MEASURING NEUTRINO PARAMETERS IN LONG BASELINE EXPERIMENTS

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– Phys Rev. D66, 053007 (2002) [hep-ph/0206038
– in preparation

- Knowledge of ν mass matrix essential for understanding nature of ν mass (see many later talks)
- ν oscillations provide information on everything but absolute mass scale and 2 Majorana phases (see Petcov)
- Must devise experimental strategies to eliminate parameter degeneracies and enable a unique determination of ν masses and mixings

Assume 3 ν's

ν oscillation parameters	where measured	Current value: best (range)	Future (to few % level)
δm^2_{21} (eV^2)	solar	5×10^{-5} ([2–50]$\times10^{-5}$)	KamLAND
$\sin^2 2\theta_{12}$		0.8 (0.56–0.95)	
δm^2_{31} (eV^2)	atmos.	2.5×10^{-3} ([1.5–5.0]$\times10^{-3}$)	long baseline
$\sin^2 2\theta_{23}$		1.0 (0.84–1.00)	$\nu_\mu \to \nu_\mu$ survival
$\sin^2 2\theta_{13}$	CHOOZ, atmos.	≤ 0.1	long baseline
δ	–	–	$\nu_\mu \leftrightarrow \nu_e$, $\nu_e \to \nu_\tau$

Long baseline experiments provide best measurement of θ_{13}, CP phase δ and sgn(δm^2_{31}) (ordering of masses)

CP Violation

- $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ in vacuum
- Matter affects ν and $\bar{\nu}$ differently
  $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ even if no intrinsic CPV
- Parameter degeneracies
  Multiple solutions for a given set of data

$\Rightarrow$ Detection of CPV not simple

Measuring CPV in long baseline experiments

Freund
Cervera et al.

Approx. expressions in matter

$$\left.\begin{aligned} P(\nu_\mu \to \nu_e) &= B(\cos\delta\cos\Delta - \sin\delta\sin\Delta) + C \\ \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e) &= \bar{B}(\cos\delta\cos\Delta + \sin\delta\sin\Delta) + \bar{C} \end{aligned}\right\} \quad \delta m^2_{31} > 0$$

$$\left.\begin{aligned} P(\nu_\mu \to \nu_e) &= \bar{B}(-\cos\delta\cos\Delta - \sin\delta\sin\Delta) + \bar{C} \\ \bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e) &= B(-\cos\delta\cos\Delta + \sin\delta\sin\Delta) + C \end{aligned}\right\} \quad \delta m^2_{31} < 0$$

$$\Delta = \frac{|\delta m^2_{31}|\, L}{4E} = 1.27 \left|\frac{\delta m^2_{31}}{eV^2}\right| \left(\frac{L}{km}\right) \Big/ \left(\frac{E_\nu}{GeV}\right)$$

$B, C, \bar{B}, \bar{C}$ depend on ν mixing angles (increase with increasing θ_{13})

B, C enhanced in matter

$\bar{B}, \bar{C}$ suppressed in matter

Intrinsic CPV from $\sin\delta$ term
Matter-induced CPV from $B \neq \bar{B}$, $C \neq \bar{C}$

Measure P and $\bar{P}$ at one L and E_ν (e.g., with a conventional narrow band ν beam)

$\Rightarrow$ determine 2 unknowns θ_{13} and δ

Problem: Three possible 2-fold parameter degeneracies

Can mix CP conserving and CP violating solutions

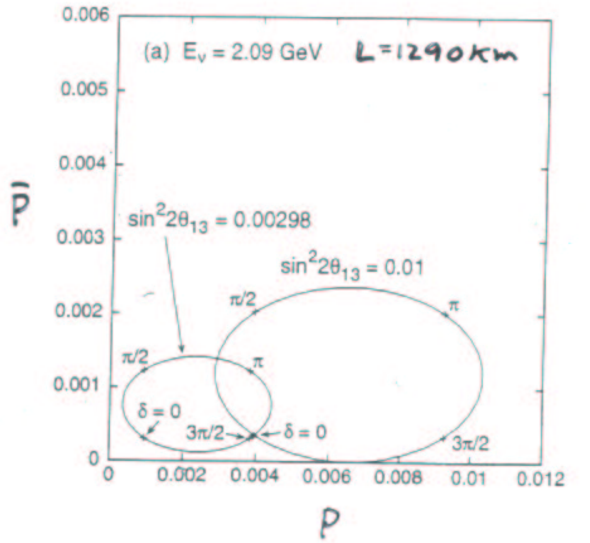
Fix θ_{13}, plot P vs. $\bar{P}$ as δ varies $\Rightarrow$ ellipse

$\boxed{(\delta, \theta_{13}) \text{ ambiguity}}$

Ellipses for different θ_{13} overlap

$\Rightarrow (\delta, \theta_{13})$ and (δ', θ'_{13}) give same $P + \bar{P}$

- θ_{13} and θ'_{13} can be very different
- large CPV/CPC confusion possible

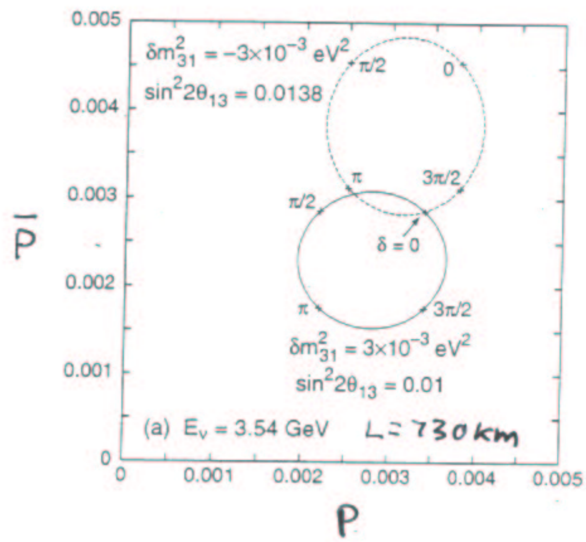


$\boxed{\text{sgn}(\delta m^2_{31}) \text{ ambiguity}}$

Ellipses for $\delta m^2_{31} > 0$ and $\delta m^2_{31} < 0$ overlap

(different due to matter effects)

- θ_{13} and θ'_{13} are somewhat different
- large CPV/CPC confusion possible

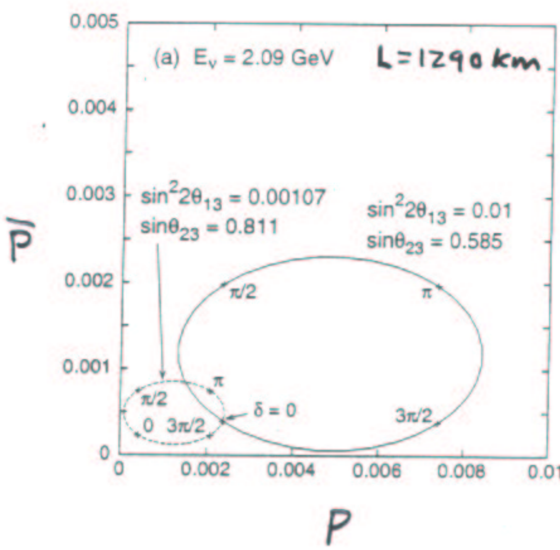


$\boxed{(\theta_{23}, \frac{\pi}{2} - \theta_{23}) \text{ ambiguity}}$

Only $\sin^2 2\theta_{23}$ measured in $\nu_\mu \to \nu_\mu$

$\Rightarrow$ two solutions $(\theta_{23} < \frac{\pi}{4}, \theta'_{23} > \frac{\pi}{4})$

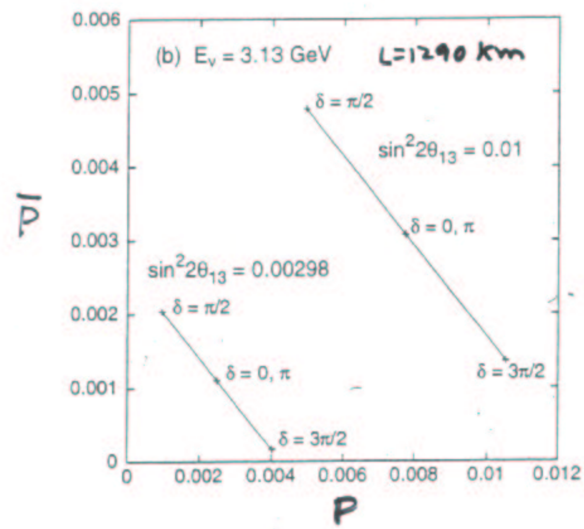
- θ_{13} and θ'_{13} can be very different
- large CPV/CPC confusion possible



Combined 8-fold degeneracy (with large CPV/CPC confusion for each type of degeneracy)

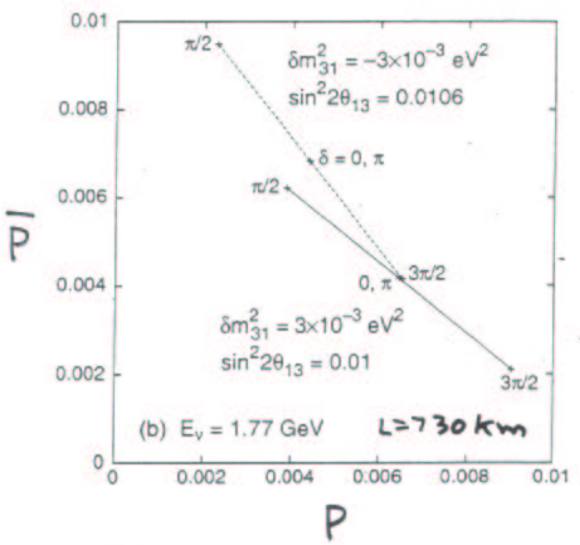
Can reduce effects of ambiguities by sitting on $\Delta = (2n-1)\frac{\pi}{2}$ (on peak of leading term of vacuum oscillation)

$\Rightarrow$ no $\cos\delta$ term, ellipses collapse to lines



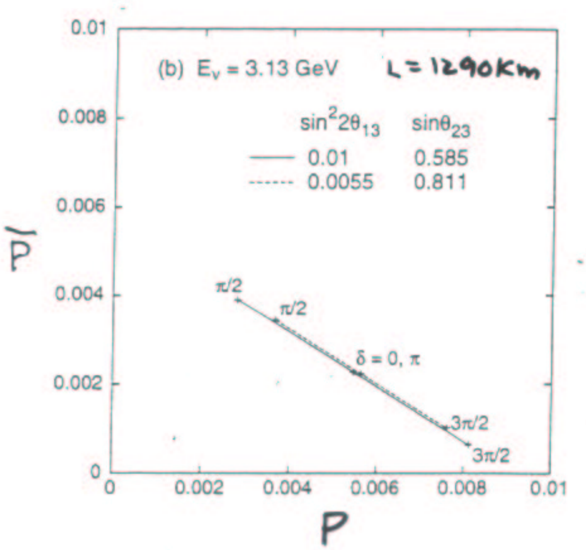
(δ, θ_{13}) ambiguity

- θ_{13} removed from degeneracy
- residual $(\delta, \pi-\delta)$ ambiguity (since only $\sin\delta$ is measured)
- no CPV/CPC confusion



$\mathrm{sgn}(\delta m^2_{31})$ ambiguity

- large CPV/CPC confusion can remain
- ambiguity avoided;
  for $\delta m^2_{31} > 0$ if $\delta \sim \frac{3\pi}{2}$
  for $\delta m^2_{31} < 0$ if $\delta \sim \pi/2$



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

- $\sin^2 2\theta'_{13} \simeq \sin^2 2\theta_{13} \tan^2\theta_{23}$
  (for $\sin^2 2\theta_{23} = 0.9$, $\sin^2 2\theta'_{13} \simeq \frac{1}{2}\sin^2 2\theta_{13}$)
- CPV/CPC confusion small
- vanishes for $\theta_{23} \simeq \frac{\pi}{4}$

"Best" scenario for one P and one $\bar{P}$ measurement:

- Choose $\Delta = \frac{\pi}{2}$ (peak)
- Choose longer L

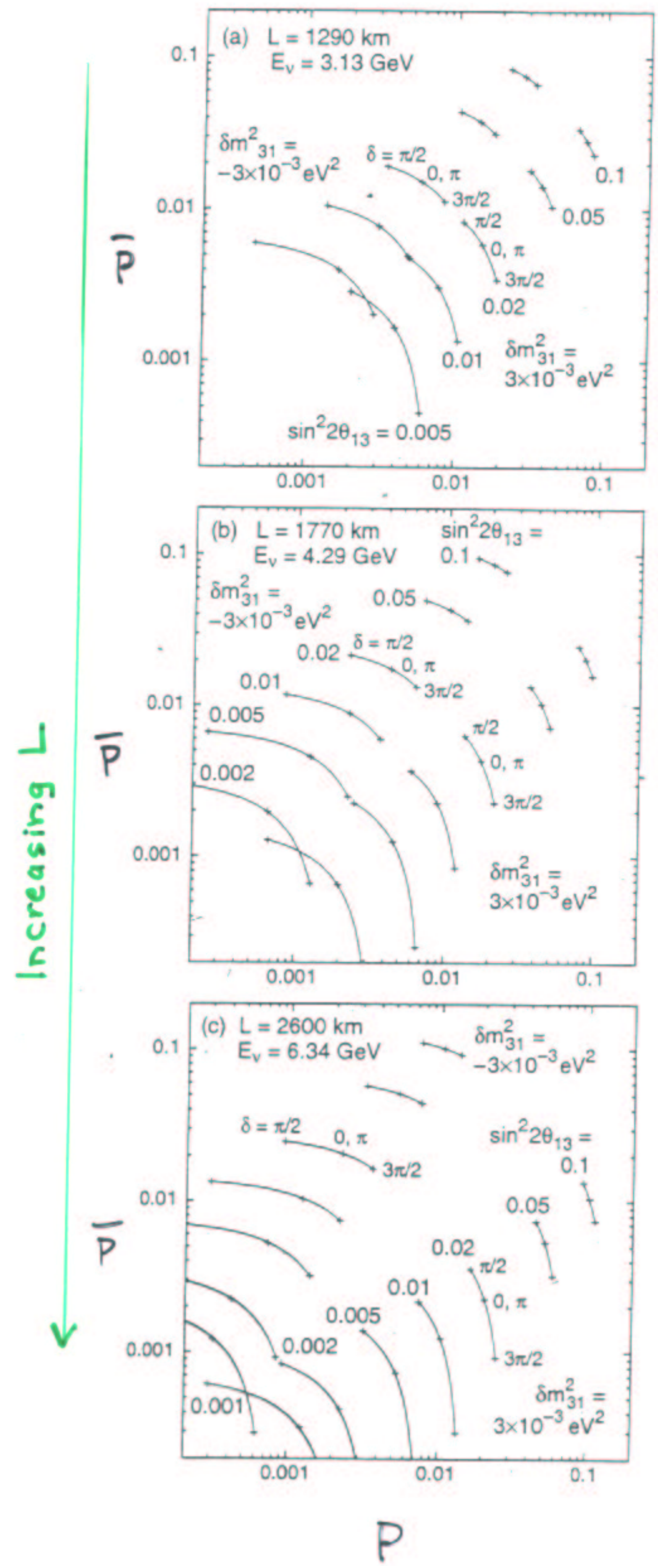
$\Rightarrow (\theta_{13}, \delta)$ determined except for

- residual $(\delta, \pi - \delta)$ ambiguity
- small CPV/CPC confusion

  if $\theta_{23} \neq \frac{\pi}{4}$

- Also, θ_{13} uniquely determined

  if $\theta_{23} \simeq \frac{\pi}{4}$



Super JHF to Hyper-K

$L \simeq 300\,\text{km}, \; E_\nu \simeq 0.7\,\text{GeV}$

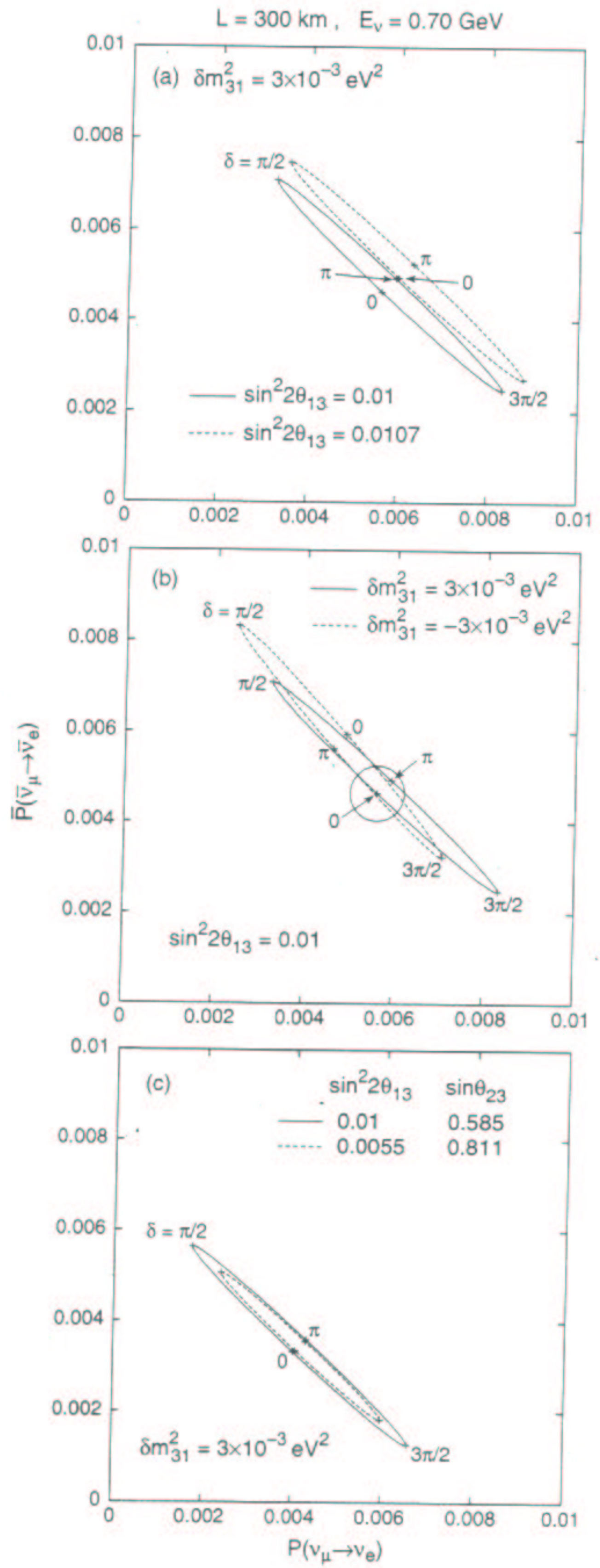
$\Delta \simeq \frac{\pi}{2}$ reduces (δ, θ_{13}) ambiguity

to simple $(\delta, \pi - \delta)$ ambiguity

$L \simeq 300\,\text{km}$ not long enough to

always resolve $\text{sgn}(\delta m^2_{31})$

θ_{23} ambiguity still possible



What else can be done?

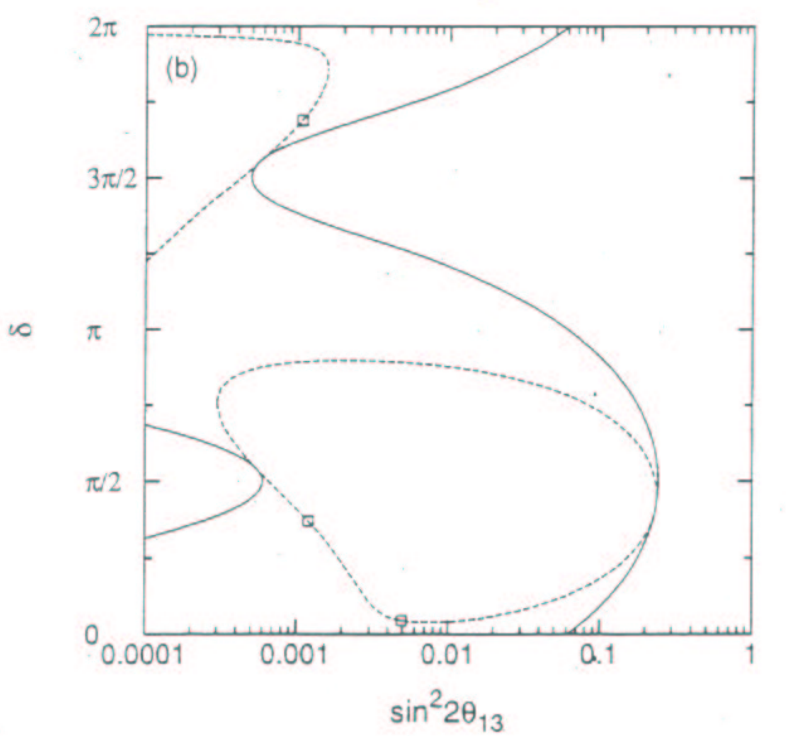
(Another set of measurements on a peak does not help $(\delta, \pi - \delta)$ ambiguity)

- One P and one $\overline{P}$ measurement $\Rightarrow$ degeneracies exist over wide areas of (δ, θ_{13}) parameter space
  $\Rightarrow$ additional measurements needed to eliminate degeneracies

- 3rd measurement reduces region where degeneracies occur to lines in (δ, θ_{13}) plane
- 4th measurement reduces degeneraces to isolated points

e.g.

Measurement	Region with degeneracies
$\nu, \bar{\nu}$ @ $\Delta = \frac{\pi}{2}$	Area between solid lines
add ν @ $\Delta = \frac{\pi}{3}$	Along dashed curves
add $\bar{\nu}$ @ $\Delta = \frac{\pi}{3}$	Boxes only



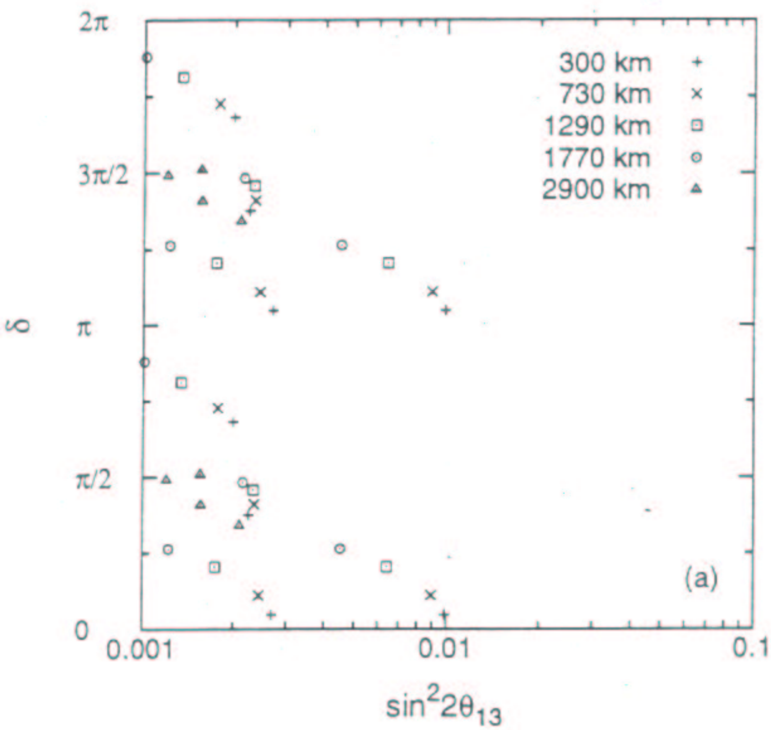
Degeneracies do not have to be removed completely; they are only a problem if they occur at $\sin^2 2\theta_{13}$ within reach of the experiment

Measurements at <u>longer</u> L reduce degeneracies

(larger matter effects help resolve $\text{sgn}(\delta m^2_{31})$ ambiguity)

ν @ $\Delta = \frac{\pi}{2}$ and $\frac{\pi}{3}$

$\bar{\nu}$ @ $\Delta = \frac{\pi}{2}$ and $\frac{\pi}{3}$



Measurements at <u>different</u> L reduce degeneracies

(different matter effects help resolve $\text{sgn}(\delta m^2_{31})$ ambiguity)

e.g. 2 at L_1, 1 at L_2 pushed degeneracies to lower θ_{13} than 4 at a single L

How can this be put into practice?

Off-axis Beams

Para

- Narrower energy spectrum than on-axis
- Smaller beam contamination
- Suppression of HE tail $\Rightarrow$ lower backgrounds in detector

One beam has flexibility in L and E_ν

$$E_\nu \propto \frac{1}{1+\gamma^2\theta_{OA}^2} \qquad \Phi_\nu \propto \frac{E_\nu^2}{L^2} \qquad \left(\gamma = \frac{E_\pi}{m_\pi}\right)$$

Multiple detectors (detector cluster) allow more than one measurement at a time

Combine data from different experiments

Realistic scenario : (Superbeams)

JHF to Super-K (2° OA beam)
- 4 MW (5 x original JHF)
- 2 yrs ν, 6 yrs $\bar{\nu}$
- $L = 295$ km, $E_\nu = 0.70$ GeV (near peak for $|\delta m^2_{31}| = 3\times10^{-3}\,eV^2$)
- 22.5 kt

FNAL aimed at SOUDAN
- 1.6 MW (4x original NuMI)
- 2 yrs ν, 5 yrs $\bar{\nu}$
- $\theta_{OA} = ?$ ($L = ?$, $E_\nu = ?$)
- 20 kt

Backgrounds : 0.5% of CC rate without oscillations known to 5%

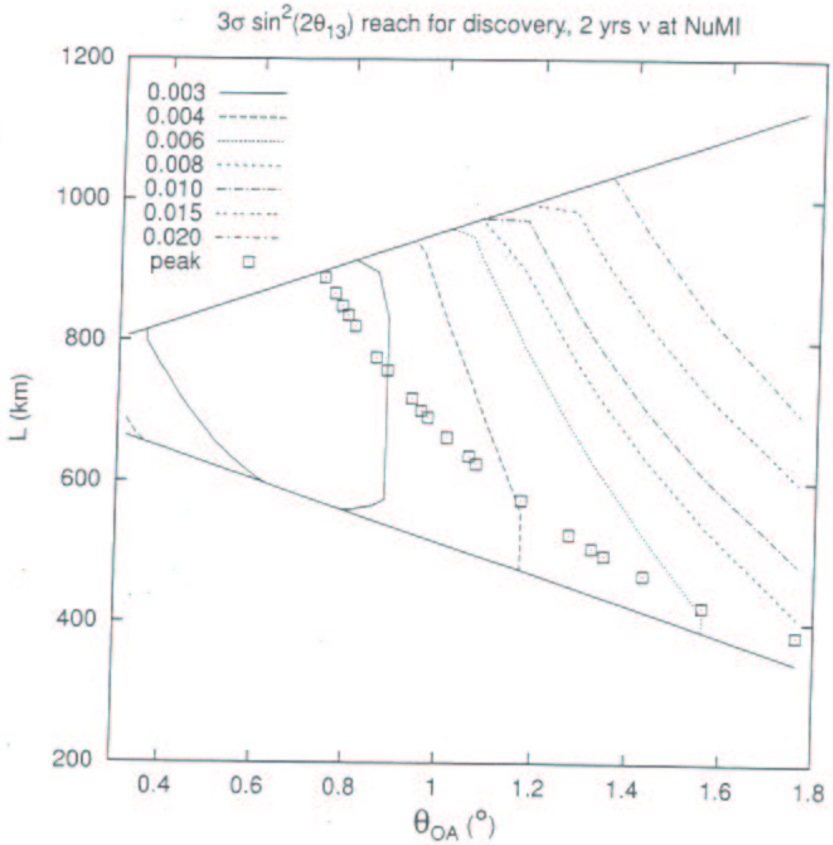
What is best θ_{OA} ($\Rightarrow L, E_\nu$) for NuMI, when used in conjunction with JHF?

Key questions:

1. Can $\mathrm{sgn}(\delta m^2_{31})$ ambiguity be resolved?
2. CPV sensitivity?
3. Can $(\delta, \pi-\delta)$ ambiguity be resolved?

Assume $|\delta m^2_{31}| = 3\times10^{-3}\,eV^2$, $\sin^2 2\theta_{23} = 1.0$

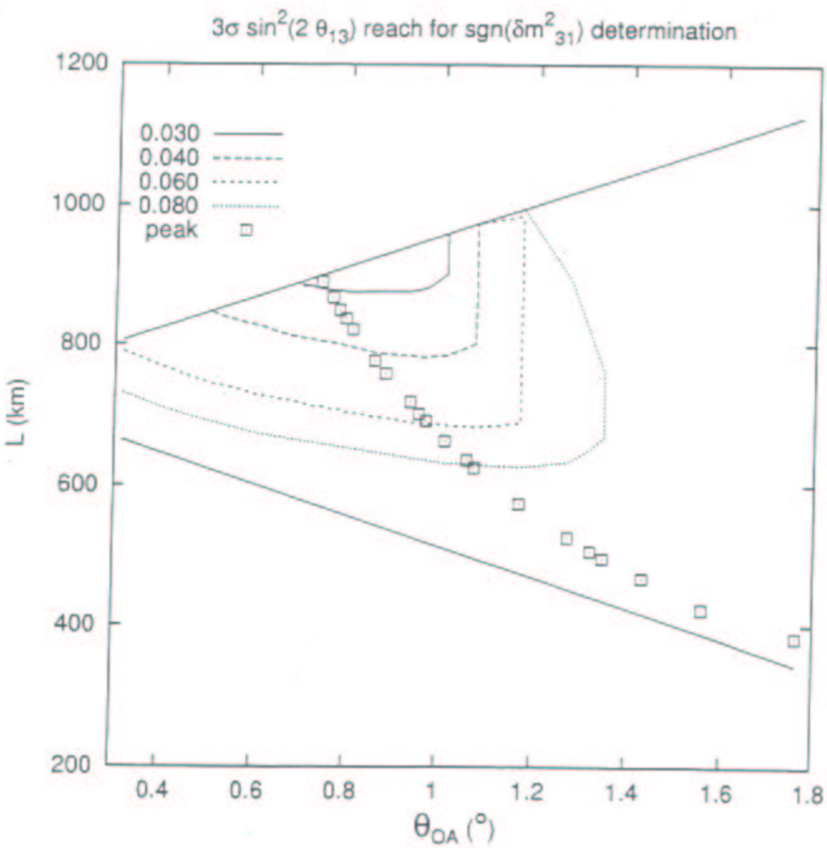
$\delta m^2_{21} = 5\times10^{-5}\,eV^2$, $\sin^2 2\theta_{12} = 0.8$



NuMI
basic
discovery
reach

(2 yrs with ν beam)

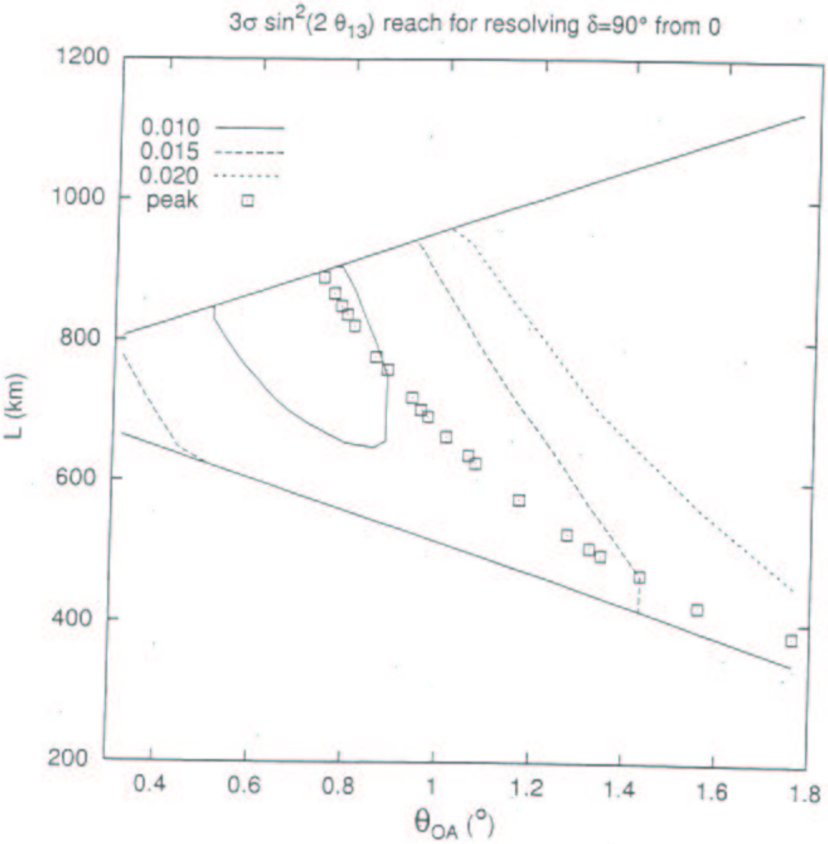
(best case; varies
with δ)



NuMI + JHF ($\nu + \bar{\nu}$)

two distances
allows sgn(δm^2_{31})
determination

Longer L for NuMI
is better

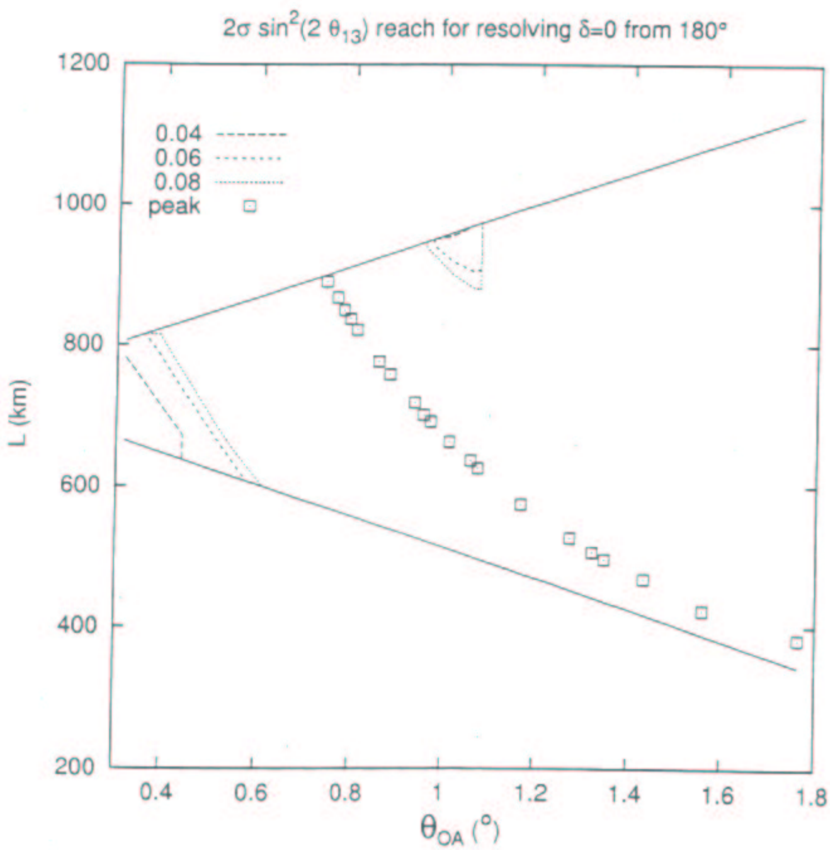


NuMI + JHF ($\nu + \bar{\nu}$)

CPV sensitivity

NuMI best near peak

Larger L preferred



NuMI + JHF ($\nu + \bar{\nu}$)

$(\delta, \pi - \delta)$ resolution

NuMI best off peak

(need some $\cos \delta$ dependence)

Good compromise (?) between $\mathrm{sgn}(\delta m^2_{31})$ and CPV sensitivities:

JHF @ 295 km + NuMI @ $\theta_{OA} = 0.7-0.8^\circ$, $L \simeq 900$ km

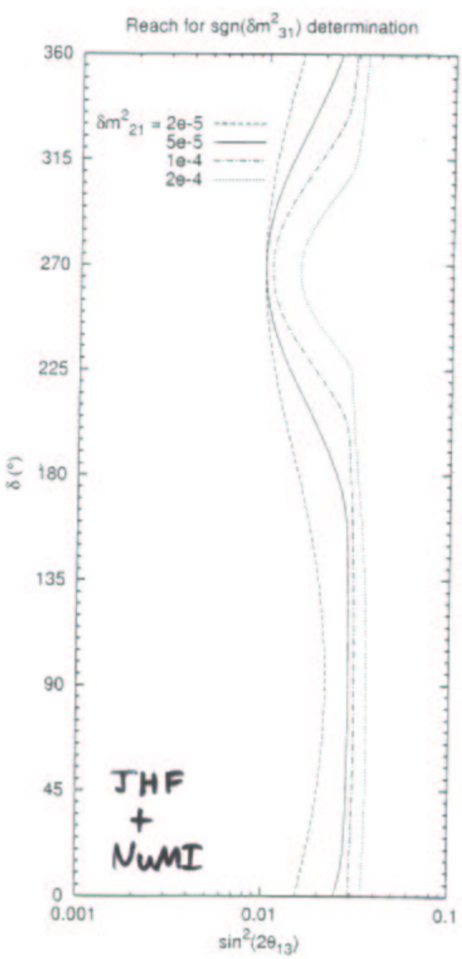
- both on peak
- leave $(\delta, \pi-\delta)$ ambiguity for a future measurement

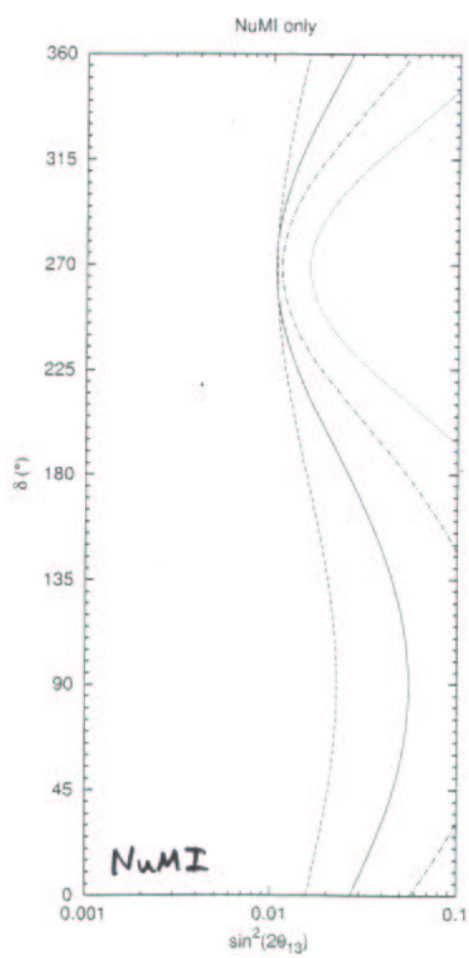
$\Rightarrow$ Same NuMI parameters as in Barenboim, De Gouvea, Szleper, Velasco (maximized for θ_{13}, CPV sensitivity)

Also good for $\mathrm{sgn}(\delta m^2_{31})$ determination when combined w/ JHF

Ability to determine $\mathrm{sgn}(\delta m^2_{31})$ with NuMI alone is very sensitive to size of solar scale δm^2_{21}

Measurements at different L greatly reduces δm^2_{21} effect





Other possibilities for measuring neutrino parameters

Huber, Lindner, Winter

- Even narrow spectrum beams have some energy info — can help resolve degeneracies at larger θ_{13}
- ν factory

Burguet-Castell et al.

- Combine superbeam and ν factory data

Donini, Meloni, Migliozzi

- $\nu_e \to \nu_\tau$ at ν factory ("silver channel")

Summary

1. ν and $\bar{\nu}$ measurement on peak plus $\mathrm{sgn}(\delta m^2_{31})$ determination $\Rightarrow$ unambiguous test of CPV

2. Two superbeam experiments at different L can resolve $\mathrm{sgn}(\delta m^2_{31})$ ambiguity (if θ_{13} not too small)
   e.g. NuMI + JHF with beam upgrades
   (Complementary experiments less bothered by large δm^2_{21})

3. $(\delta, \pi-\delta)$ and $(\theta_{23}, \frac{\pi}{2}-\theta_{23})$ ambiguities do not significantly interfere with CPV tests
   $\Rightarrow$ best left for additional measurements?
   (θ_{13} uncertainty possible for $\theta_{23} \neq \pi/4$)