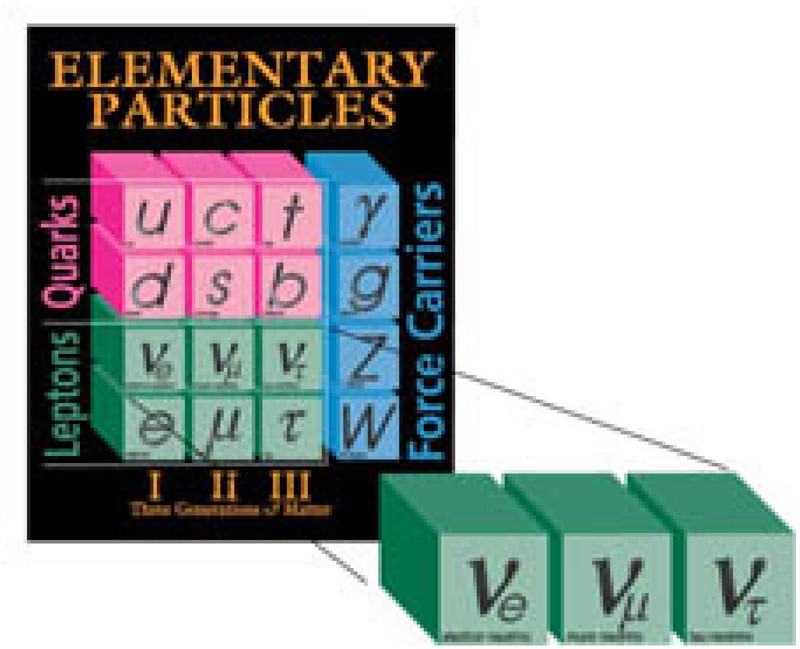
First K's

Now B's

Next ν's

Neutrino Mixing Parameters from Long Baseline Expts.

Stephen Parke – FermiLab



- CP violation
- Summary of Nu Osc Data
- $\nu_\mu \rightarrow \nu_e$
- θ_{13}, $\sin\delta$ and sign δm^2
- Experiments:
- Summary and Conclusions:

Leptonic CP and T Violation in Oscillations

		CP		
	$\nu_\mu \leftrightarrow \nu_e$	$\Longleftrightarrow$	$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$	Super-Beams
T	$\Updownarrow$		$\Updownarrow$	T
	$\nu_e \leftrightarrow \nu_\mu$	$\Longleftrightarrow$	$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$	Nu-Factory
		CP		

CP Violation here

? $\Rightarrow$? Leptogenesis

? $\Rightarrow$? 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 $c_{ij} = \cos\theta_{ij}$)

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

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

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

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.

Leptonic CP and T Violation in Oscillations

CP

$\nu_\mu \leftrightarrow \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ Super-Beams

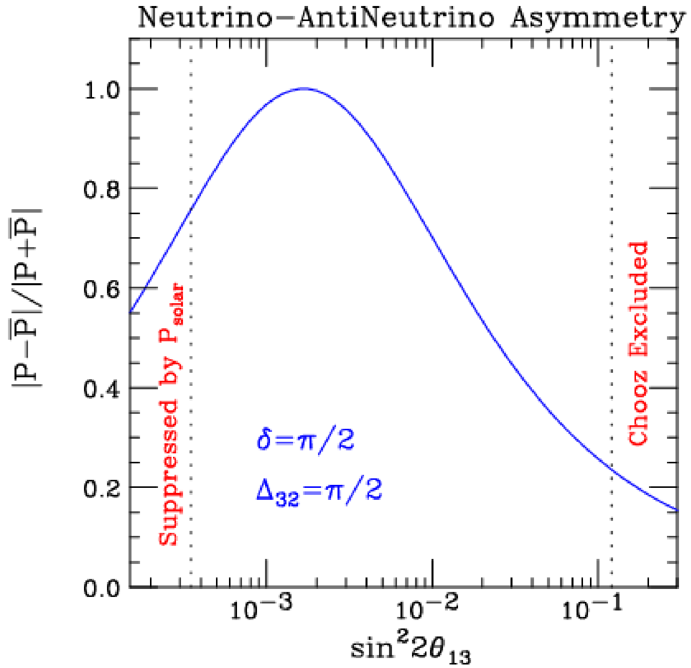
T $\Updownarrow$ $\Updownarrow$ T

$\nu_e \leftrightarrow \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ Nu-Factory

CP

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

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.

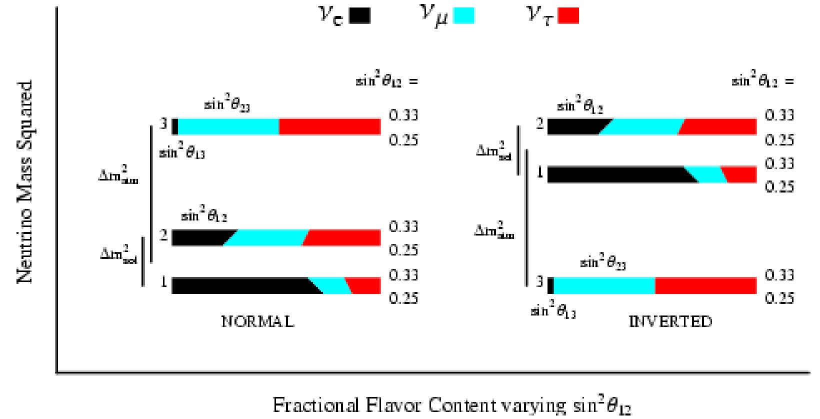


CAN BE LARGE!!!.

Important parameters are θ_{13} and δ.

Mixings and Masses Overview:

O. Mena and SP hep-ph/0312312



(12)-Sector: SNO, KamLAND, SK

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

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

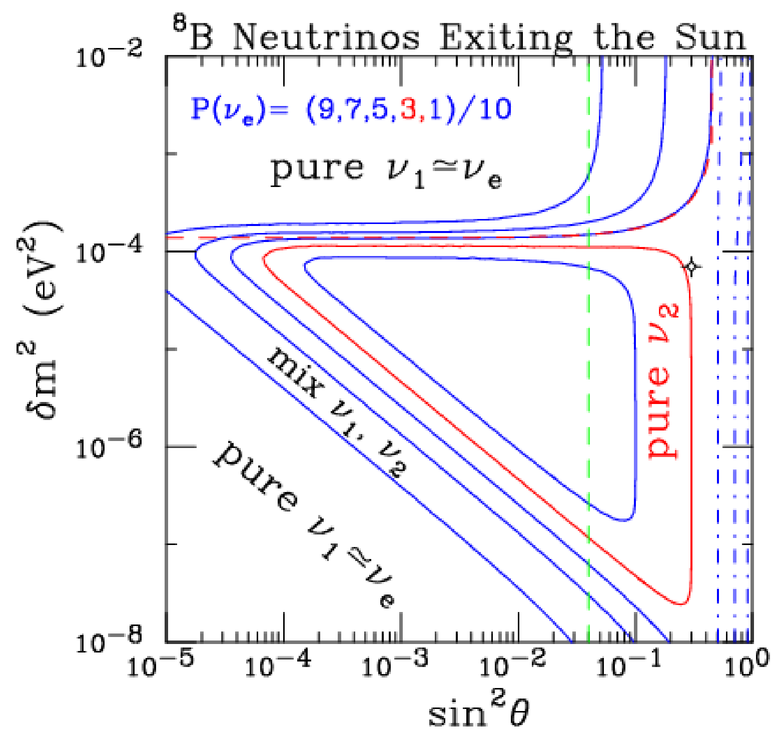
$\sin^2\theta_{12} \geq \frac{1}{2}$ excluded at $> 5\ \sigma$!

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 $\quad \frac{CC}{NC} = \sin^2\theta_{12}$

Consistency between SNO (0.3) and KamLAND (0.6) will be an important test of Neutrino Oscillations and Matter Effects.



$\nu_1 = c_\theta \nu_e + s_\theta \nu_x \qquad \nu_2 = -s_\theta \nu_e + c_\theta \nu_x$

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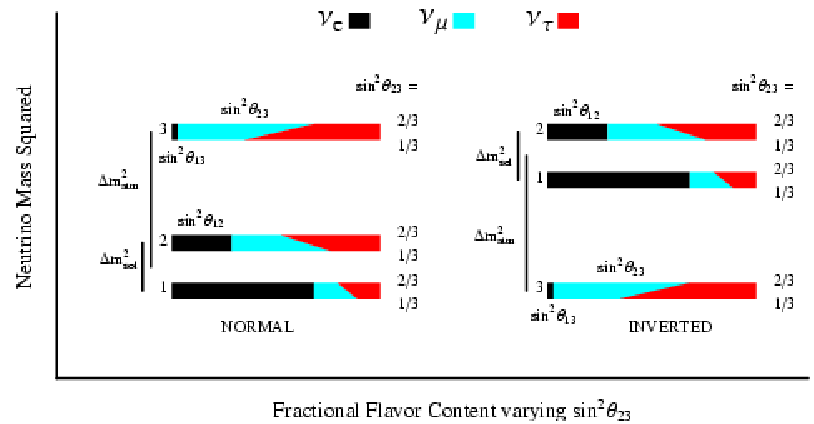


(23)-Sector: SK, K2K

$$|\delta m^2_{32}| = 1.9 - 3.0 \times 10^{-3}\ eV^2$$

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

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

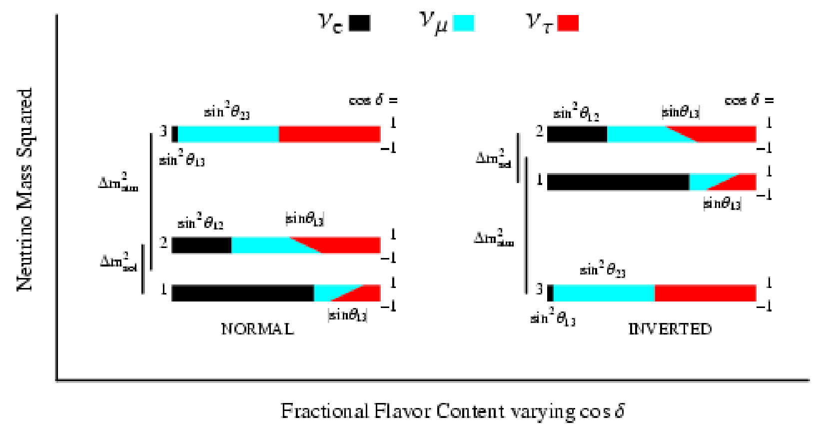
Magnitude of δm^2_{32} and $\sin^2\theta_{23}$ both poorly known!

Sign of δm^2_{32} Unknown !!!

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

also tests ν-Oscillations.

Mixings and Masses Overview:



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(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!

Figures are insensitive to sign of $\sin\delta_{CP}$

(23) Parameters: SK, K2K

$$|\delta m^2_{32}| = 1.9 - 3.0 \times 10^{-3}\ eV^2$$

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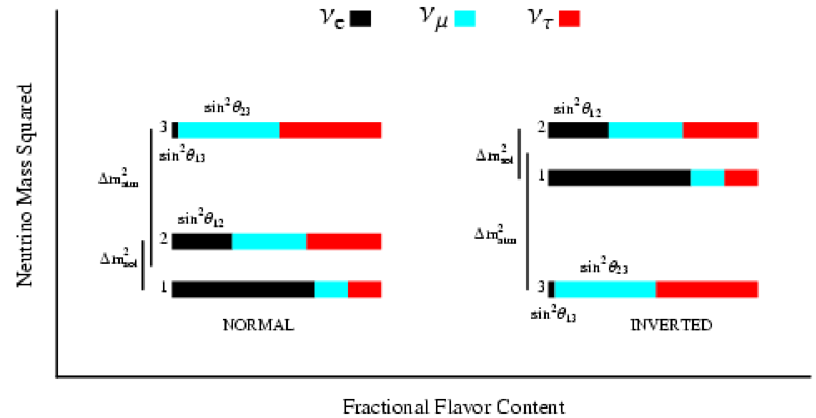


For $\mu \Leftrightarrow \tau$ symmetry

$\theta_{23} = \pi/4$ and

$\delta = \pi/2$ or $3\pi/2$

unless $\theta_{13} \equiv 0$

(13) Parameters: Chooz, SK, K2K

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

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

3 flavor – $\nu_\mu \to \nu_e$

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

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

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

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

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

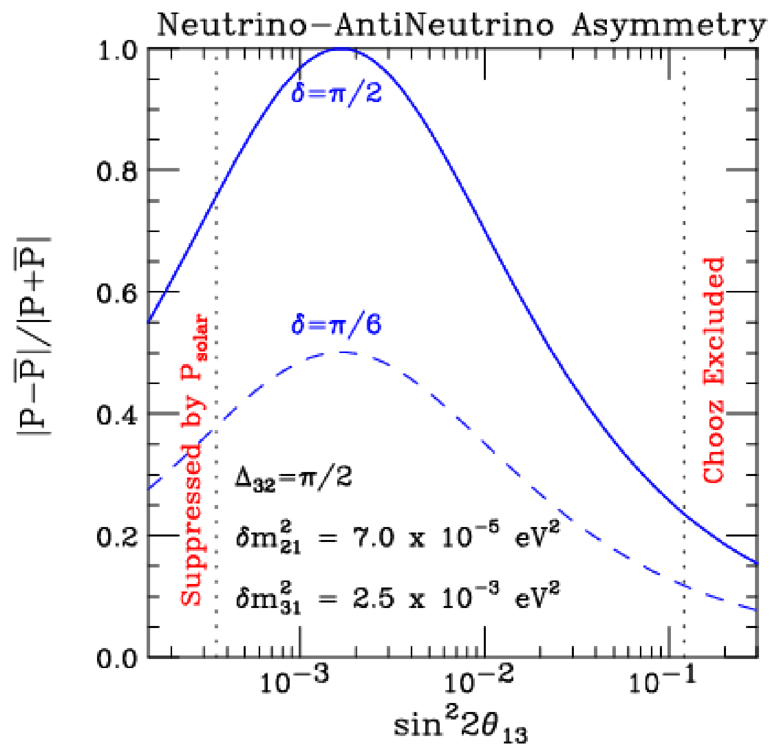
$$P_{\mu\to e} \approx \left| 2 s_{23} s_{13} c_{13} \sin\Delta_{31} e^{-i(\Delta_{32}\pm\delta)} + 2 c_{23} c_{13} s_{12} c_{12} \sin\Delta_{21} \right|^2$$

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

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

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

$$\approx 0.002$$



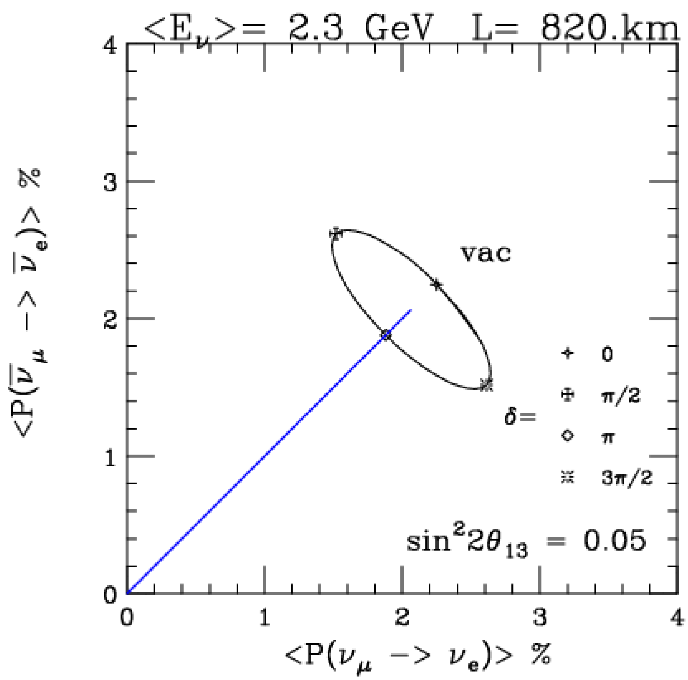
At the second oscillation maximum, $\Delta_{32} = \frac{3\pi}{2}$, the peak in the Asymmetry occurs when $\sin^2 2\theta_{13}$ is 9 times larger. BNL $\to$???.

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:

Rule:

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

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

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

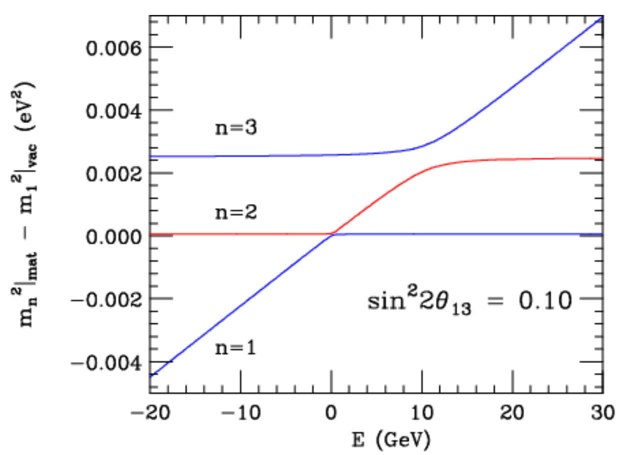
Comes from the invariant (2 component)

$$\{\delta m^2 \sin 2\theta\}_{mttr} = \{\delta m^2 \sin 2\theta\}_{vac}$$

and

$$\{\delta m^2\}_{mttr} \approx \{\delta m^2\}_{vac} \mp 4aE$$

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



Works because the resonances are clearly separated.

IMPORTANT when

$$\left(\frac{\Delta}{\Delta \mp aL}\right) \sin(\Delta \mp aL) \neq \sin\Delta \text{ for } \Delta_{31}.$$

For $\Delta_{21} \ll aL < 1$ only important for very LBL.

Thus

$$P_{\mu\to e} \approx 4(s_{23}s_{13})^2 \left(\frac{\Delta_{31}}{\Delta_{31} \mp aL}\right)^2 \sin^2(\Delta_{31} \mp aL)$$

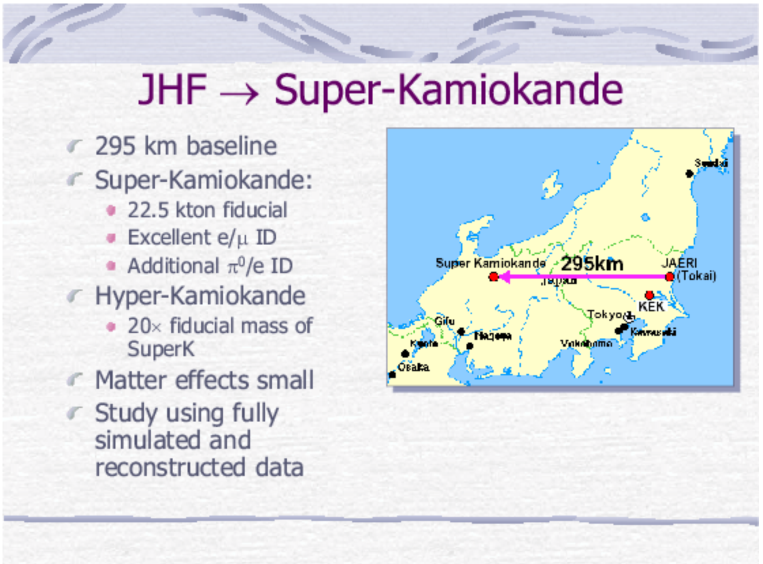
$$+8(s_{23}s_{13}) \left(\frac{\Delta_{31}}{\Delta_{31} \mp aL}\right) \sin(\Delta_{31} \mp aL) c_{23}s_{12}c_{12}\Delta_{21}$$

$$\times\{\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta\}$$

$$+\ 4c_{23}^2 s_{12}^2 c_{12}^2 \Delta_{21}^2$$

The $\sin\delta$ term is the CP violating part of the interference.

Proposed Experiments:

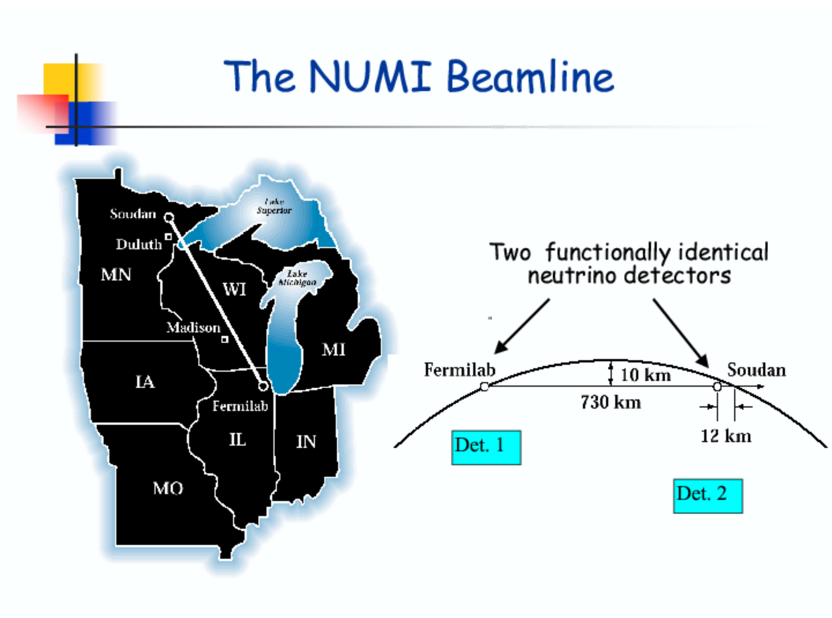


Narrow Beams - Counting Expts:

L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m_{32}^2}{2.5\times 10^{-3}\ eV^2} \right\}$$



L=700 - 1000 km and

Energy near 2 GeV

$$E_{vom} = 1.8\ GeV \left\{ \frac{\delta m_{32}^2}{2.5\times 10^{-3}\ eV^2} \right\} \times \left\{ \frac{L}{820\ km} \right\}$$

Off-Axis Neutrino Beams:

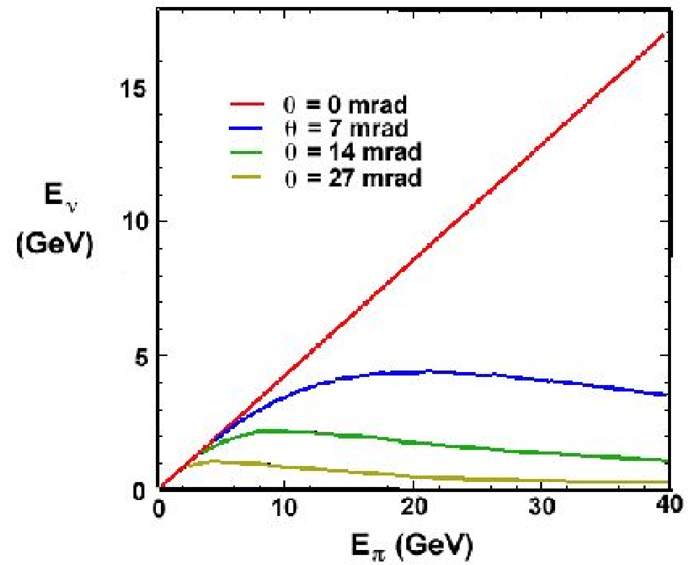
$$E_\nu = \frac{0.43 E_\pi}{(1+\theta^2\gamma_\pi^2)}$$

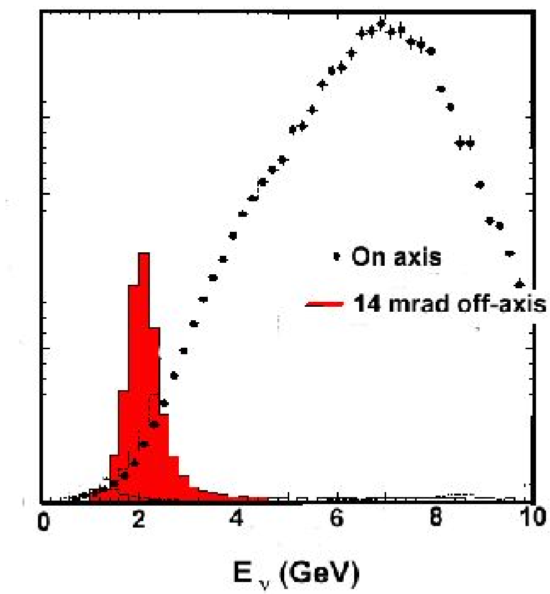
Off-Axis the beams are Narrow!
approx. gaussian with spread
20% $< E_\nu >$

GREAT !!!

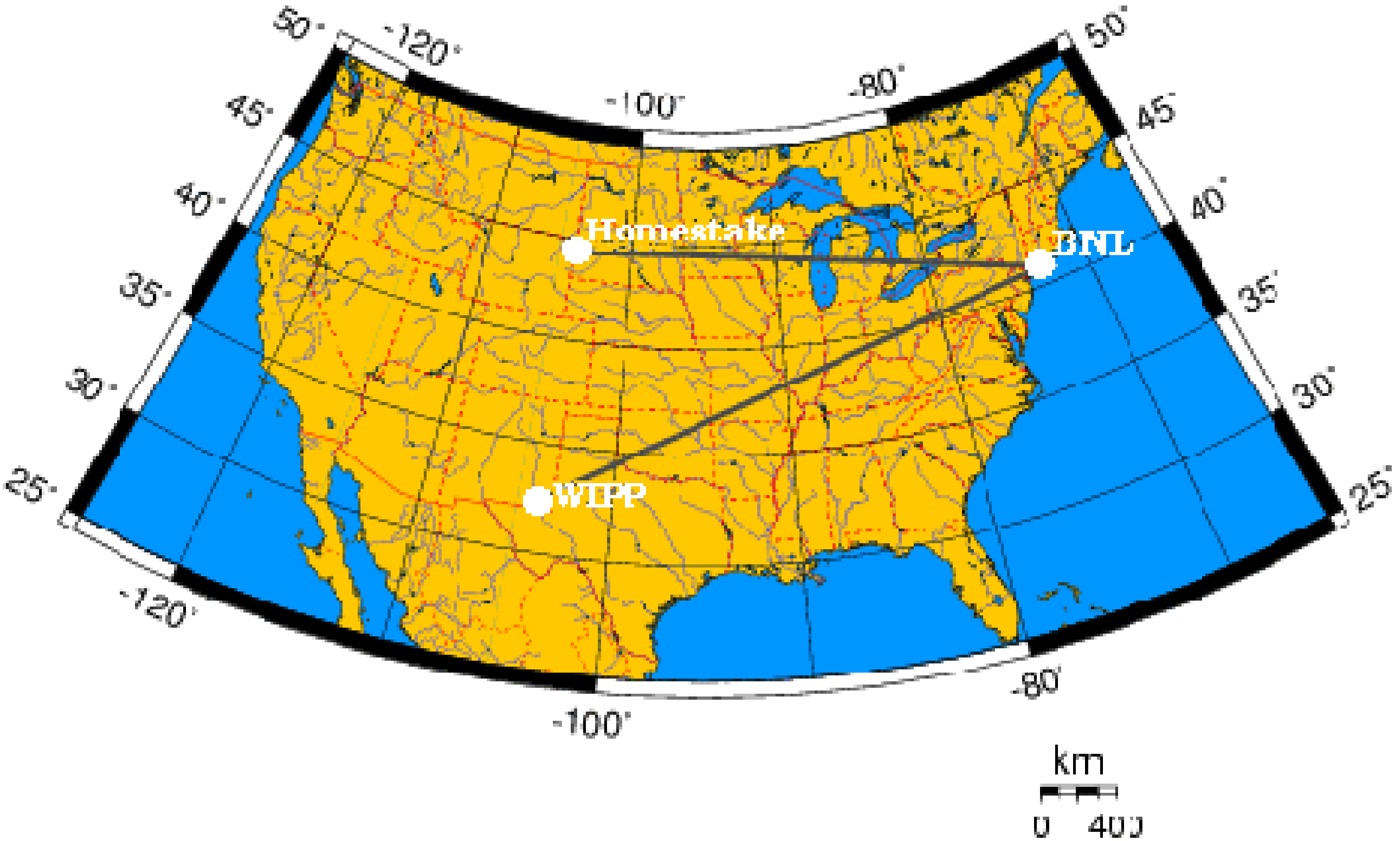
as the primary bckgrd to ν_e detection is π^0 coming from higher energy NC events. (ν_e contamination in beam is small 0.5% and apprx known.)

BNL-proposal '94





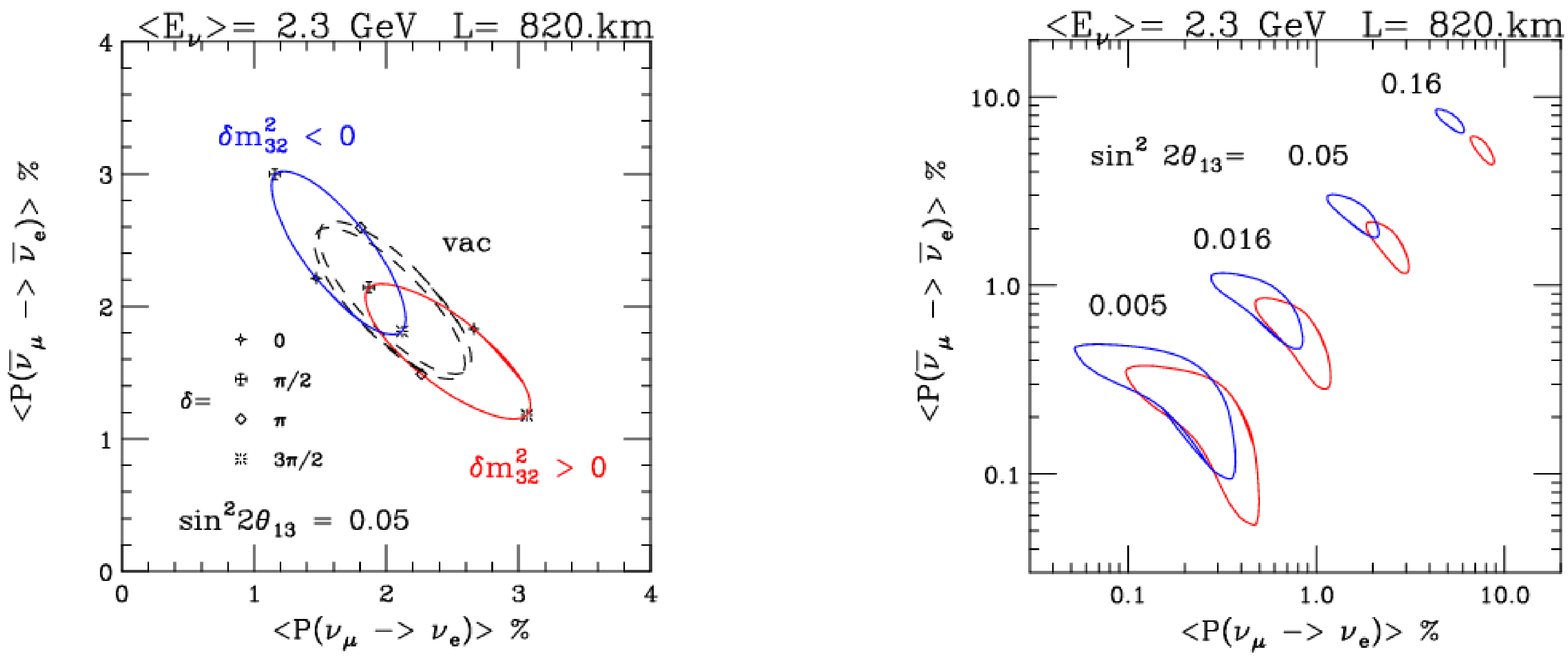
Broad Beams - Spectral Shape Experiments:



Questions:

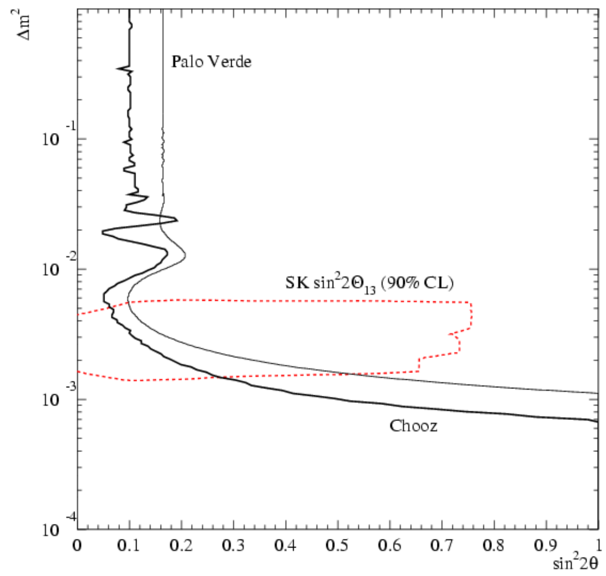
Backgrounds ? and Optimization of E and L?

Matter Effects in NOνA:

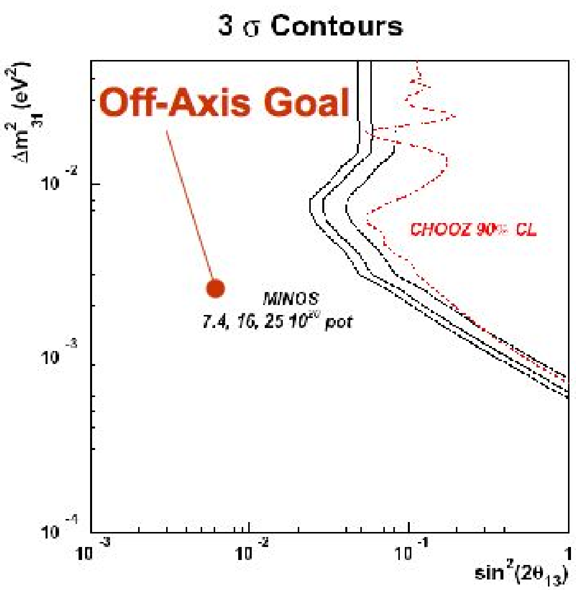


Matter Effects important for NuMI-OFF-Axis ($\sim$800 km),
less so for T2K (295 km).

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.

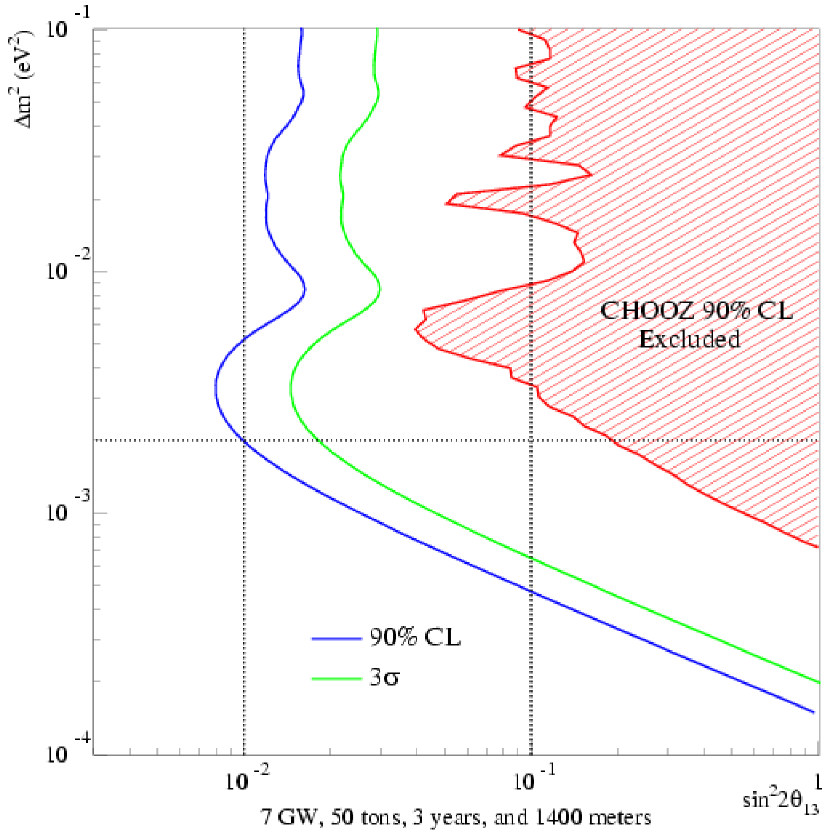
New Reactor Experiments:

"Super-Chooz:"

interest in Japan, Europe, Russia, China 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.



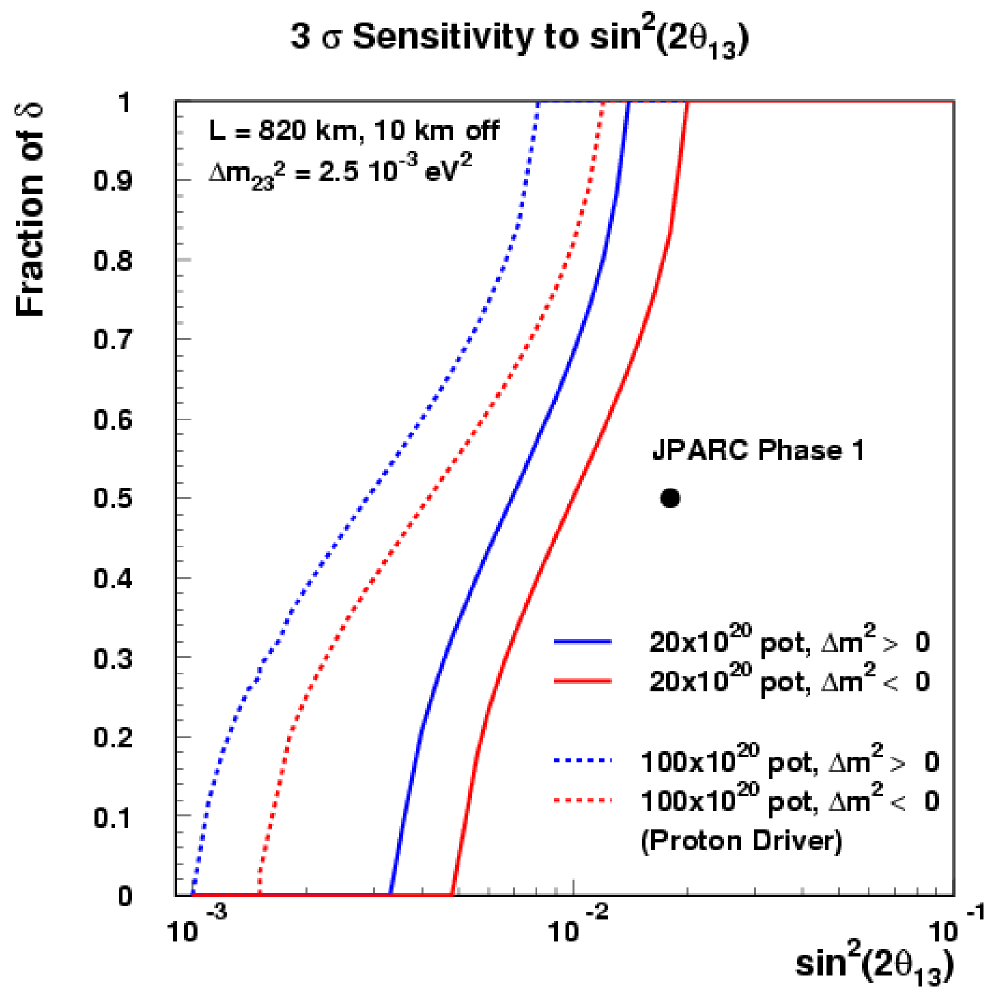
$$1 - P_{\nu_e \to \nu_e} = \sin^2 2\theta_{13} \left[\sin^2 \Delta_{atm} + \mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right) \right] + \mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right)^2$$

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}.

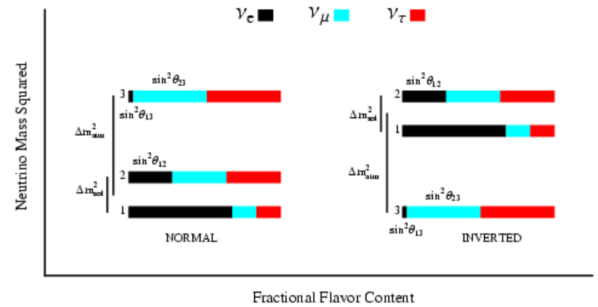


Assumes $\sin^2 2\theta_{23} = 1$ i.e. $\theta_{23} = \pi/4$.

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., $\Delta_{32} = \frac{\pi}{2}$

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

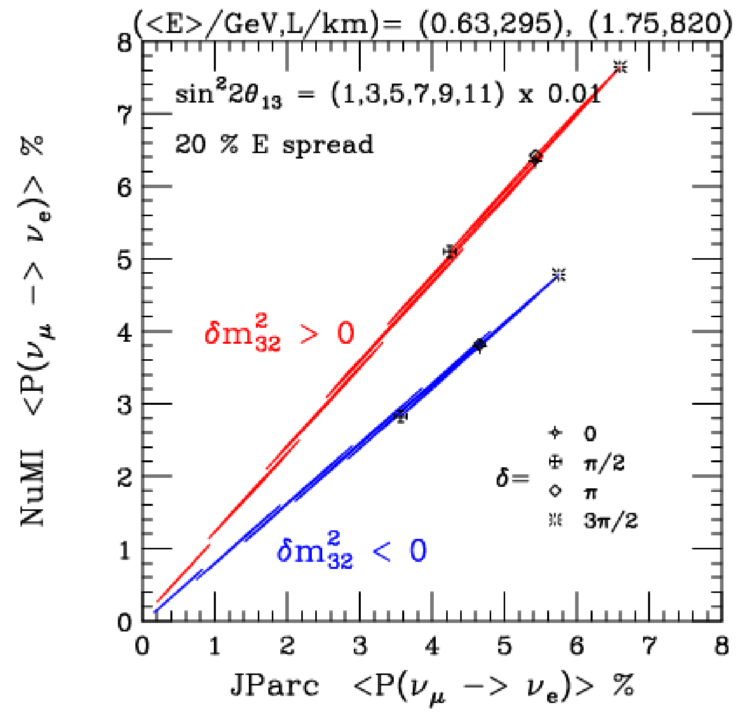
where $E_R \simeq 12$ GeV.

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

Need about 100 events in each expt.



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

Minakata, Nunokawa and SP – hep-ph/0301210

sign δm^2_{32} conti.

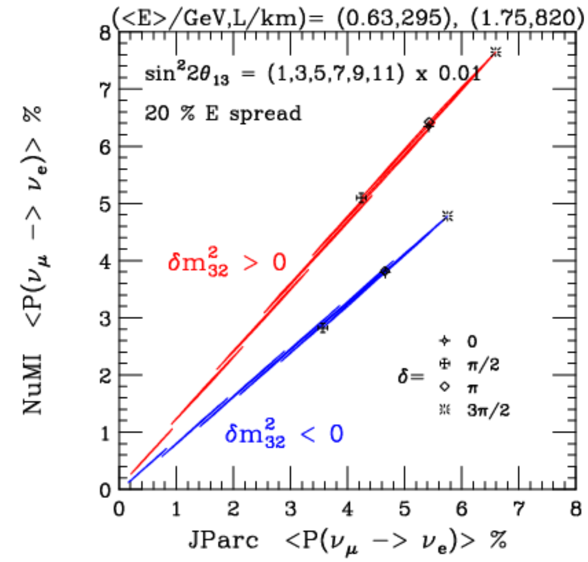
For NuMI above Vac. Oscillation Maximum, $E = E_{vom} + \Delta E$

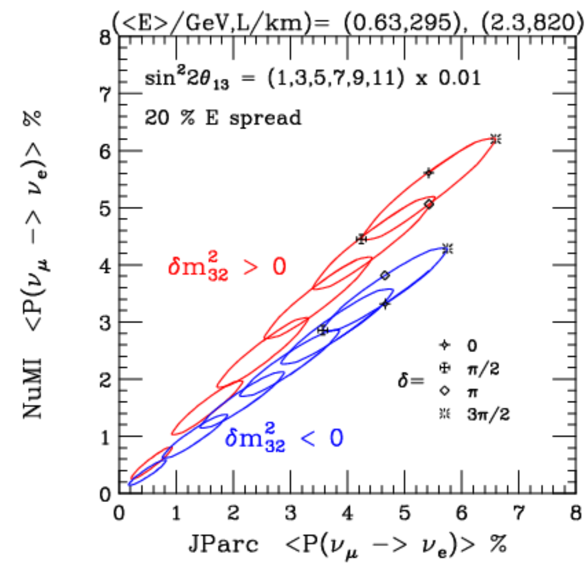
$$P_{mat} = \left(1 \pm 2\frac{E_{vom}}{E_R} \mp \frac{(\pi^2-4)}{2}\ \frac{\Delta E}{E_R}\right) P_{vac}$$

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.



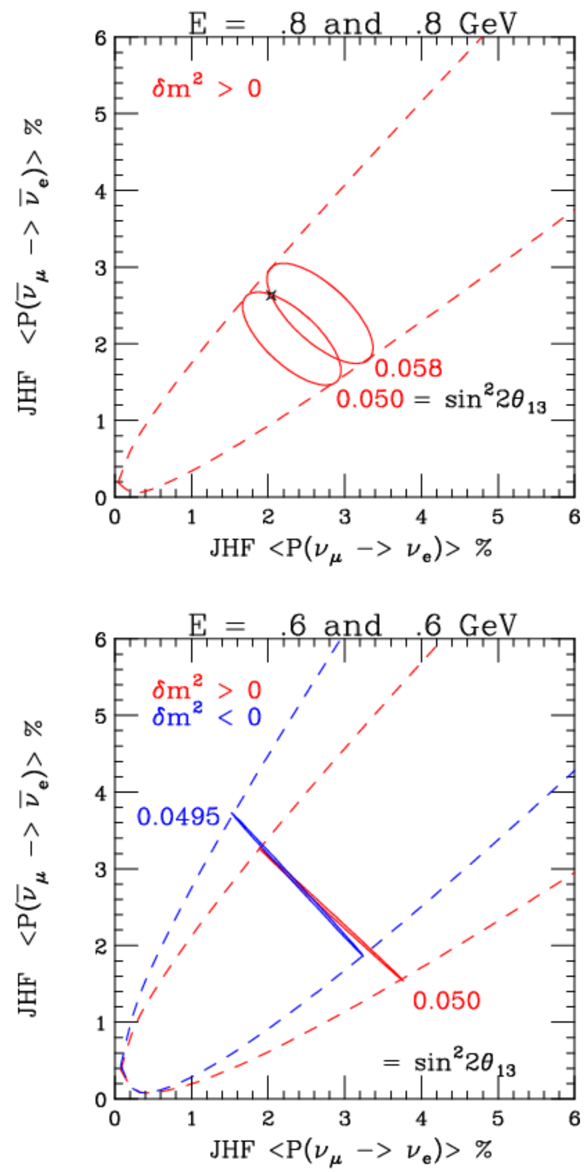


θ_{13} and δ

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

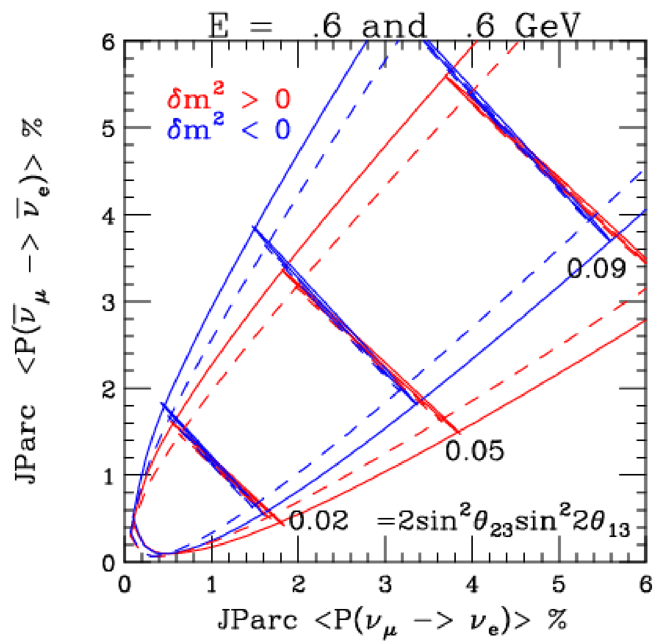
$\theta_{23} \leftrightarrow (\frac{\pi}{2} - \theta_{23})$

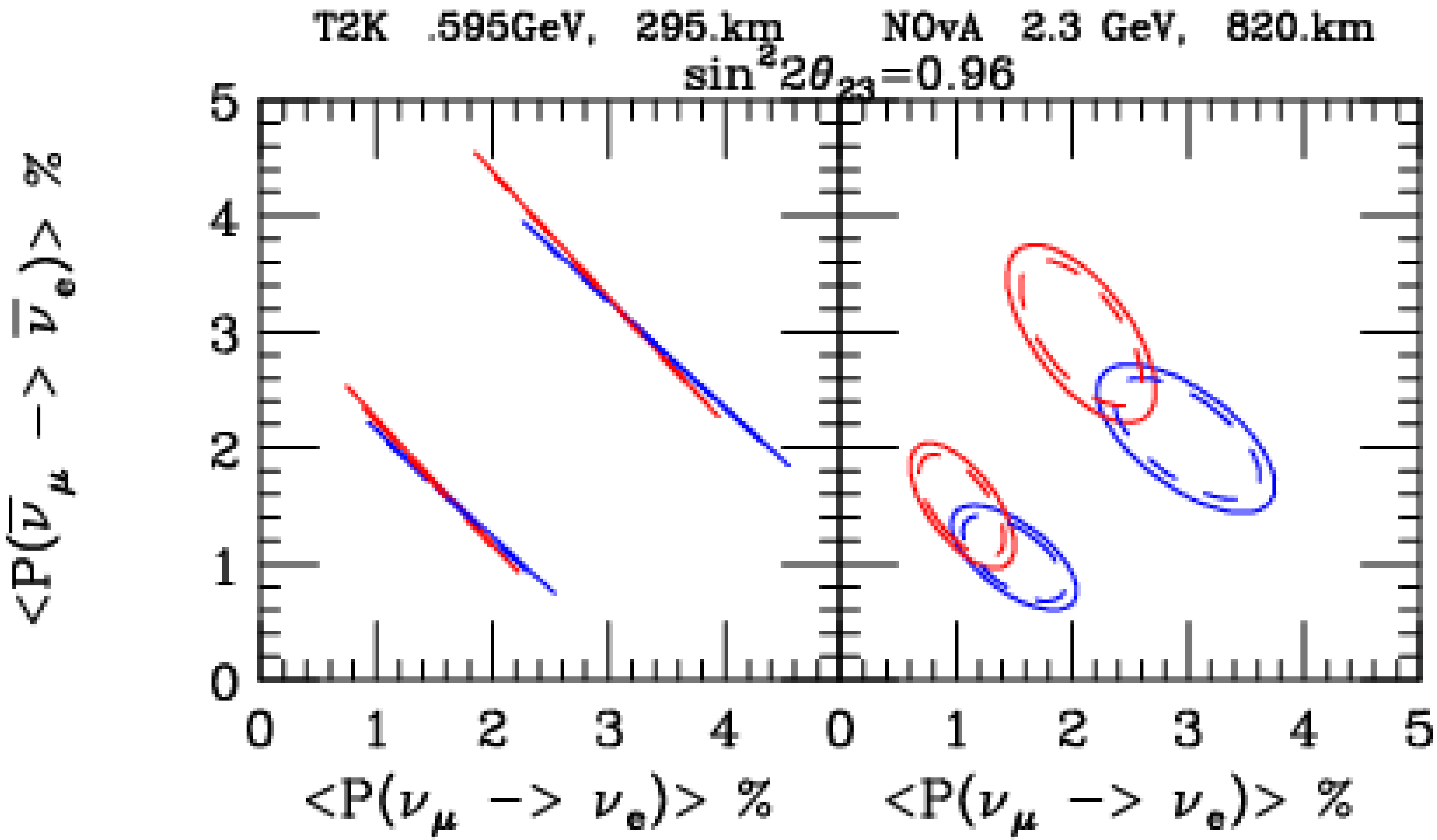
$\theta_{23} = \frac{\pi}{4}$ is $\nu_\mu \leftrightarrow \nu_\tau$ sym. pt.

$\sin^2 2\theta_{23}$ from dissapp. exp.
however even if $\sin^2 2\theta_{23} = 0.96$:
$\sin^2 \theta_{23} = 0.40$ *or* 0.6

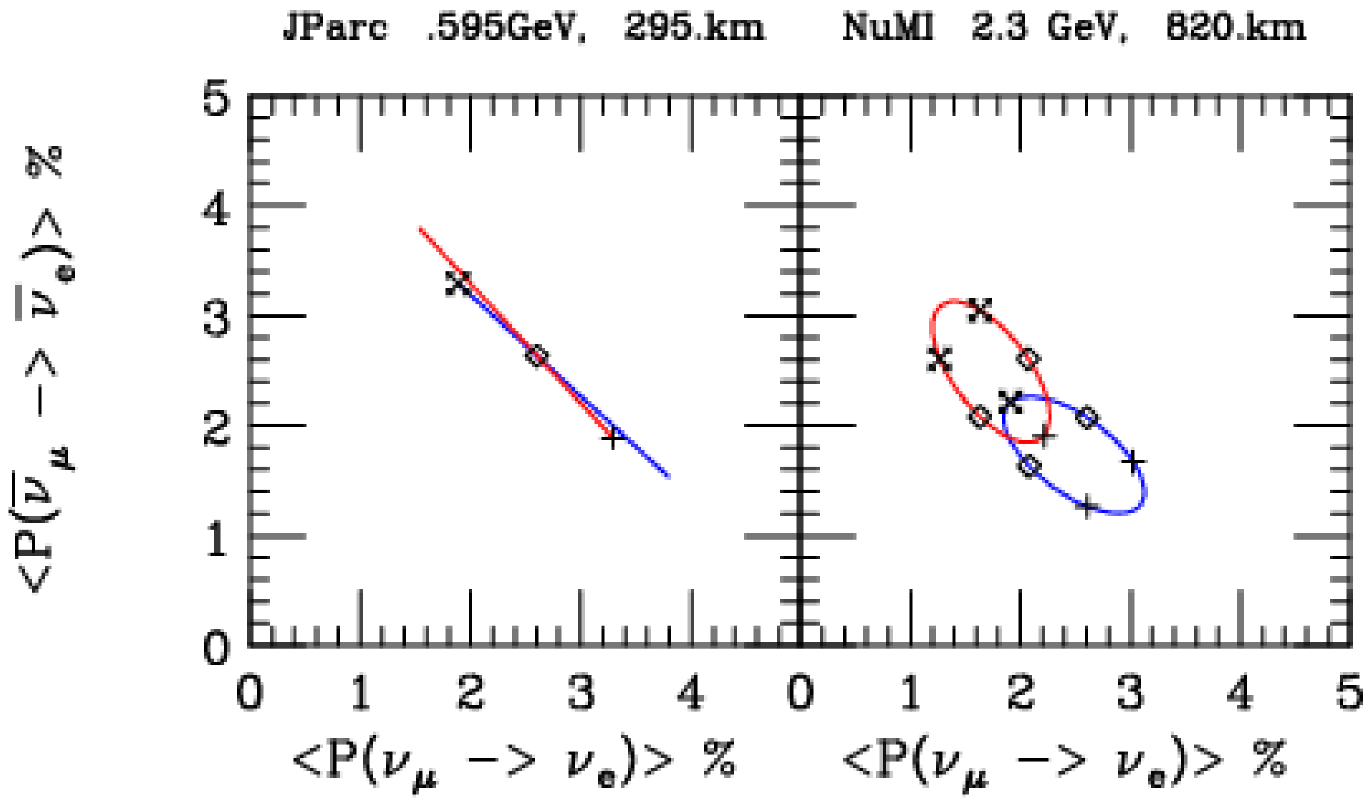
LBL at Vac. Osc. Max. with ν and $\bar{\nu}$ measurements
$\sin\theta_{23}\sin\theta_{13}$ & $\cos\theta_{23}\sin\delta$.

However determining $\cos\delta$ requires running above Vac. Osc. Max. This splits δ from $\pi - \delta$.
Very high precision needed!!





A LBL measurement of $\sin^2\theta_{23}\sin^2\theta_{13}$ combined with a precision reactor measurement of $\sin^2\theta_{13}$ is best way to determine $\sin^2\theta_{23}$!!!!



T2K will give two different $\sin\delta$, one for each hierarchy, with no information on $\cos\delta$. In NOνA these two different values will in general split into four points. Two for each hierarchy because the matter effects are different and two for each sign of $\cos\delta$.

Thus the hierarchy and δ can be determined with sufficient statistics!!!!

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$\sin\delta$ and sign δm^2

For T2K:

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diff. hierarchy $|\sin\delta_+ - \sin\delta_-| = 0.5\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$

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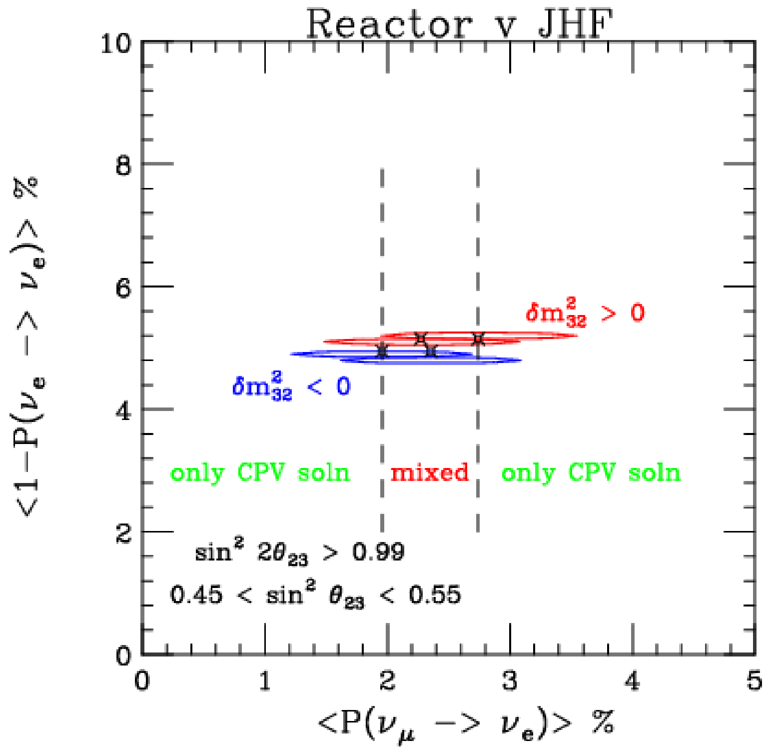
For the WRONG hierarchy

the difference in the values of $\sin\delta$

will be greater than $1.0\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$.

Reactor and $P(\nu_\mu \rightarrow \nu_e)$

Combining a Reactor measurement and LBL neutrino measurement.



At the edges of the allowed region could determine that $\sin\delta \neq 0$

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 a few 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}?