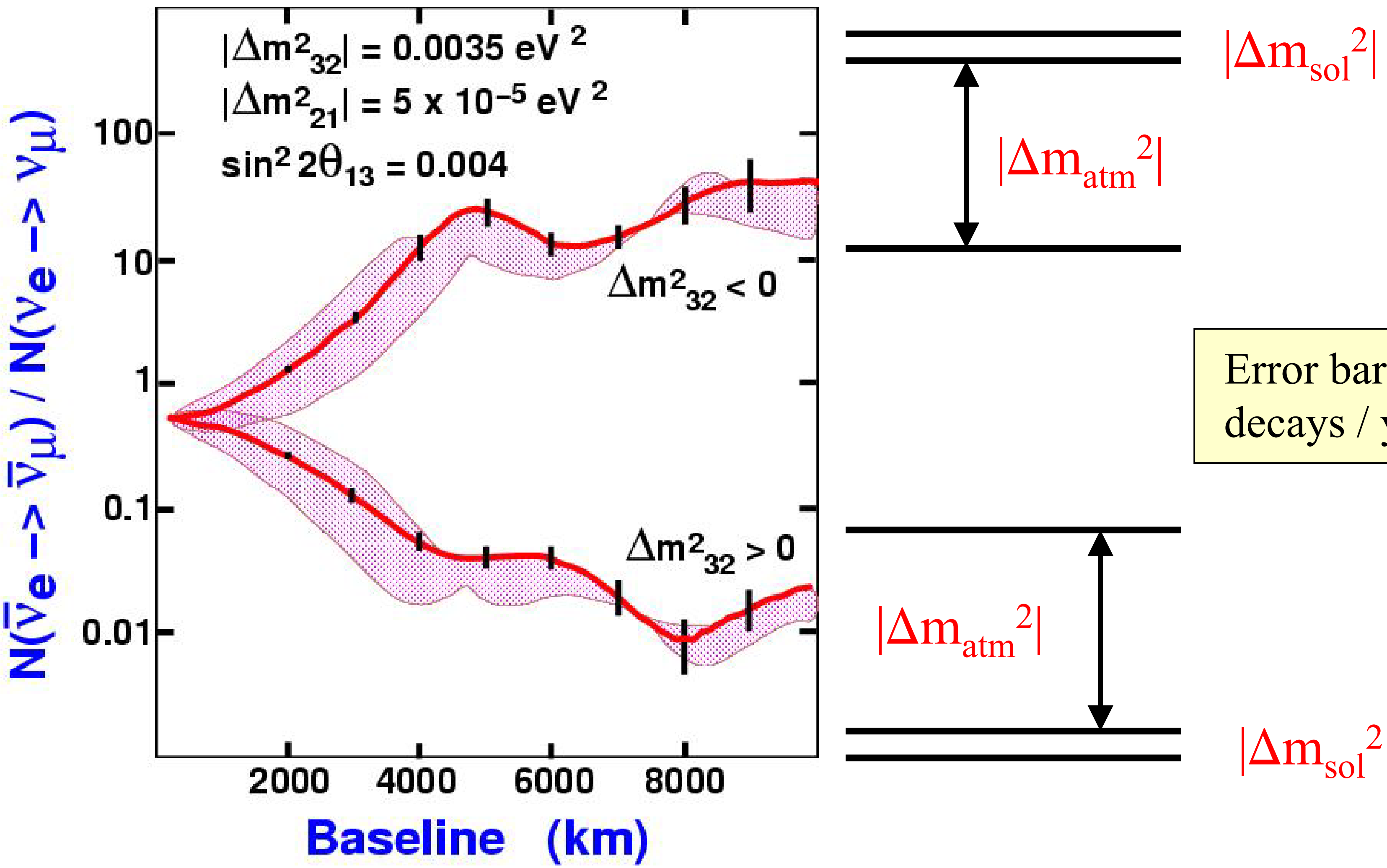
+tve Δm_{32}^2 gives larger rate & softer spectrum than –tve Δm_{32}^2

μ^+ Appearance

+tve Δm_{32}^2 gives smaller rate & harder spectrum than –tve Δm_{32}^2

CP-Violation & the pattern on neutrino masses - 3

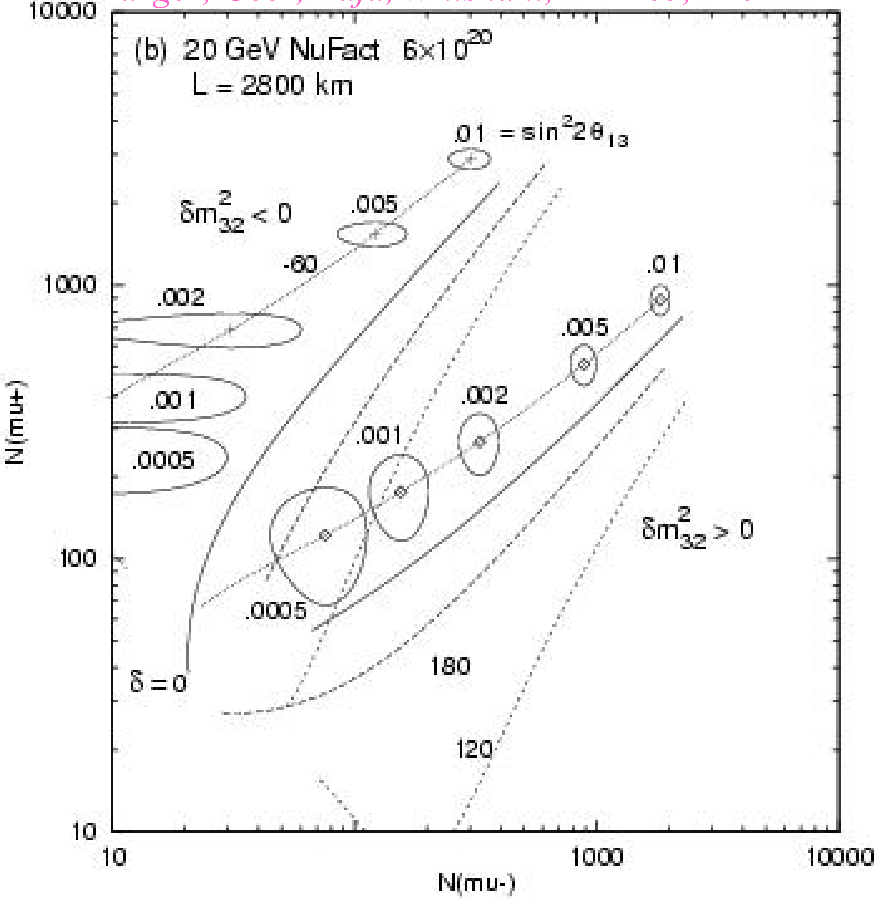
Barger, Geer, Raja, Whisnant, PRD 62, 073002
S. Geer, hep-ph/0008155



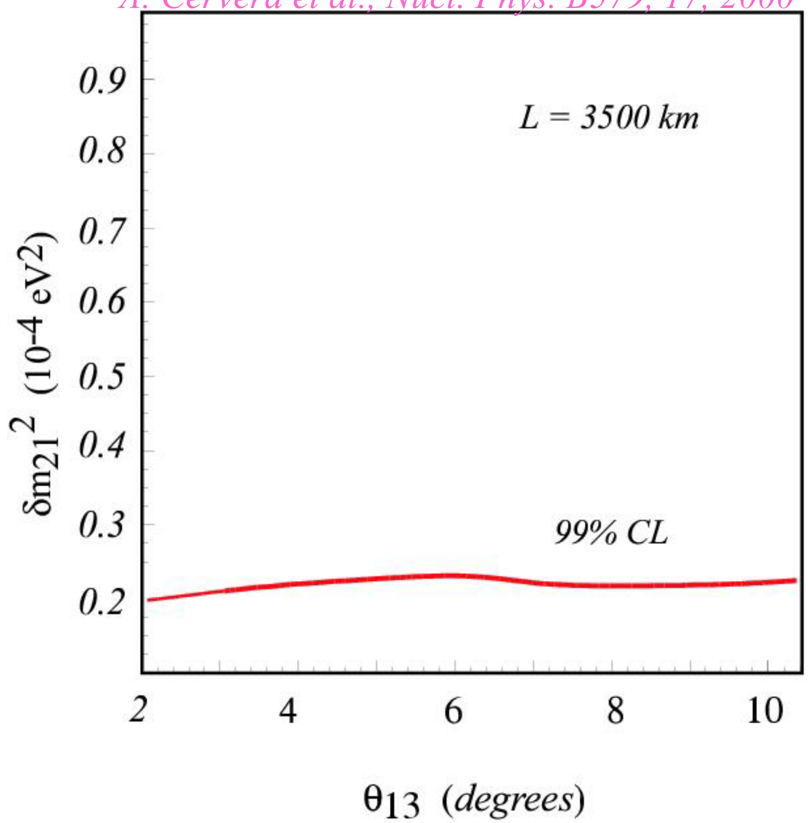
Error bars → 2×10^{20} decays / yr for 5 years

CP-Violation – Detailed Fitting

Barger, Geer, Raja, Whisnant, PRD 63, 11011



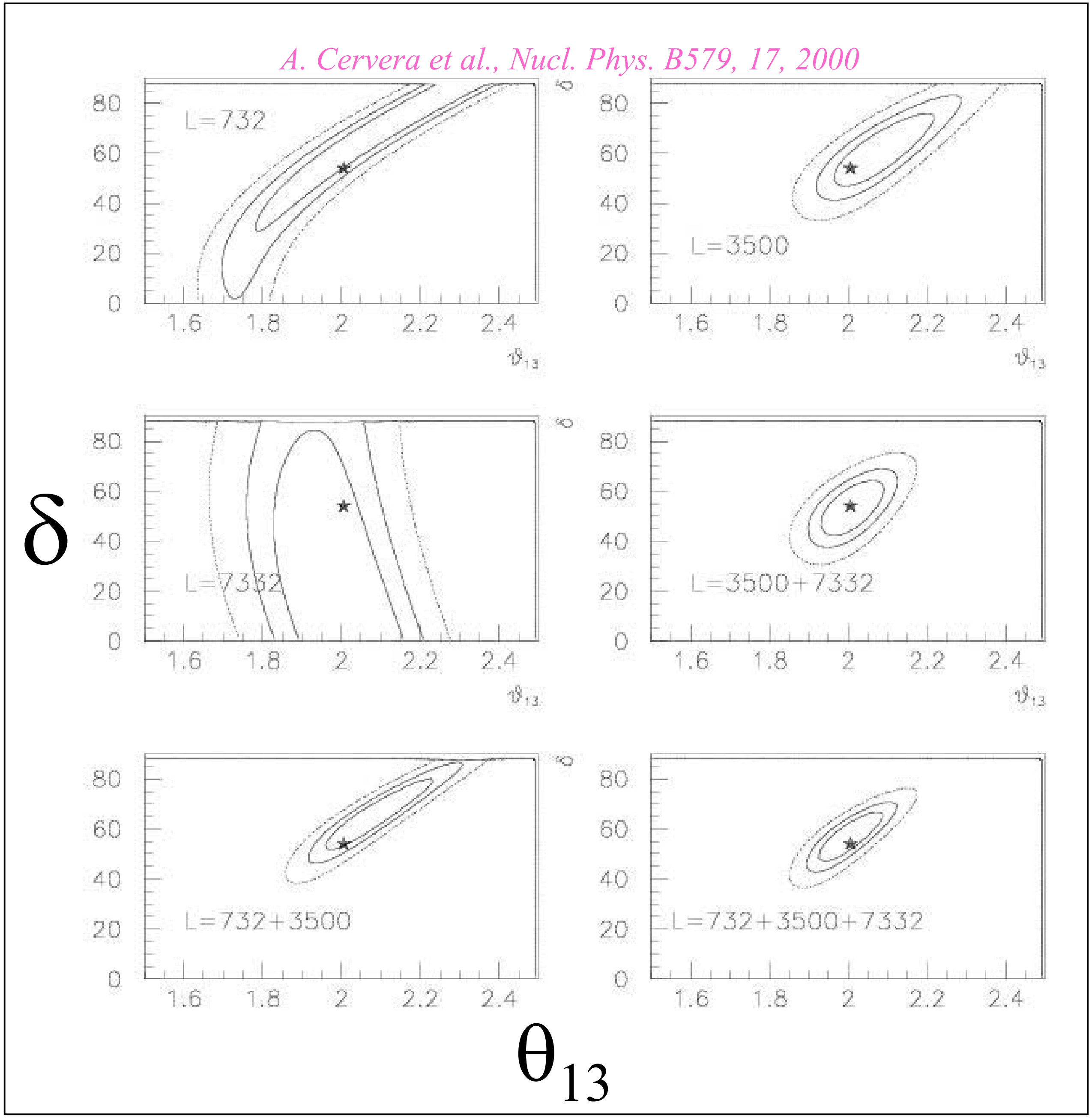
A. Cervera et al., Nucl. Phys. B579, 17, 2000



Sensitivity to pattern of neutrino masses & CP violation extends down to values of $\sin^2 2\theta_{13} \sim 10^{-3}$

Detailed fits have shown that good sensitivity is maintained provided $|\Delta m_{21}^2| > 2 \times 10^{-5}$ eV^2 → over the entire LMA region !

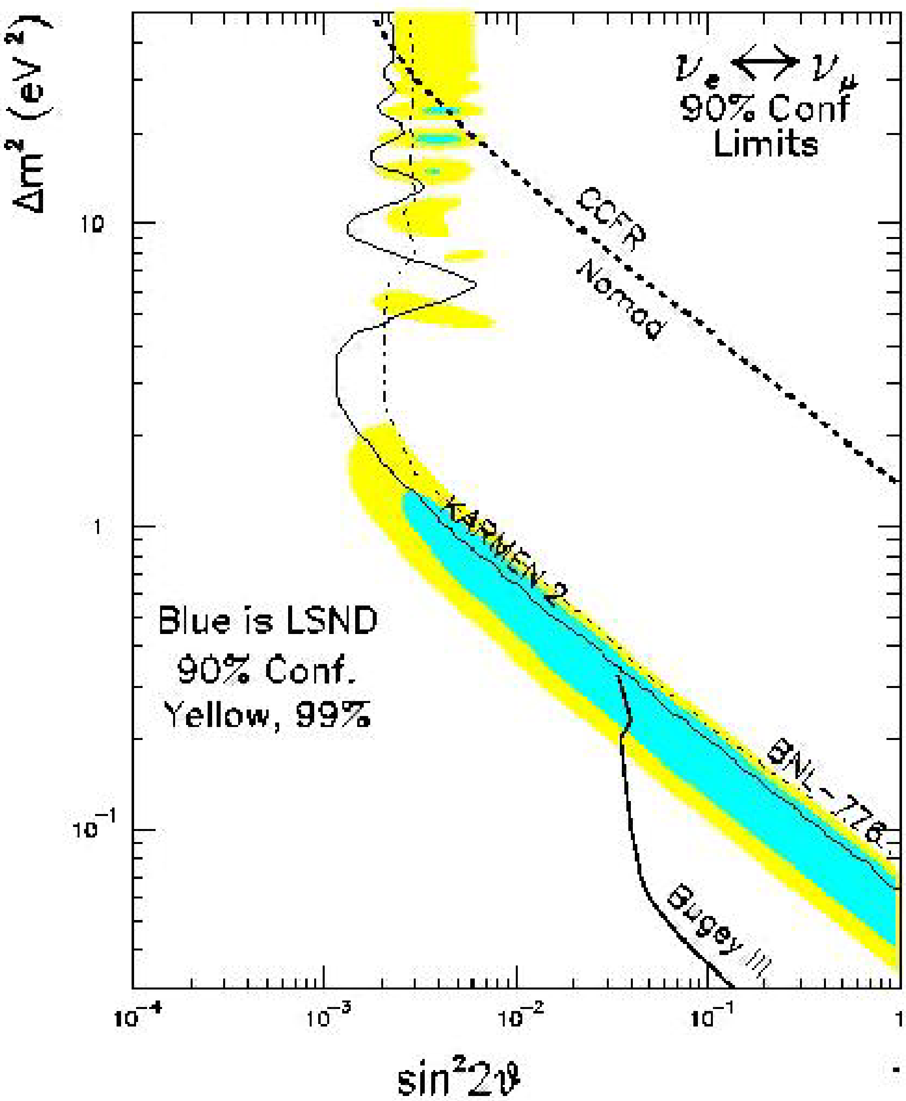
CP-Violation – Detailed Fitting



For a single baseline we expect a strong correlation between the extracted values of $\sin^2 2\theta_{13}$ and δ.

However, the correlation can reduced with two (or more) baselines → motivation for more than two straight sections.

Potential for Surprises - LSND



LSND see evidence for $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ oscillations with a $|\Delta m^2|$ scale $|\Delta m_{LSND}^2| \gg |\Delta m_{ATM}^2| \gg |\Delta m_{SOL}^2|$

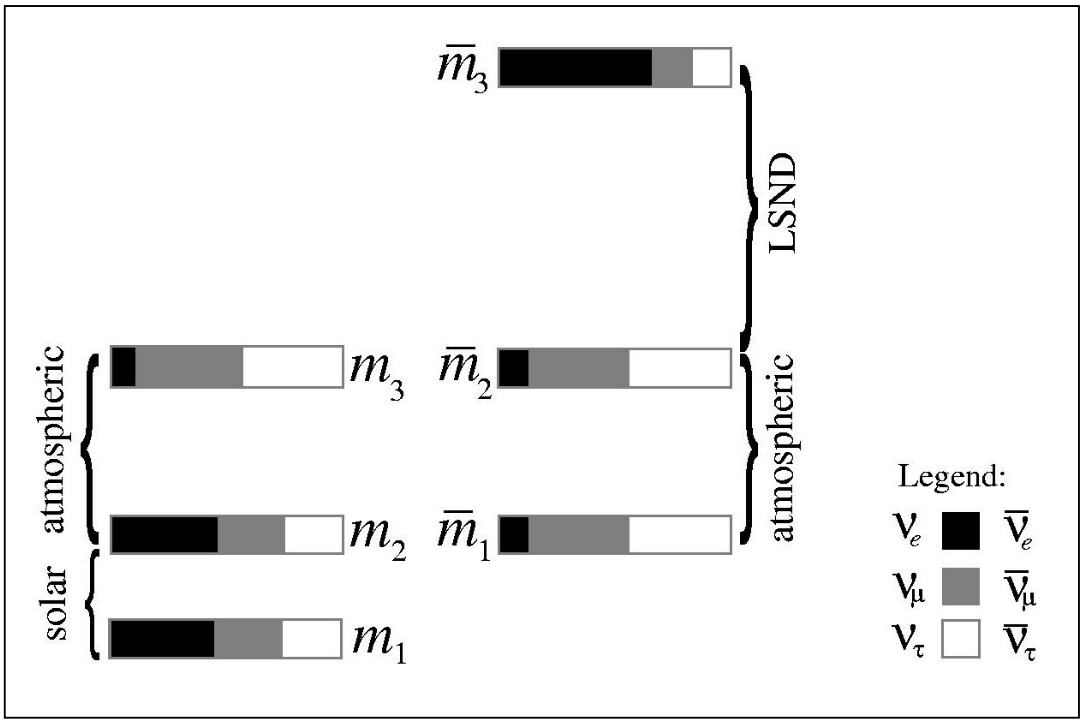
If confirmed by MiniBooNE, then we have three mass-splitting scales which cannot be accommodated Within a framework in which there are only three mass eigenstates.

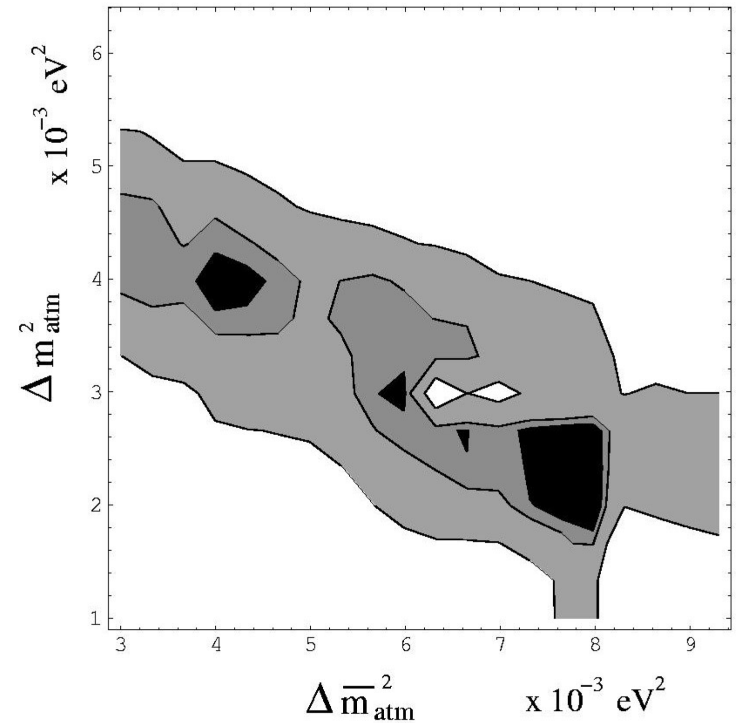
The 3-flavor mixing framework would have to be modified → BIG DISCOVERY !

CPT Violation

The "LSND" problem could be solved if CPT is violated so that the neutrino mass eigenstates are different from the antineutrino mass eigenstates:

Barenboim, Borissov, Lykken; hep-ph/0201080

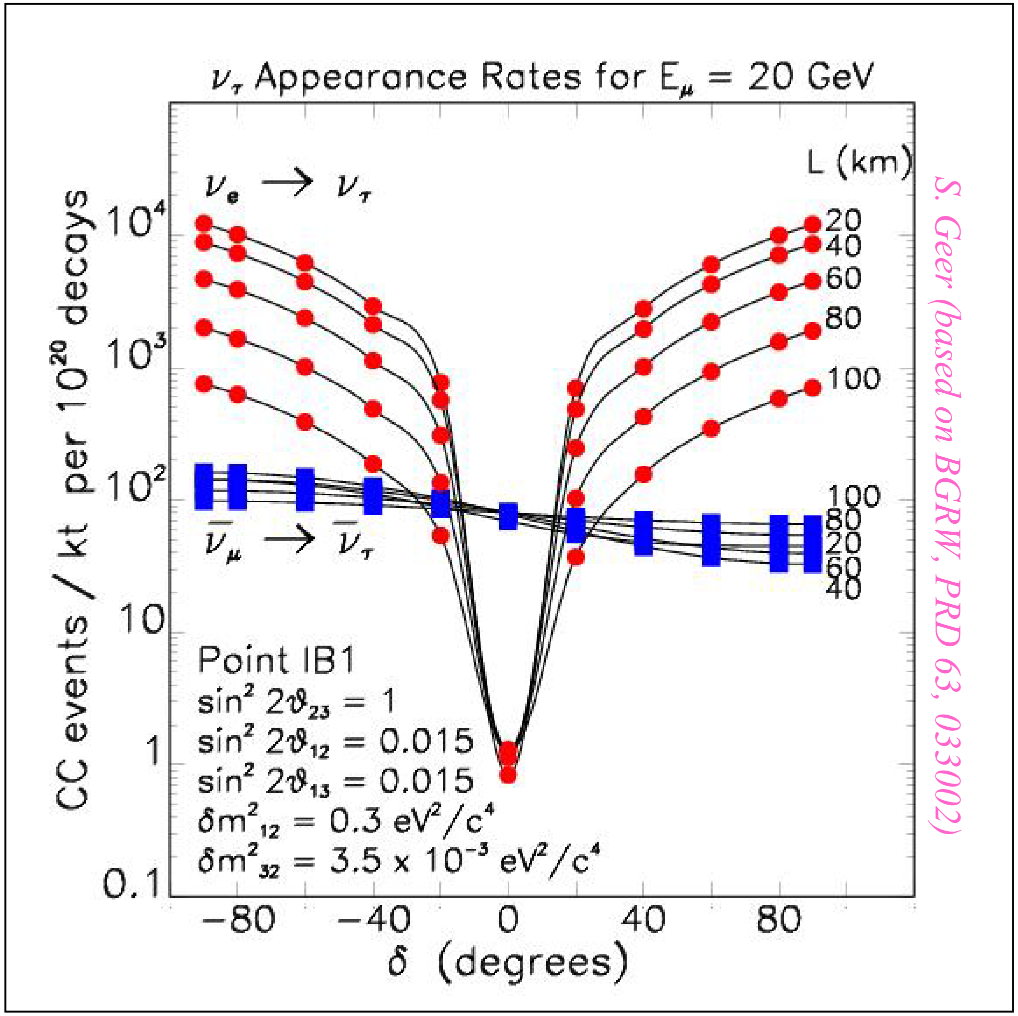




Fit to SuperK Atmospheric Neutrino Data
(90, 95, & 99% CL regions)

Sterile Neutrinos

The "LSND" problem could be solved if there were more than three light neutrino mass eigenstates → 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 !

Summary – Important Points for Nu-Factory Design

1. Solar neutrinos oscillate, and it is looking increasing like the LMA solar solution → good news for Neutrino Factories

2. In general the neutrino oscillation physics goals require that Neutrino Factories deliver ≥ 10^{20} useful muon decays / year with energies ≥ about 20 GeV → exciting physics program.

3. If MiniBooNE confirms LSND we might imagine a case for a learning Neutrino Factory delivering only 10^{18} decays / year. In fact any big surprise might motivate a low intensity Neutrino Factory … we should be prepared for this scenario.

APPENDIX

Three – Flavor Mixing - 1

Within the framework of 3-flavor mixing, the 3 known flavor eigenstates (ν_e, ν_μ, ν_τ) are related to 3 neutrino mass eigenstates (ν_1, ν_2, ν_3) :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 3\times 3 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Let the 3 × 3 mixing matrix U_{MNS} have elements U_{ij}. If a given neutrino beam has an initial flavor ν_α the time evolution of the beam is given by:

$$\Psi_\alpha (x,t) = \exp\{ip_\nu x\} \sum_i U_{\alpha i} \exp\{-i\, E_i\, t\} \;\; \nu_i$$

Since in practice neutrinos are always highly relativistic $E_i \approx p_\nu + m_i^2 / 2p_\nu$ and :

$$\Psi_\alpha (x,t) = \exp\{ip_\nu(x-t)\} \sum_i U_{\alpha i} \exp\{-i\, (m_i^2 / 2p_\nu)\, t\} \;\; \nu_i$$

Three – Flavor Mixing - 2

At the point x = t (the central location of the beam at time t) = the baseline L :

$$\Psi_\alpha(t) = \sum_i U_{\alpha i} \exp\{-i\,(m_i^2 / 2E_\nu)\,L\}\ \ \nu_i$$

The transition amplitude :

$$A(\nu_\alpha \to \nu_\beta) = \sum_i U^*_{\alpha i}\ \exp\{-i\, m_i^2\,(L / 2E_\nu)\}\ U_{\beta i}$$

Defining $\Delta m_{ij}^2 = m_i^2 - m_j^2$ the transition probability $|A(\nu_\alpha \to \nu_\beta)|^2 =$

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i}\, U_{\beta i}\, U_{\alpha j}\, U^*_{\beta j})\,\sin^2(\Delta m_{ij}^2\ L / 4E_\nu) + 2\sum_{i>j} \Im(U^*_{\alpha i}\, U_{\beta i}\, U_{\alpha j}\, U^*_{\beta j})\,\sin(\Delta m_{ij}^2\ L / 2E_\nu)$$