PROSPECTS FOR DETERMINING NEUTRINO PARAMETERS IN LONG-BASELINE EXPERIMENTS

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V. Barger, D. Marfatia, KW – hep-ph/0108090
– Phys. Rev. D65, 073023 (2002) [hep-ph/0112119]
– Phys. Rev. D66, 053007 (2002) [hep-ph/0206038]
– hep-ph/0210428

- Knowledge of ν mass matrix essential for understanding nature of ν mass + leptonic CP violation
- Currently there are two unknown parameters in ν mixing matrix
- Must devise experimental strategies to eliminate parameter degeneracies and enable a unique determination of ν masses and mixings

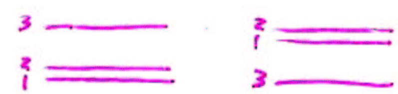
Assume 3 ν's

ν oscillation parameters	where measured	Current value: best (range)	Future (to few % level)
δm^2_{21} (eV^2)	solar, KamLAND	7×10^{-5} ($[5-20]\times10^{-5}$)	KamLAND
$\sin^2 2\theta_{12}$	solar, KamLAND	0.83 (0.59–0.95)	
$\lvert\delta m^2_{31}\rvert$ (eV^2)	atmos.	2.5×10^{-3} ($[1.5-5.0]\times10^{-3}$)	long baseline $\nu_\mu\to\nu_\mu$ survival
$\sin^2 2\theta_{23}$	atmos.	1.0 (0.84–1.00)	long baseline $\nu_\mu\to\nu_\mu$ survival
$\sin^2 2\theta_{13}$	CHOOZ, atmos.	≤ 0.1	long baseline $\nu_\mu \leftrightarrow \nu_e$, $\nu_e\to\nu_\tau$
δ	–	–	long baseline $\nu_\mu \leftrightarrow \nu_e$, $\nu_e\to\nu_\tau$

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

CP Violation

- $P(\nu_\alpha\to\nu_\beta) \neq \bar{P}(\bar\nu_\alpha\to\bar\nu_\beta)$ in vacuum
- Matter affects ν and $\bar\nu$ differently
  $P(\nu_\alpha\to\nu_\beta) \neq \bar{P}(\bar\nu_\alpha\to\bar\nu_\beta)$ even if no intrinsic CPV



mass splittings

enhances P enhances $\bar{P}$

$\Rightarrow$ Detection of CPV not easy
Can use matter effect to determine mass ordering

Both intrinsic CPV and matter effects require $\theta_{13} \neq 0$

Measuring CPV in long baseline experiments 3

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 (in principle)

Problem: Three possible 2-fold parameter degeneracies

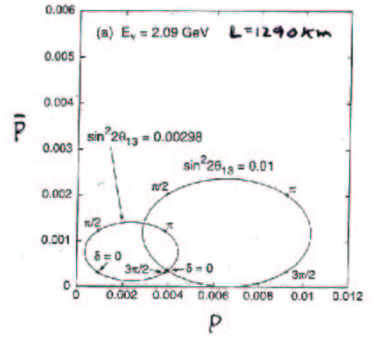
can mix CP conserving and CP violating solutions

Fix θ_{13}, plot P vs. $\bar{P}$ as δ varies $\Rightarrow$ ellipse 4

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

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

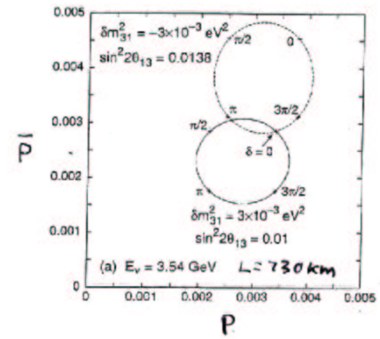
- θ_{13} and θ'_{13} can be very different
- large CPV/CPC confusion possible



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

Ellipses for $\delta m^2_{31} > 0$ and $\delta m^2_{31} < 0$ overlap
(different due to matter effects)

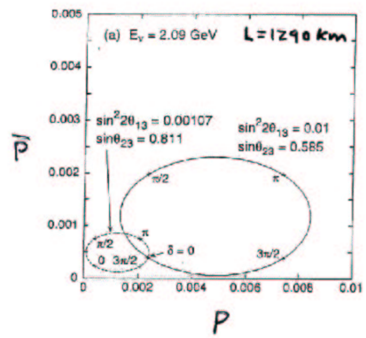
- θ_{13} and θ'_{13} are somewhat different
- large CPV/CPC confusion possible



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

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) is possible

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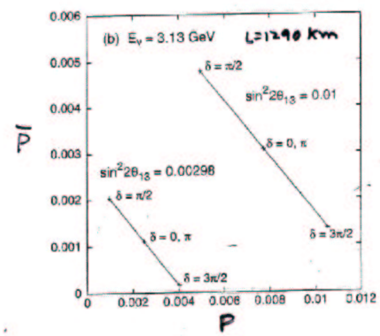
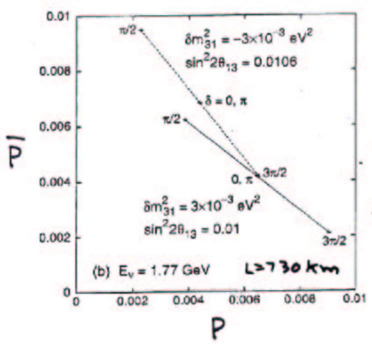
Can reduce effects of ambiguities by sitting on $\Delta = (2n-1)\frac{\pi}{2}$ (on peak of leading term of vacuum oscillation)

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



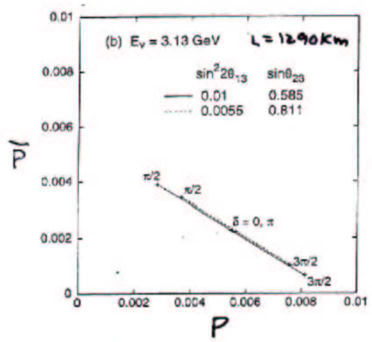
(δ, θ_{13}) ambiguity

- 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

- θ_{13} uncertainty is small
- 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 $\theta_{23} \simeq \frac{\pi}{4}$

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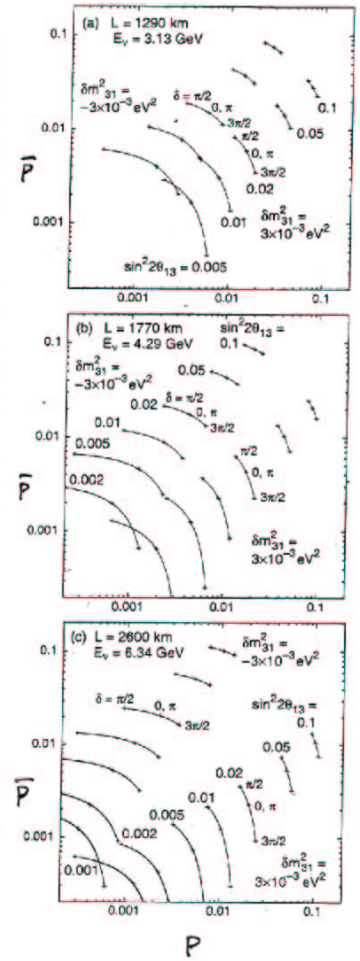
Good scenario for one P and $\bar{P}$ measurement:

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

$\Rightarrow$

- $\mathrm{sgn}(\delta m^2_{31})$ determined if θ_{13} large enough
- small CPV/CPC confusion for any θ_{23}
- residual $(\delta, \pi - \delta)$ ambiguity
- θ_{13} uniquely determined if $\theta_{23} \simeq \pi/4$

Increasing L



Super JHF to Hyper-K

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

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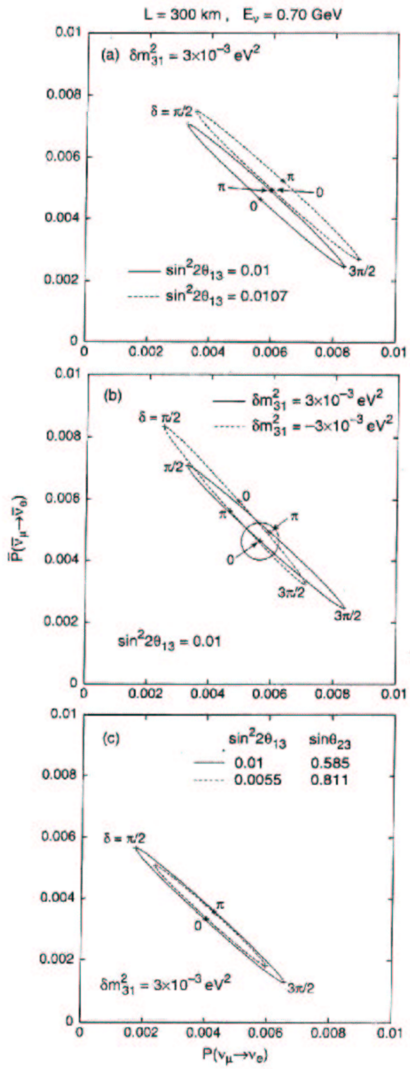
$\Delta \simeq \frac{\pi}{2}$ reduces (δ, θ_{13}) ambiguity to simple $(\delta, \pi-\delta)$ ambiguity



$L \simeq 300\,\mathrm{km}$ not long enough to always resolve $\mathrm{sgn}(\delta m^2_{31})$

θ_{23} ambiguity still possible

What else can be done?

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

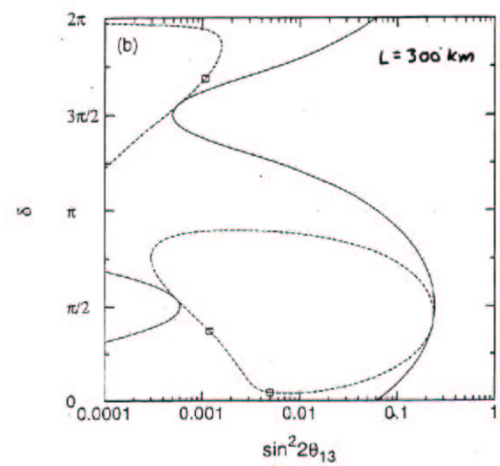
- One P and one $\overline{P}$ measurement $\Rightarrow$ degeneracies exist over wide areas of (δ, θ_{13}) parameter space 8

  $\Rightarrow$ 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

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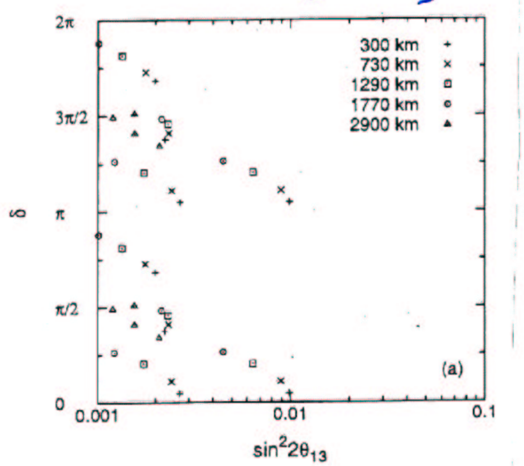
Measurements at longer L reduce degeneracies

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

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

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



Measurements at different L reduce degeneracies

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

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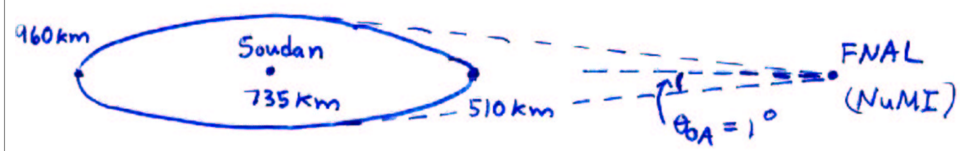
BNL E-889

Para, Szleper

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

One beam has flexibility in L and E_ν



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

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

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

Assume $|\delta m^2_{31}| = 3\times10^{-3}\,eV^2$, $\sin^2 2\theta_{23} = 1.0$
$\delta m^2_{21} = 5\times10^{-5}\,eV^2$, $\sin^2 2\theta_{12} = 0.8$

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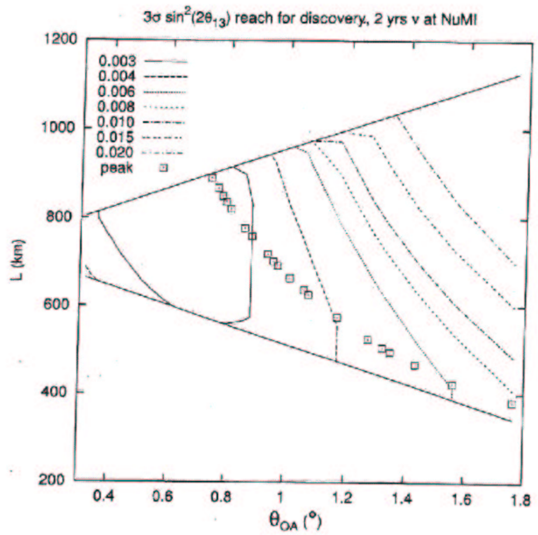
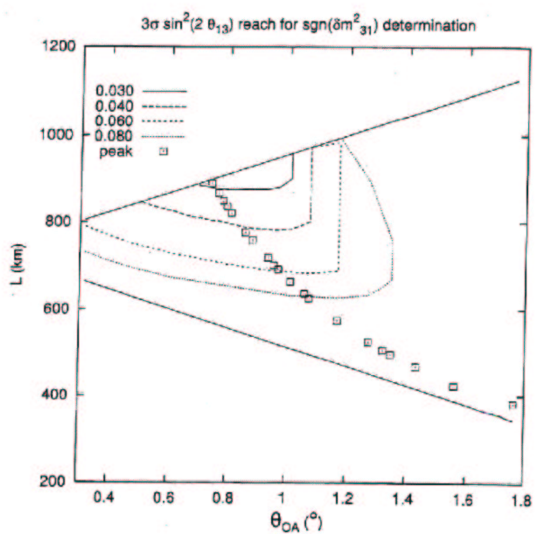


NuMI basic discovery reach

(2 yrs with ν beam)

(best case; varies with δ)



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

two distances allows $sgn(\delta m^2_{31})$ determination

Longer L for NuMI is better

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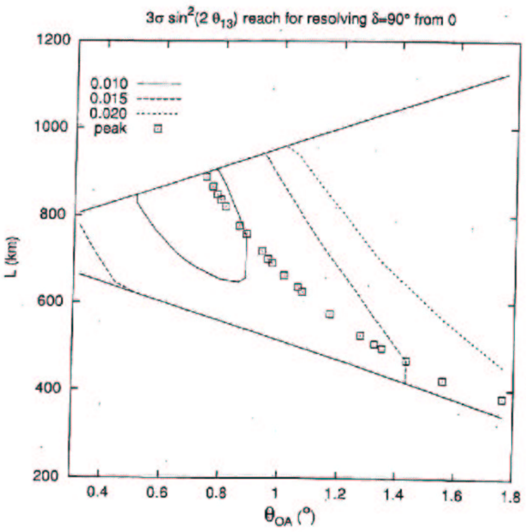
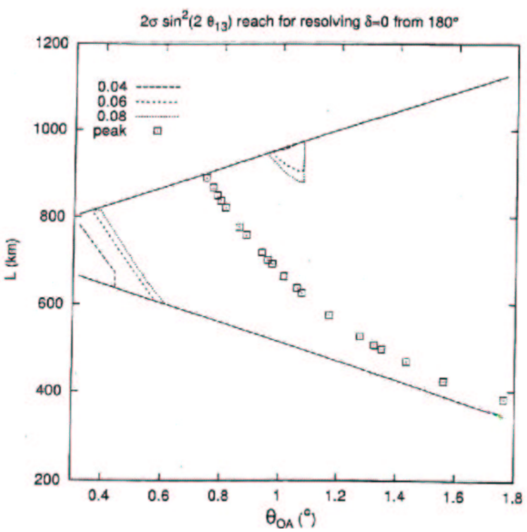


NuMI + JHF ($\nu + \bar{\nu}$)

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 δ dependence)

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

JHF @ 295 km + NuMI @ $\theta_{OA} = 0.7$–$0.8°$, $L \simeq 400$ km

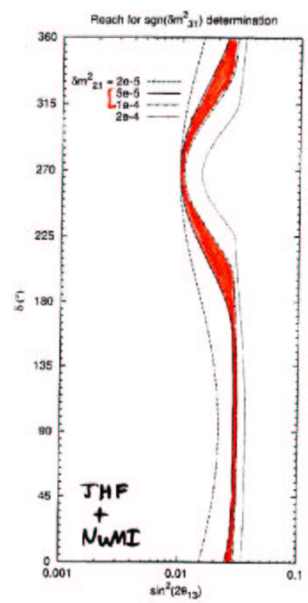
- both on peak
- leave ($\delta, \pi - \delta$) ambiguity for a future measurement

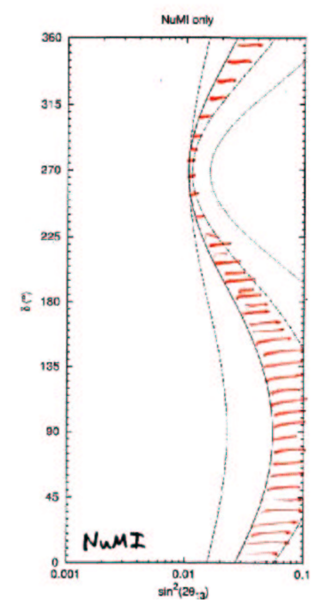
⇒ Same NuMI parameters as in Barenboim, De Gouvea, Szleper, Velasco (maximized for θ_{13}, CPV sensitivity)

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





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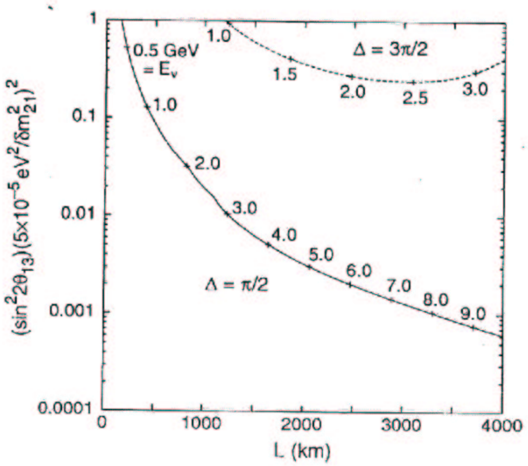
Higher peaks ($\Delta = \frac{3\pi}{2}, \frac{5\pi}{2}, \ldots$)

- peaks at $\Delta = (2n-1)\frac{\pi}{2}$
- $\vec{B} \to B$, $\bar{C} \to C$ as n increases

$\Rightarrow$ loss of $\mathrm{sgn}(\delta m^2_{31})$ sensitivity for $n > 1$

$\sin^2 2\theta_{13}$ reach for no overlap of $\delta m^2_{31} > 0$ and $\delta m^2_{31} < 0$



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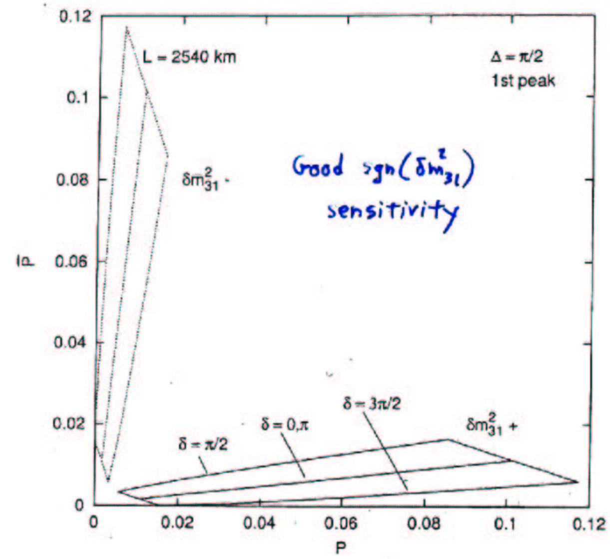
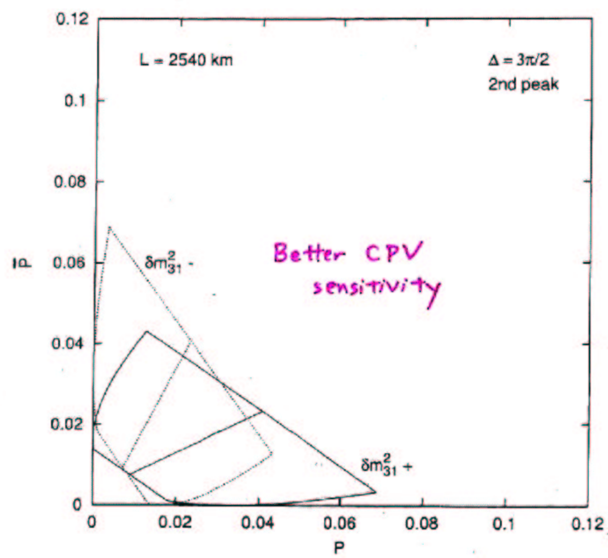
1st peak vs. 2nd peak





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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 (see talk by Geer)

Burguet-Castell et al.

- Combine superbeam and ν factory data

Donini, Meloni, Migliozzi

- $\nu_e \to \nu_\tau$ at ν factory ("silver channel")
- Helps (δ, θ_{13}) and $(\theta_{23}, \frac{\pi}{2}-\theta_{23})$ ambiguities

Diwan et al. (BNL)

- single wide band ν beam
- ν energy discrimination $\Rightarrow$ many measurements at different E_ν
- may need to supplement with $\bar{\nu}$ beam (especially for $\delta m^2_{31} < 0$)
- energy resolution + background discrimination essential

Minakata, Nunokawa, Parke

- P(JHF) vs. P(NuMI)
- P(JHF) vs. $\bar{P}$(NuMI) similar to P vs. $\bar{P}$ at a single machine

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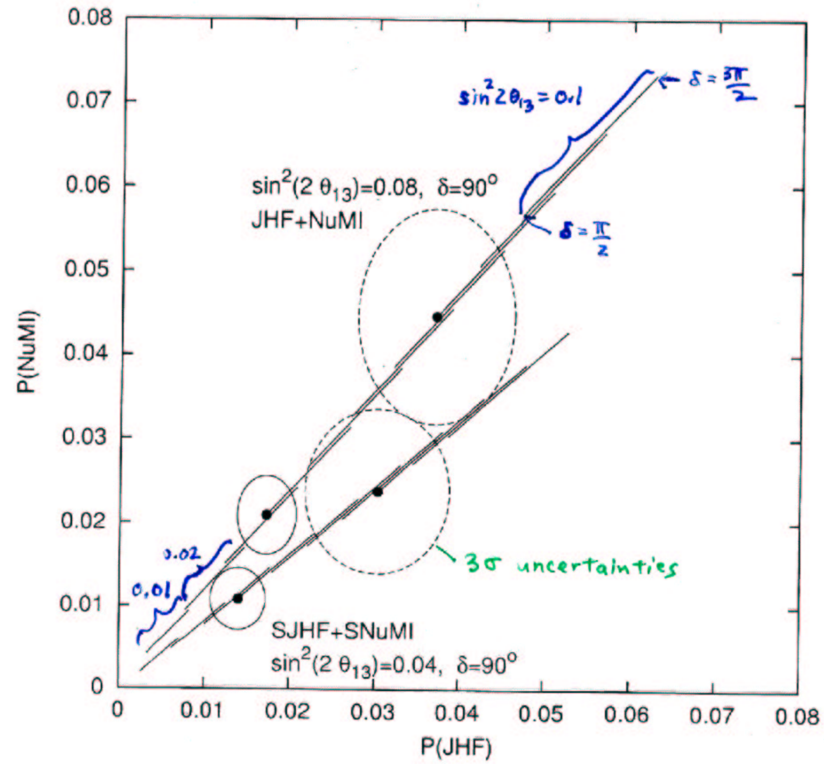
P(JHF) vs. P(NuMI)

- $\delta m^2_{31} > 0$ separated from $\delta m^2_{31} < 0$
- Substantial ambiguity in δ and θ_{13}



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SUMMARY

- Any two narrow-band appearance measurements not enough to completely determine δ and θ_{13}
- $\bar{P}$ vs. P on peak at longer L can determine $\mathrm{sgn}(\delta m^2_{31})$ if θ_{13} is not too small
  - unambiguous test of CPV
  - unambiguous measurement of θ_{13} if $\theta_{23} \simeq \pi/4$
- P_2 vs. P_1 separates $\delta m^2_{31} > 0$ from $\delta m^2_{31} < 0$, but has large uncertainty in δ and θ_{13}
- $\bar{P}$ vs. P at two different L (e.g. JHF and NuMI) can also determine $\mathrm{sgn}(\delta m^2_{31})$ if θ_{13} is not too small (combined experiments less bothered by large δm^2_{21})
- Wide-band beam offers theoretical possibility of determining $\mathrm{sgn}(\delta m^2_{31})$, θ_{13} and δ in one measurement (if $\theta_{23} \simeq \pi/4$) (must have good energy resolution and control of backgrounds)
- $(\delta, \pi - \delta)$ 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 $\theta_{23} \neq \pi/4$)
- Best way to resolve $(\theta_{23}, \frac{\pi}{2} - \theta_{23})$ ambiguity, if it exists, is via $\nu_e \to \nu_\tau$ in ν factory