First K's

Now B's

Next ν's

CP Violation in the Neutrino Sector

Stephen Parke – FermiLab

- What CP violation?
- Why?
- Summary of Nu Osc Data
- $\nu_\mu \to \nu_e$
- θ_{13} + ...
- Experiments:
- Summary and Conclusions:

Mexican DPF, Colima

Leptonic CP and T Violation in Oscillations

$$
\begin{array}{ccccc}
 & & \text{CP} & & \\
 & \nu_\mu \leftrightarrow \nu_e & \Longleftrightarrow & \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e & \text{Super-Beams} \\
\text{T} & \Updownarrow & & \Updownarrow & \text{T} \\
 & \nu_e \leftrightarrow \nu_\mu & \Longleftrightarrow & \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu & \text{Nu-Factory} \\
 & & \text{CP} & &
\end{array}
$$

CP Violation in Neutrino Oscillations

is related to Leptogenesis

and hence Baryogenesis.

Neutrino Mixing Matrix:

Like the Quark Sector:

The Neutrino Mass Eigenstates, $|\nu_i\rangle$, are a Mixture of Flavor States, $|\nu_\alpha\rangle$:

$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle.$$

(using $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$)

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{13} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

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$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

For Majorana Nu's

$$U \to U \begin{pmatrix} 1 & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}$$

Phases α_2, α_3 are unobservable in oscillation phenomena, $(U_{\alpha i}U^*_{\beta i})$.

Important in neutrinoless double beta decay.

CP Violation and Leptogenesis

- For most Neutrino Mass Models there is a relationship between the Dirac CP phase δ and Majorana CP phases $\alpha_2,\ \alpha_3$.
- At a minimum they are all zero or all non-zero.
- $\alpha_2,\ \alpha_3$ are responsible for Leptogenesis in the early universe by allowing for different decay rates of Neutral Heavy Leptons:

$$N \to l^+\phi^- \text{ and } N \to l^-\phi^+$$

- $B = \frac{1}{2}(B-L) + \frac{1}{2}(B+L)$, however $(B+L)$ violated.
- Hence the Dirac CP violating phase, δ, is a handle on Leptogenesis and hence Baryogenesis.

Fukugita and Yanagida, Phys. Lett. B174, 45 (1986)
Frampton, Glashow and Yanagida – hep-ph/0208157
Endoh, Kaneko, Kang, Morozumi – hep-ph/0209098

.....

Leptonic CP and T Violation in Oscillations

$$\begin{array}{ccccc} & & \text{CP} & & \\ \nu_\mu \leftrightarrow \nu_e & & \Longleftrightarrow & & \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e \\ \text{T} \quad \Updownarrow & & & & \Updownarrow \quad \text{T} \\ \nu_e \leftrightarrow \nu_\mu & & \Longleftrightarrow & & \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu \\ & & \text{CP} & & \end{array}$$

Super-Beams

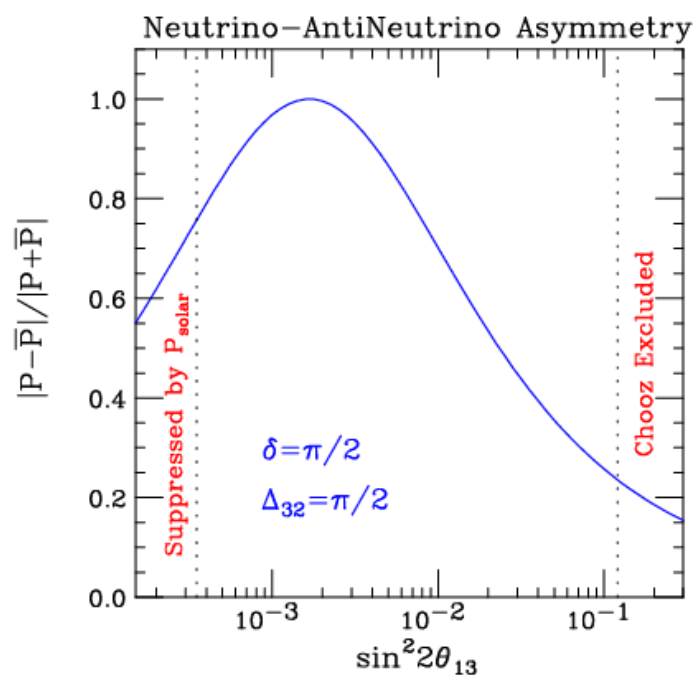
Nu-Factory

$$P_{\nu_\mu \to \nu_e} = \mid a^{atm}_{\mu \to e} \; + \; a^{sol}_{\mu \to e} \mid^2$$

CP Violation comes from the Difference in the Interference of $a^{atm}_{\mu \to e}$ amd $a^{sol}_{\mu \to e}$ for neutrinos verses anti-neutrinos.

CAN BE LARGE!!!.

Important parameters are θ_{13} and δ.



Mixings and Masses Overview:

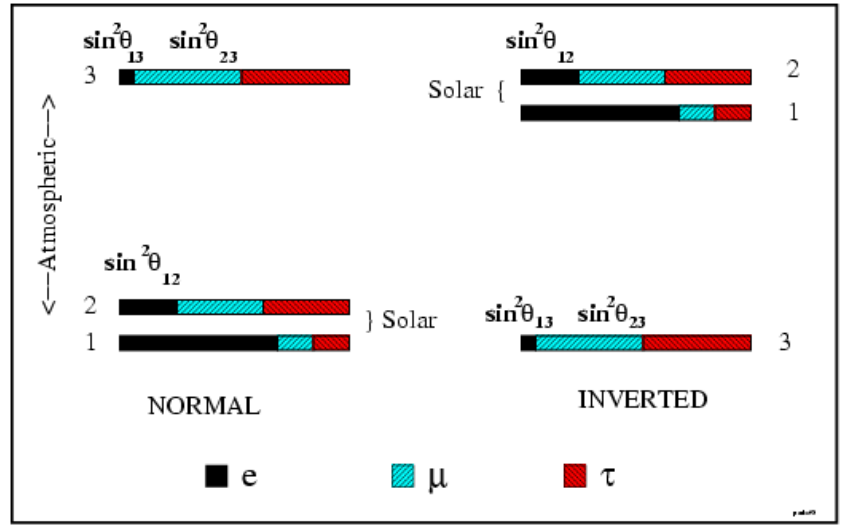
(12)-Sector: SNO, KamLAND, SK

$$\delta m^2_{21} = +7.1 \pm 2.0 \times 10^{-5}\ eV^2$$

$$0.23 < \sin^2\theta_{12} < 0.35$$

$\sin^2\theta_{12} \geq \frac{1}{2}$ excluded at $> 5\ \sigma$!

Sign of δm^2_{21} determined at this C.L.



Due to matter effects
the ^{8}B solar neutrinos exit the sun as ν_2.

Thus SNO's $\frac{CC}{NC} = \sin^2\theta_{12}$

Consistency between SNO and KamLAND will be an important test of Neutrino Oscillations and Matter Effects.

Mixings and Masses Overview:

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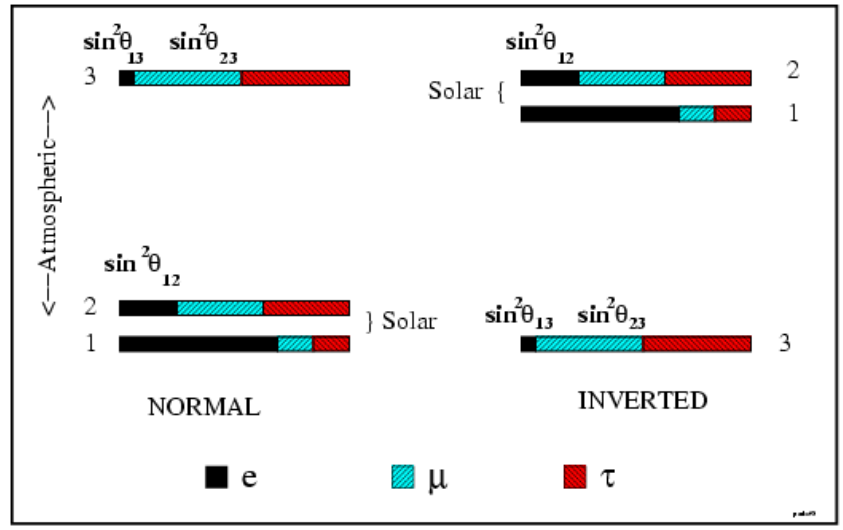

(23)-Sector: SK, K2K

$$|\delta m^2_{32}| = 1.5 - 3.5 \times 10^{-3}\ eV^2$$

$$0.35 < \sin^2\theta_{23} < 0.65$$

(obtained from $\sin^2 2\theta_{23} > 0.91$)

Magnitude of δm^2_{32} and $\sin^2\theta_{23}$ both poorly known!

Sign of δm^2_{32} Unknown !!!

$\Rightarrow$ MINOS $|\delta m^2_{32}|$ ♠

also tests ν-Oscillations.

Mixings and Masses Overview:

(12) Parameters: SNO, KamLAND, SK

$$\delta m^2_{21} = +7.1 \pm 2.0 \times 10^{-5}\ eV^2$$

$$0.23 < \sin^2\theta_{12} < 0.35$$

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sign of δm^2_{21} determined at this C.L.

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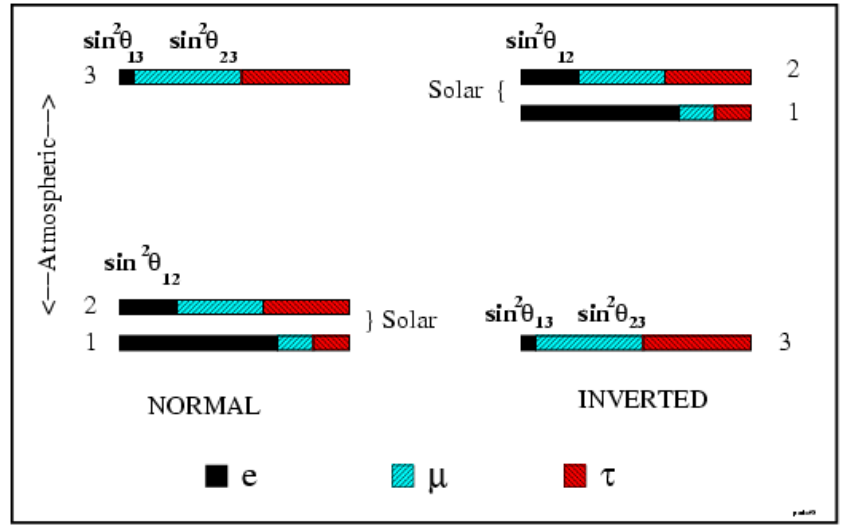

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$$0.35 < \sin^2\theta_{23} < 0.65$$

(obtained from $\sin^2 2\theta_{23} > 0.91$)

Magnitude of δm^2_{32} and $\sin^2\theta_{23}$ both poorly known! ♠ MINOS $|\delta m^2_{32}|$ ♠

Sign of δm^2_{32} Unknown !!!

(13) Parameters: Chooz, SK, K2K

$$\sin^2\theta_{13} < 0.03 - 0.05$$

limit $|\delta m^2_{32}|$ dependent

$$0 \leq \delta_{CP} < 2\pi$$

Unknown!

Oscillation Primer: 2 flavors

amplitude for $\nu_\mu \to \nu_e = \; U^*_{\mu 1}\, U_{e1} e^{-iE_1 t} \; + \; U^*_{\mu 2}\, U_{e2} e^{-iE_2 t}$

$$E_j = \sqrt{p^2 + m_j^2} \approx p + \frac{m_j^2}{2p} + \cdots \qquad\qquad E_j t \approx pt \; + \; \frac{m_j^2 L}{2E}$$

For 2 components:

$$U_{\alpha j} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$P_{\mu\to e} = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4E}$$

Oscillation Length, $L = \frac{4E}{\delta m^2}\,\pi$, where $\delta m^2 = m_j^2 - m_i^2$.

What happens as $\hbar \to 0$???

Does Osc. Length go to ZERO or INFINITY ???

Oscillation Primer: 2 flavors

amplitude for $\nu_\mu \to \nu_e = \sum_j U^*_{\mu j}\, U_{ej} e^{-iE_j t/\hbar}$

$$E_j = \sqrt{p^2 + m_j^2} \approx p + \frac{m_j^2}{2p} + \cdots \qquad \frac{E_j t}{\hbar} \approx \frac{pt}{\hbar} + \frac{m_j^2 L}{2\hbar E}$$

For 2 components:

$$P_{\mu\to e} = \sin^2 2\theta \sin^2 \frac{\delta m^2 L}{4\hbar E} \qquad \left(= \sin^2 2\theta \sin^2 1.27 \frac{\delta m^2 L}{E}\right)$$

Oscillation Length, $L = \frac{4\hbar E}{\delta m^2}\,\pi$, where $\delta m^2 = m_j^2 - m_i^2$.

What happens as $\hbar \to 0$???

Osc. Length goes to ZERO !!!

$L \to 0$ same as if $\delta m^2 \to LARGE$!!! (– quarks –)

Nu Oscillations are a Macroscopic Quantum Phenomena.

Oscillation Primer: 2 flavors

amplitude for $\nu_\mu \to \nu_e = \sum_j U^*_{\mu j}\, U_{ej} e^{-iE_j t/\hbar}$

$$E_j = \sqrt{p^2c^2 + m_j^2c^4} \approx pc + \frac{m_j^2c^4}{2pc} \qquad \frac{E_j t}{\hbar} \approx \frac{pct}{\hbar} + \frac{m_j^2c^4L}{2\hbar cE}$$

For 2 components:

$$P_{\mu\to e} = \sin^2 2\theta \sin^2 \frac{\delta m^2 c^4 L}{4\hbar cE} \qquad \left(= \sin^2 2\theta \sin^2 1.27\frac{\delta m^2 L}{E}\right)$$

Oscillation Length, $L = \frac{4\hbar cE}{\delta m^2 c^4}\,\pi$, where $\delta m^2 = m_j^2 - m_i^2$.

Now

$$\hbar c = 197\ MeV\,fm = 0.197\ (ev^2/GeV)km$$

$$\frac{1}{4\times 0.197} = 1.2669\cdots\ !!!$$

3 flavor – $\nu_\mu \to \nu_e$

$$P_{\mu\to e} = \left| \sum_j U^*_{\mu j}\, U_{ej} e^{-i m_j^2 L/2E} \right|^2$$

Elimate $U^*_{\mu 1} U_{e1}$
using unitarity of U.
Use $\Delta_{ij} = \delta m^2_{ij} L/4E = 1.27 \delta m^2_{ij} L/E$

$$P_{\mu\to e} = \left| 2U^*_{\mu 3} U_{e3} \sin\Delta_{31} e^{-i\Delta_{32}} + 2U^*_{\mu 2} U_{e2} \sin\Delta_{21} \right|^2$$

Square of Atmospheric+Solar amplitude:

$U^*_{\mu 3} U_{e3} = s_{23} s_{13} c_{13} e^{\mp i\delta}$ for ν and $\bar{\nu}$:

Approx. $U^*_{\mu 2} U_{e2} \approx c_{23} c_{13} s_{12} c_{12} + \mathcal{O}(s_{13})$:

$$P_{\mu\to e} \approx \left| 2 s_{23} s_{13} c_{13} \sin\Delta_{31} e^{-i(\Delta_{32} \pm \delta)} + 2 c_{23} c_{13} s_{12} c_{12} \sin\Delta_{21} \right|^2$$

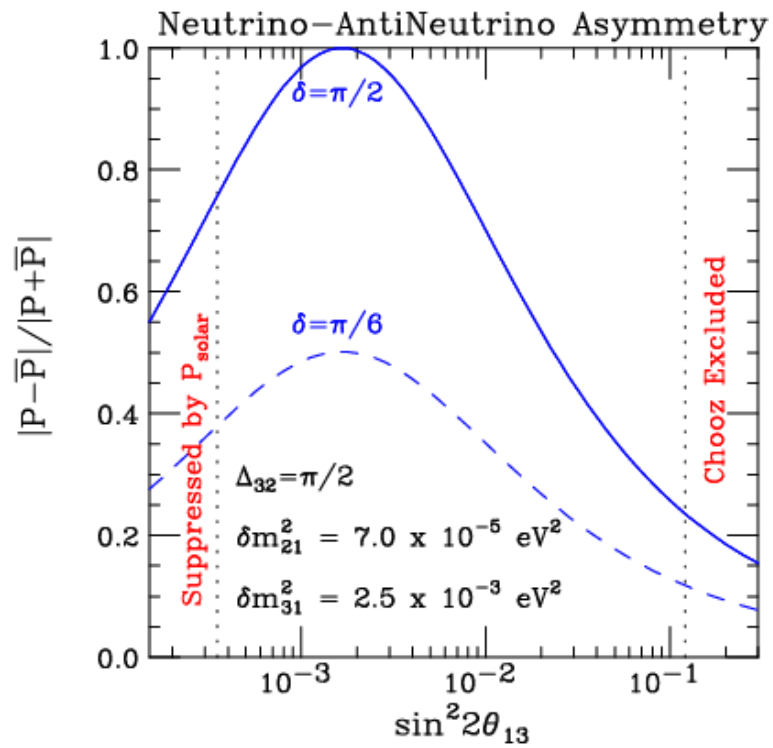
Interference term different for ν and $\bar{\nu}$: CP violation !!!

$$P_{\mu\to e} \approx \left| \, 2s_{23}s_{13}c_{13}\sin\Delta_{31}e^{-i(\Delta_{32}\pm\delta)} + 2c_{23}c_{13}s_{12}c_{12}\sin\Delta_{21} \, \right|^2$$

At the first atmospheric oscillation maximum, $\Delta_{32} = \frac{\pi}{2}$, the Neutrino-AntiNeutrino Asymmetry is maximum when

$$|a^{atm}| = |a^{sol}|$$

$$\sin^2 2\theta_{13} \approx \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}}\left[\frac{\pi}{2}\,\frac{\delta m^2_{21}}{\delta m^2_{31}}\right]^2$$



At the second oscillation maximum, $\Delta_{32} = \frac{3\pi}{2}$, the peak in the Asymmetry occurs when $\sin^2 2\theta_{13}$ is 9 times larger. BNL $\rightarrow$???.

Expanding and using $J_r = J/\sin\delta = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2$:

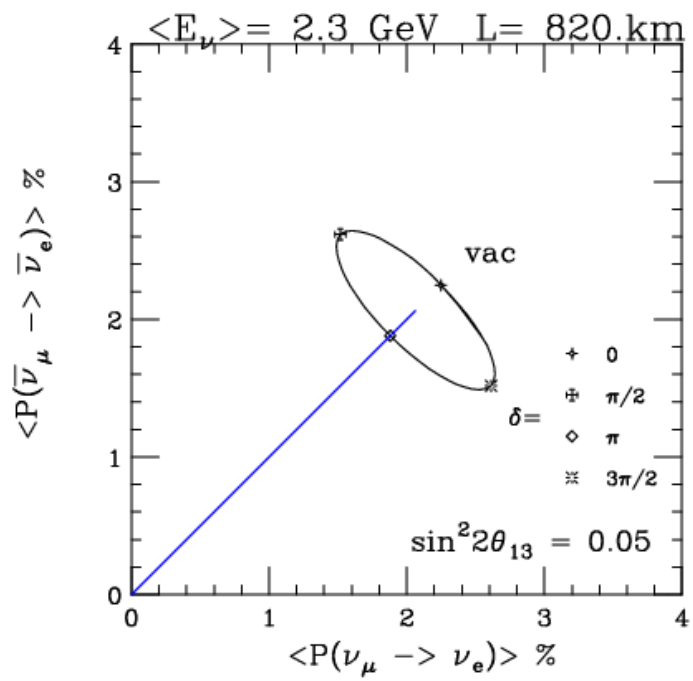
$$P_{\mu\to e} \approx 4s_{23}^2 s_{13}^2 c_{13}^2 \sin^2\Delta_{31} + 4c_{23}^2 c_{13}^2 s_{12}^2 c_{12}^2 \sin^2\Delta_{21}$$

$$+8J_r \sin\Delta_{21}\sin\Delta_{31}\cos\Delta_{32}\cos\delta$$

$$\mp 8J_r \sin\Delta_{21}\sin\Delta_{31}\sin\Delta_{32}\sin\delta$$

The last term is the CP violating part of the interference.

Bi-Probability Plots:
Minakata and Nunokawa
hep-ph/0108085



Matter Effects:

$$\sin\Delta_{31} \Rightarrow \left(\frac{\Delta_{31}}{\Delta_{31}\mp aL}\right)\sin(\Delta_{31}\mp aL)$$

$$\sin\Delta_{21} \Rightarrow \left(\frac{\Delta_{21}}{\Delta_{21}\mp aL}\right)\sin(\Delta_{21}\mp aL)$$

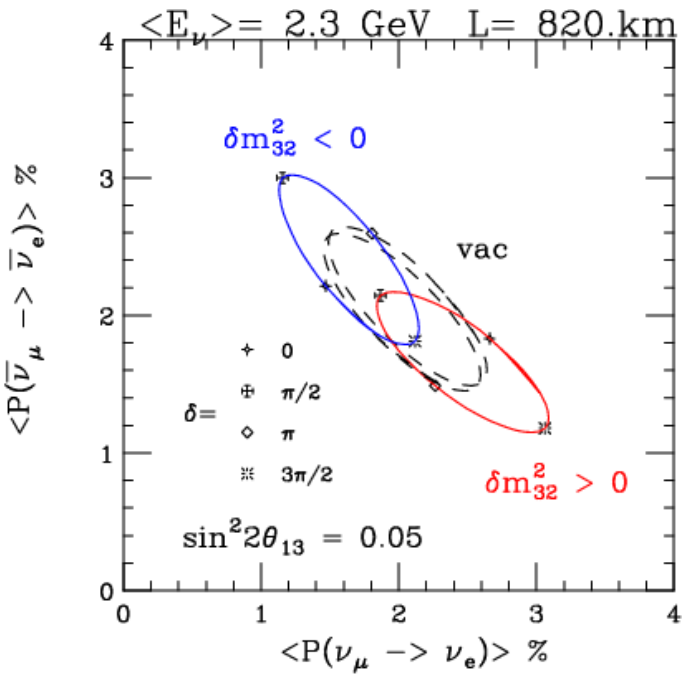
$$\sin\Delta_{32} \Rightarrow \sin\Delta_{32}$$

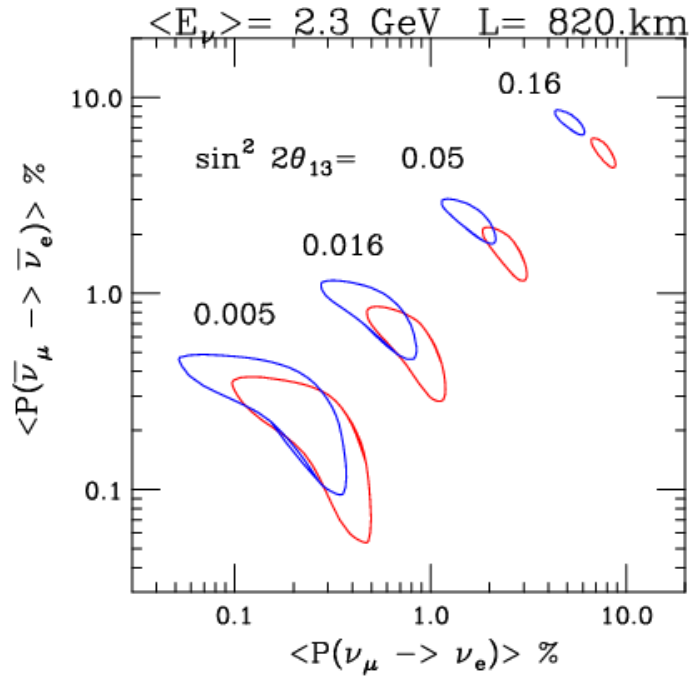
$\{\delta m^2 \sin 2\theta\}$ is invariant

and

$$a = G_F N_e/\sqrt{2}$$
$$= (4000\ km)^{-1}$$

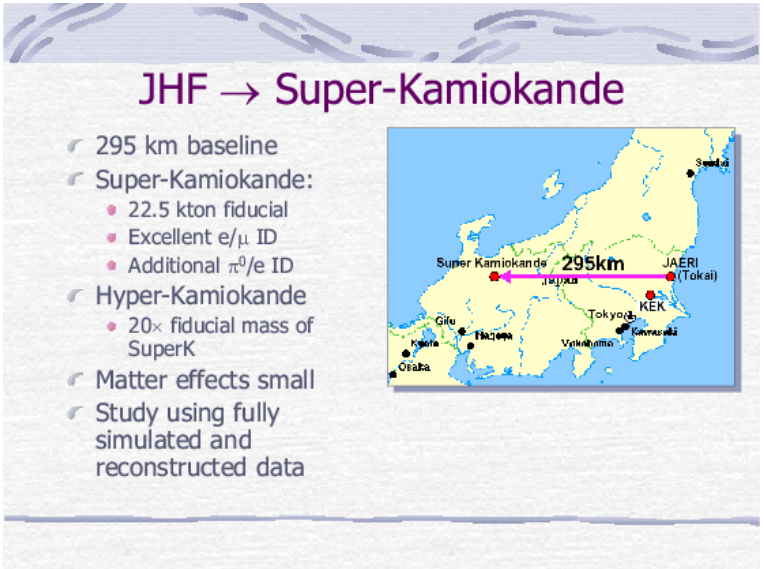
Matter effects are IMPORTANT when $\sin(\Delta \mp aL) \neq (\Delta \mp aL)$.





Matter Effects important for NuMI-OFF-Axis (800 km), less so for JParc (295 km).

Proposed Experiments:

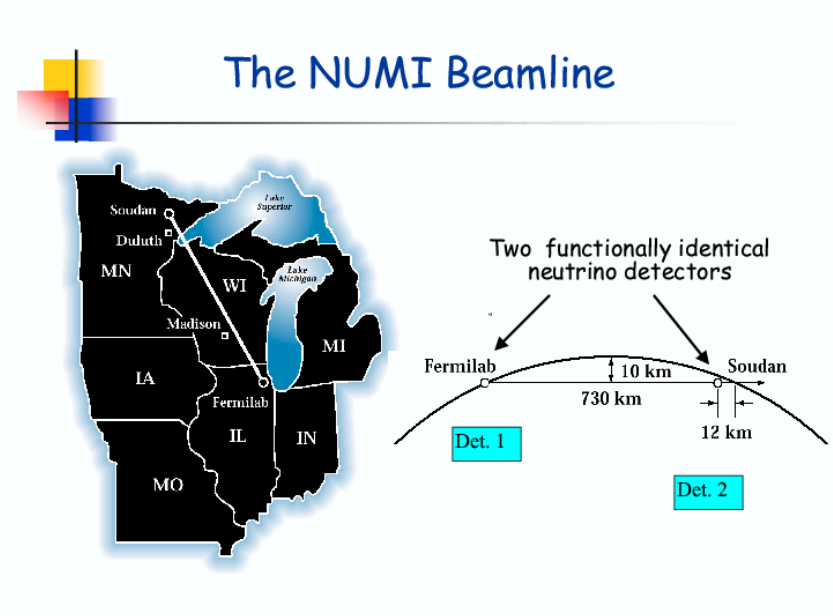


Narrow Beams - Counting Expts:

L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\}$$



L=700 - 1000 km and

Energy near 2 GeV

$$E_{vom} = 1.8\ GeV\ \left\{ \frac{L}{820\ km} \right\} \times \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\}$$

Off-Axis Neutrino Beams:

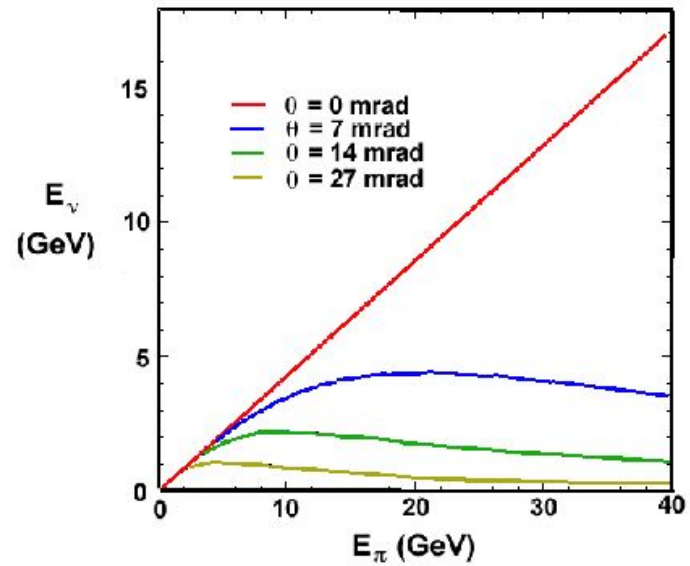
$$E_\nu = \frac{0.43 E_\pi}{(1+\theta^2\gamma_\pi^2)}$$

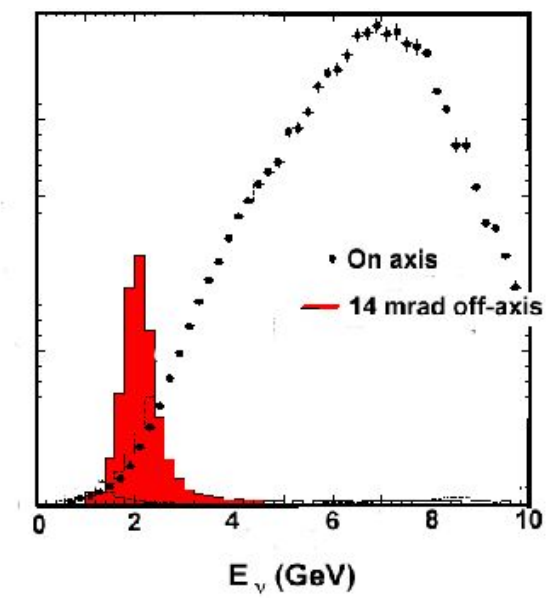
Off-Axis the beams are Narrow!
approx. gaussian with spread
20% $< E_\nu >$

GREAT !!!

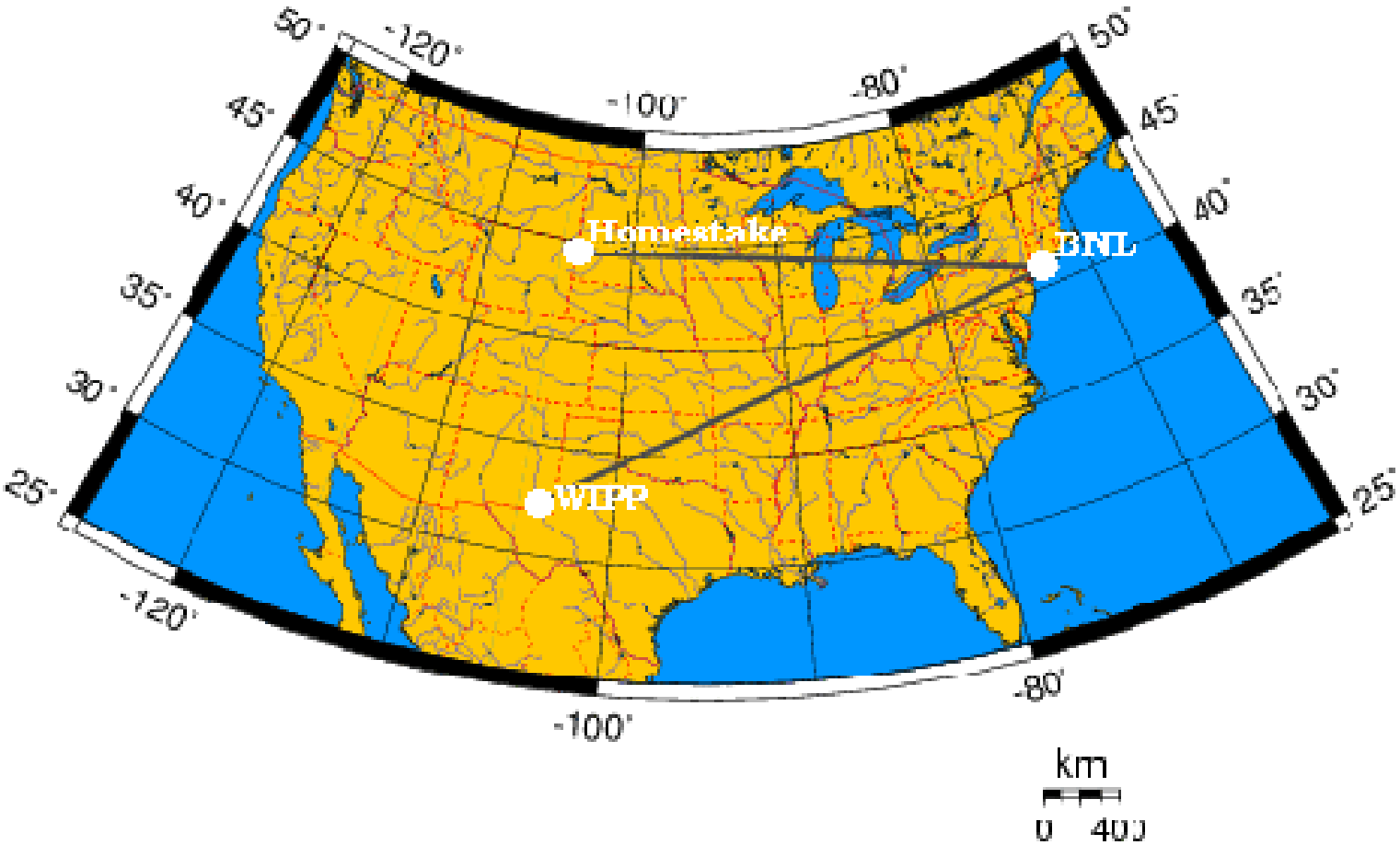
as the primary bckgrd to ν_e detection is π^0 coming from higher energy NC events. (ν_e contamination in beam is small 0.5% and apprx known.)

BNL-proposal '94





Broad Beams - Spectral Shape Experiments:



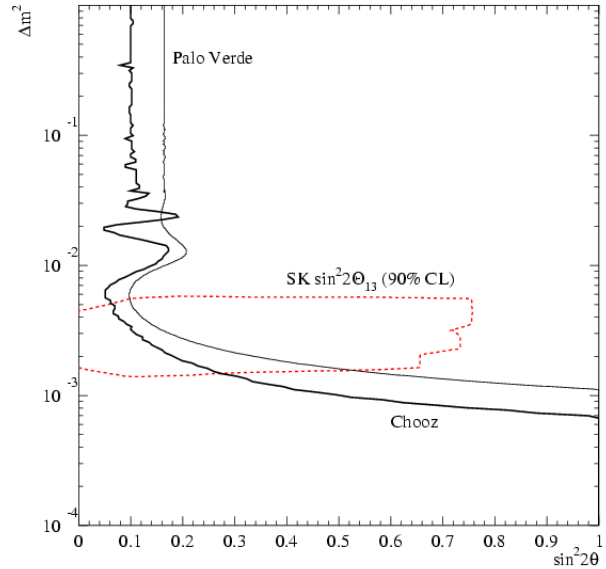
See A. Mann talk:

Questions:

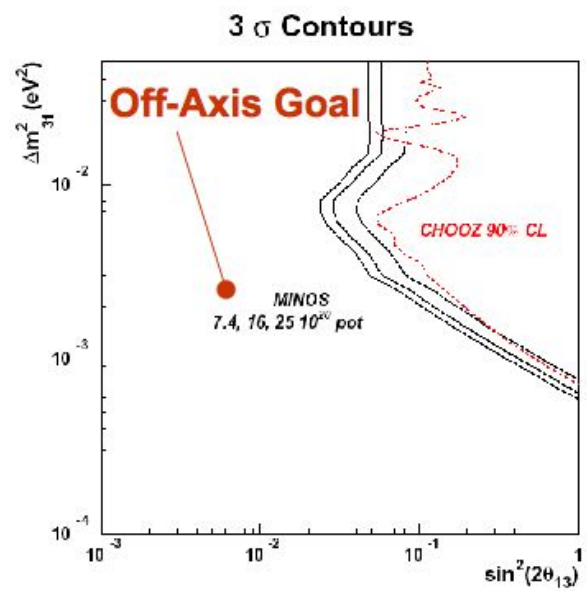
Backgrounds ? and Optimization of E and L?

Limits on θ_{13}

Chooz and SuperKamiokande:
Chooz was a $\bar{\nu}_e$ dissappearance experiment using Reactors. Energies few MeV.
K2K.



MINOS:
Has some sensitivity to ν_e above backgrounds.
Primary goal is to measure $|\delta m^2_{32}|$ to 10% —- VERY IMPORTANT.

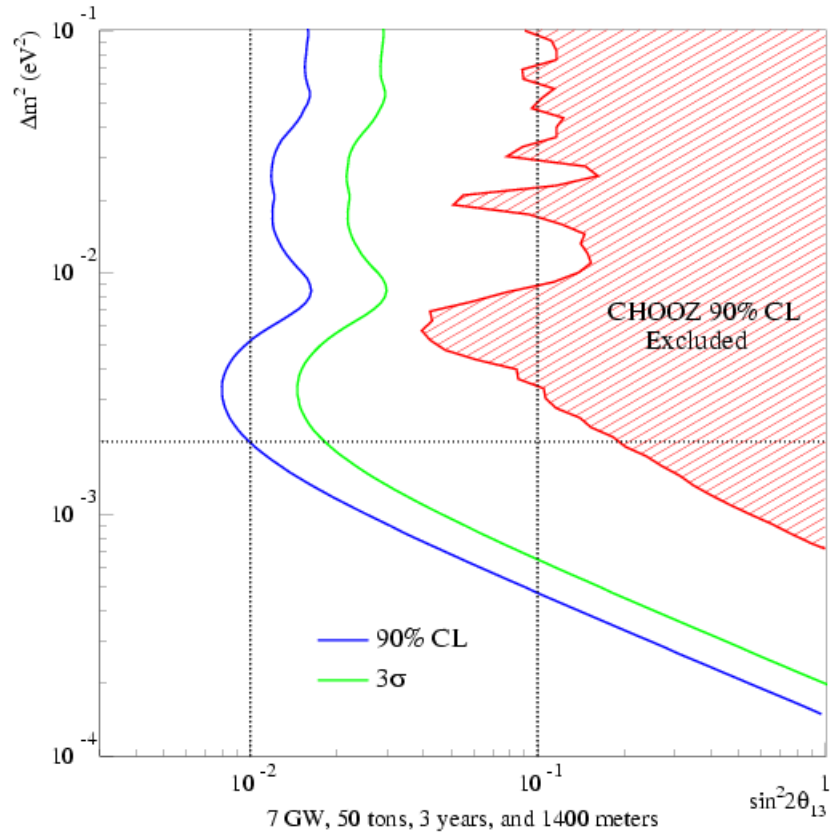


New Reactor Experiments:

"Super-Chooz:"

interest in Japan, Europe, Russia and USA (CA & IL).

Figure from J. Link, Columbia U. Using two detectors with the far detector being able to be moved to along side the near detector for relative calibration.



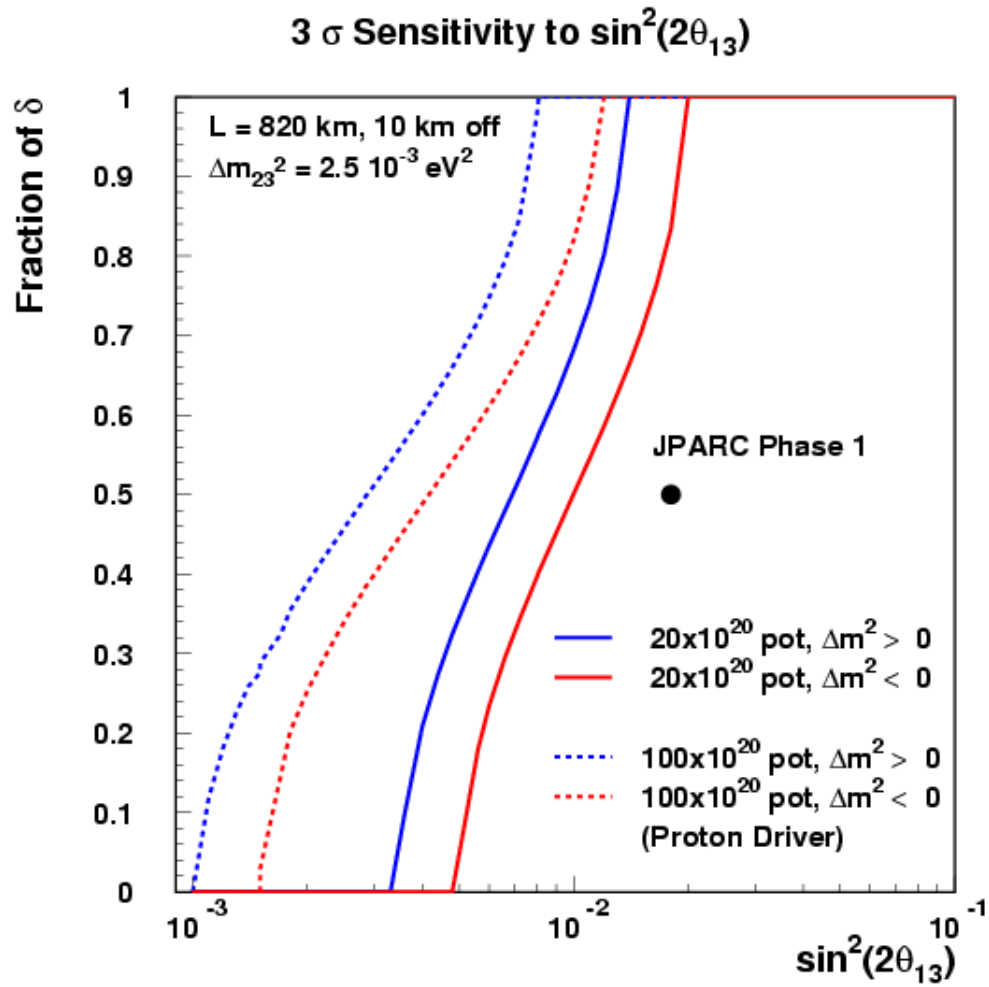
Systematics Limited experiment.

Clean measurement of $\sin^2 2\theta_{13}$ down to ~0.01.

Could be a "quick" and "cheap" experiment, but ...

θ_{13} Off-Axis: NuMI & JParc

$P(\nu_\mu \to \nu_e)$ depends on θ_{13}, sign of δm^2_{32}, CP phase δ and θ_{23}.

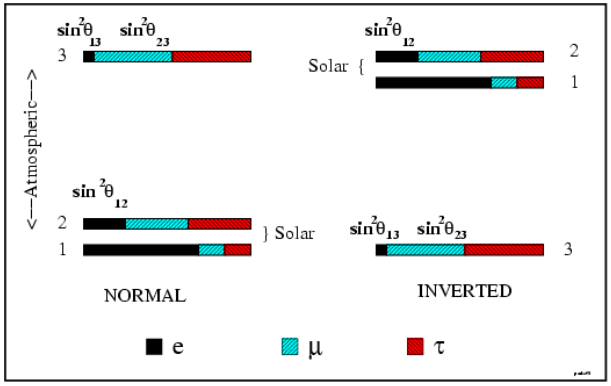


Assumes $\sin^2 2\theta_{23} = 1$ i.e. $\theta_{23} = \pi/4$.

LBL has a Rich Physics Program:

- **sign δm^2_{32}:**

  Normal or Inverted Hierarchies:



- **θ_{13} and δ:**

  Typically more than one solution:
  Factorization at Vac. Osc. Max.

- **$\theta_{23} \leftrightarrow (\frac{\pi}{2} - \theta_{23})$:**

  ν_μ disappearance measures $\sin^2 2\theta_{23} \equiv 1 - \epsilon^2$ then $\sin^2\theta_{23} = \frac{(1\mp\epsilon)}{2}$ and $\cos^2\theta_{23} = \frac{(1\pm\epsilon)}{2}$

  $\sin^2 2\theta_{23} = 0.96 \Rightarrow \sin^2\theta_{23} = 0.4 \; or \; 0.6$

BNL proposal will fit spectrum to all parameters:

Degeneracy Tasting:

sign δm^2_{32}

At Vac. Osc. Max., $\Delta_{32} = \frac{\pi}{2}$

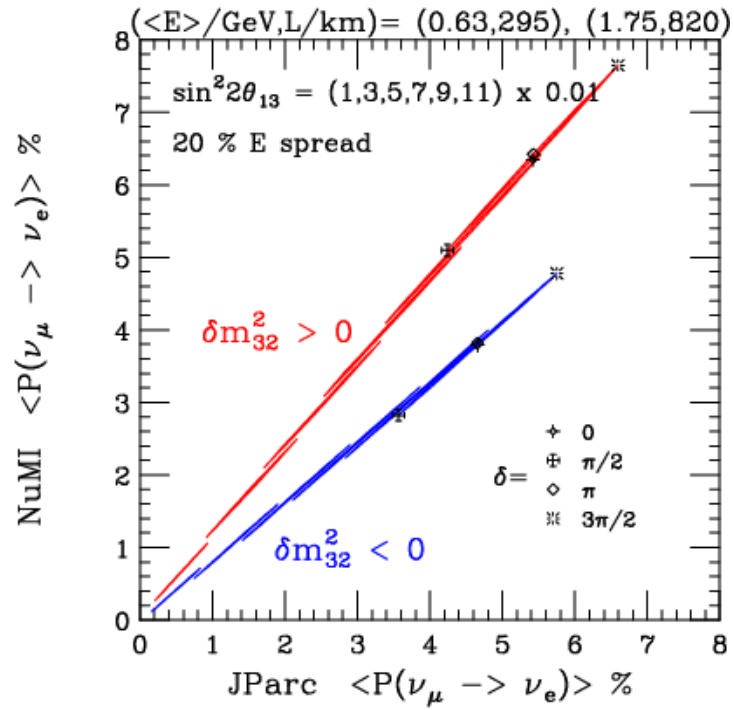
$$P_{mat} = \left(1 \pm 2\frac{E}{E_R}\right) P_{vac}$$

where $E_R \simeq 12$ GeV.

Therefore, if NuMI and JParc both run Neutrinos at Vac. Osc. Max.

$$P_N = \left(1 \pm 2\frac{(E^N - E^J)}{E_R}\right) P_J$$

i.e. $P_N \approx (1.2 \; or \; 0.8) P_J$



Separation degraded for $E^N > E_{vom}$.

Minakata, Nunokawa and SP – hep-ph/0301210

sign δm^2_{32} conti.

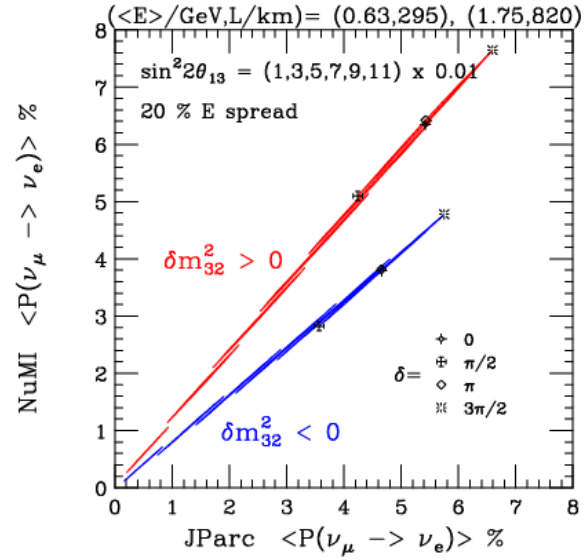
For NuMI above Vac. Oscillation Maximum, $E = E_{vom} + \Delta E$

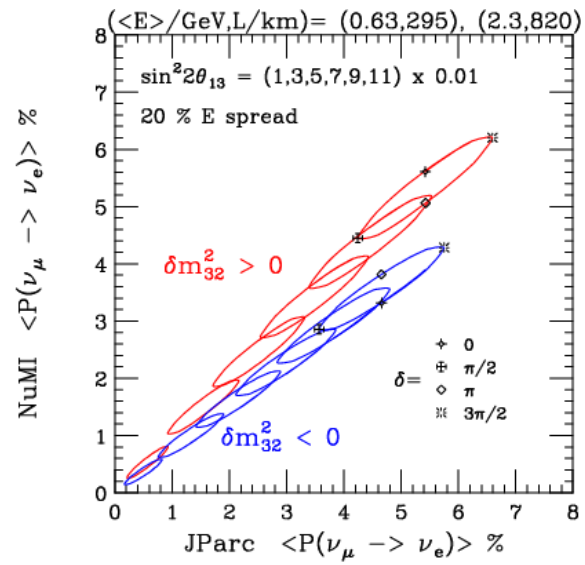
$$P_{mat} = \left(1 \pm 2\frac{E_{vom}}{E_R} \mp \frac{(\pi^2-4)}{2}\ \frac{\Delta E}{E_R}\right) P_{vac}$$

where $E_R \simeq 12$ GeV.

This extra factor $\sim 3\ \frac{\Delta E}{E_R}$ degrades the separation of the center of the ellipses.

Also the ellipses become FAT, compare bottom to top figures.

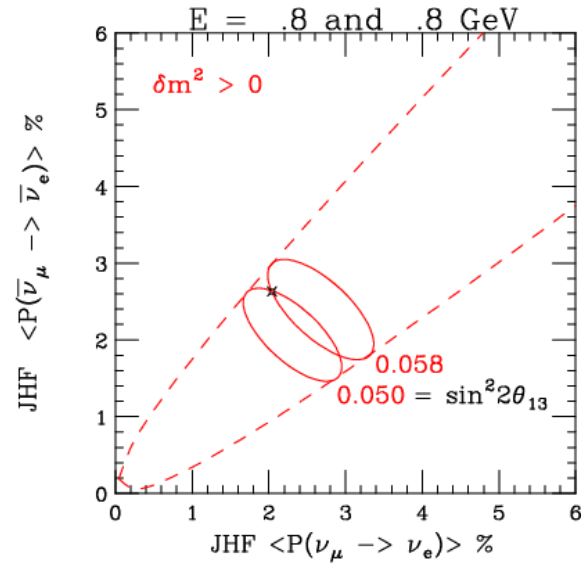




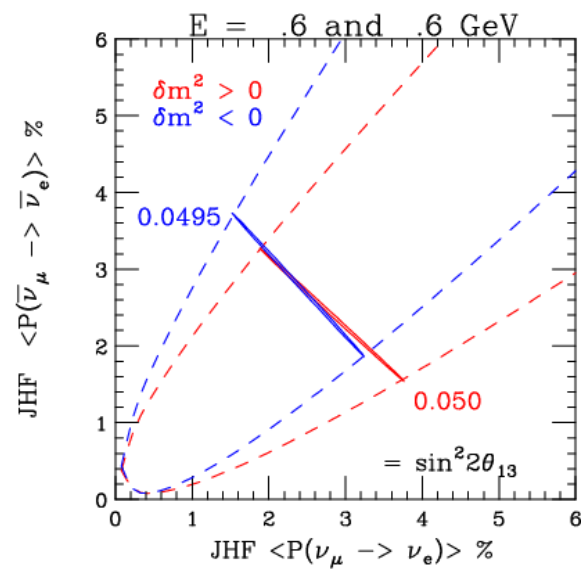
θ_{13} and δ

For a given Neutrino and Anti-Nu Measurement:

There are two solutions for θ_{13} and δ.



At Vac. Osc. Max. these factorize into a single measurement of θ_{13} but two values of δ. [δ and $\pi - \delta$]



Kajita, Minakata and Nunokawa – hep-ph/0112345

$\theta_{23} \leftrightarrow (\frac{\pi}{2} - \theta_{23})$

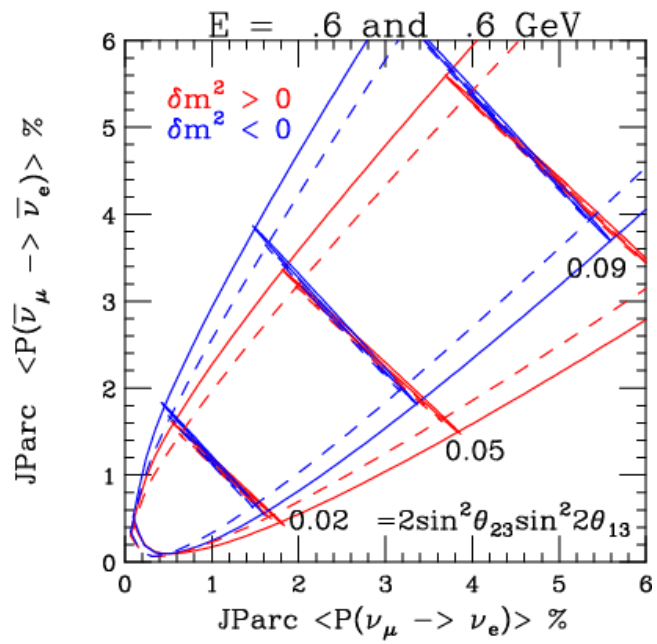
$\theta_{23} = \frac{\pi}{4}$ is $\nu_\mu \leftrightarrow \nu_\tau$ sym. pt.

$\sin^2 2\theta_{23}$ from dissapp. exp.
however even if $\sin^2 2\theta_{23} = 0.96$:

$\sin^2 \theta_{23} = 0.40$ *or* 0.6

LBL at Vac. Osc. Max. with ν and $\bar{\nu}$ measurements
$\sin\theta_{23}\sin\theta_{13}$ & $\cos\theta_{23}\sin\delta$.

Combined with a precision reactor measurement of $\sin^2\theta_{13}$ can determine $\sin^2\theta_{23}$.



However determining $\cos\delta$ requires running above Vac. Osc. Max. This splits δ from $\pi - \delta$.

Summary and Conclusion

- θ_{13}:
  Can be measured by Reactor Exp., Long Baseline Exp. and eventually Nu Factories depending on its value.
- sign of δm^2_{23} or Normal/Inverted Hierarchy:
  Two Long Baseline Exp,. one with significant matter effects, both running neutrinos at Vac. Osc. Max.
- $\sin\delta$ and CP violation: Leptogenesis
  Long Baseline Exp. running neutrinos and anti-neutrinos. Asymmetry gets larger as θ_{13} gets smaller until solar amplitude dominates. For smaller values we need to enhance the atmospheric amplitude by significant matter effects - Nu Factory.

Summary and Conclusion (conti.)

- θ_{23}:
  Breaking the $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ degeneracy.
  Combination of Reactor and Long Baseline Exps.

- $\cos\delta$ (sign?)
  LBL experiment running above Vac. Osc. Max.

If the size of θ_{13} is in range of the LBL experiments, $\sin^2 2\theta_{13} \geq 0.005$, then three carefully choosen counting experiments with sufficient accuracy can determine

$$\theta_{13}, \quad \delta_{CP}, \quad \text{sign of } \delta m^2_{23}, \quad \theta_{23}.$$

A Fabulous Opportunity in the Neutrino Osc. Sector!!!

Leaving the Questions of Majorana v Dirac?, Steriles? and Absolute Mass Scale, M_{lite}?