Combining Superbeams

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NuFact '03

7 Jun 03

OUTLINE

I. Parameter degeneracies

II. Combining superbeams

III. Summary

3-ν mixing matrix

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

θ_{12} solar ν mixing

θ_{23} atmos. ν mixing

θ_{13} amount of $\nu_\mu \to \nu_e$ in atmos. ν

δ CP phase (Dirac)

Note: for Majorana ν's there are 2 more CP phases, unmeasurable by ν oscillations

Measuring CPV in long baseline experiments

Approx. expressions in matter

Freund
Cervera et al.

$$P(\nu_\mu \to \nu_e) = B(\cos\delta\cos\Delta - \sin\delta\sin\Delta) + C$$
$$\bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e) = \bar{B}(\cos\delta\cos\Delta + \sin\delta\sin\Delta) + \bar{C}$$
$$\Big\} \quad \delta m^2_{31} > 0$$

$$P(\nu_\mu \to \nu_e) = \bar{B}(-\cos\delta\cos\Delta - \sin\delta\sin\Delta) + \bar{C}$$
$$\bar{P}(\bar{\nu}_\mu \to \bar{\nu}_e) = B(-\cos\delta\cos\Delta + \sin\delta\sin\Delta) + C$$
$$\Big\} \quad \delta m^2_{31} < 0$$

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

$B, C, \bar{B}, \bar{C}$ 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 $E\nu$ (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

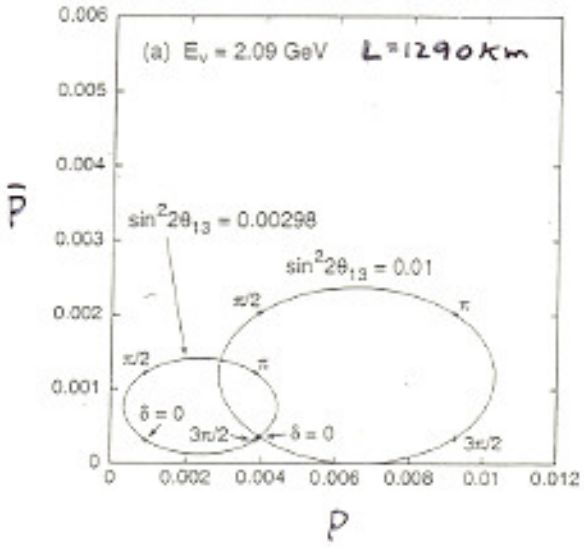
Can mix CP conserving and CP violating solutions

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

(δ, θ_{13}) ambiguity

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

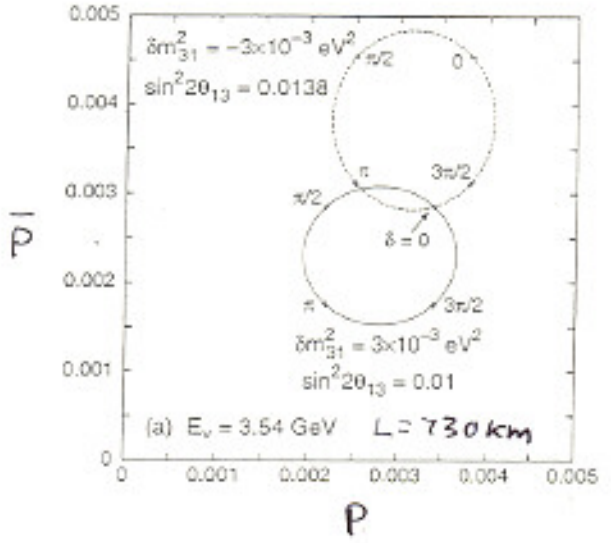
- θ_{13} and θ_{13}' can be very different
- large CPV/CPC confusion possible



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

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

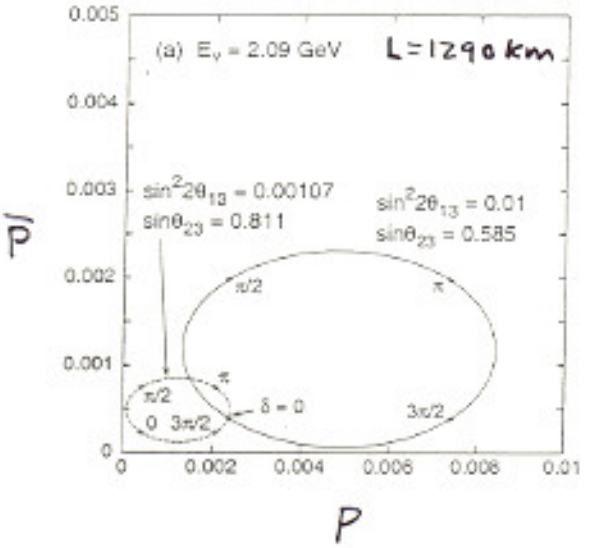
- θ_{13} and θ_{13}' are somewhat different
- large CPV/CPC confusion possible



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

Only $\sin^2 2\theta_{23}$ measured in $\nu_\mu \to \nu_\mu$
$\Rightarrow$ two solutions ($\theta_{23} < \frac{\pi}{4}$, $\theta_{23}' > \frac{\pi}{4}$)

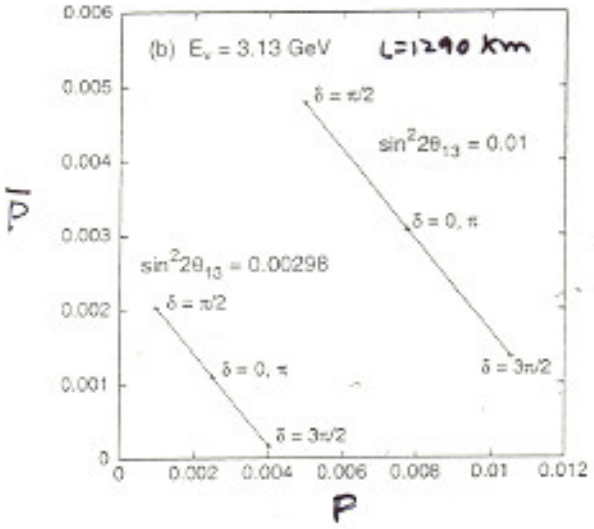
- θ_{13} and θ_{13}' can be very different
- large CPV/CPC confusion possible



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

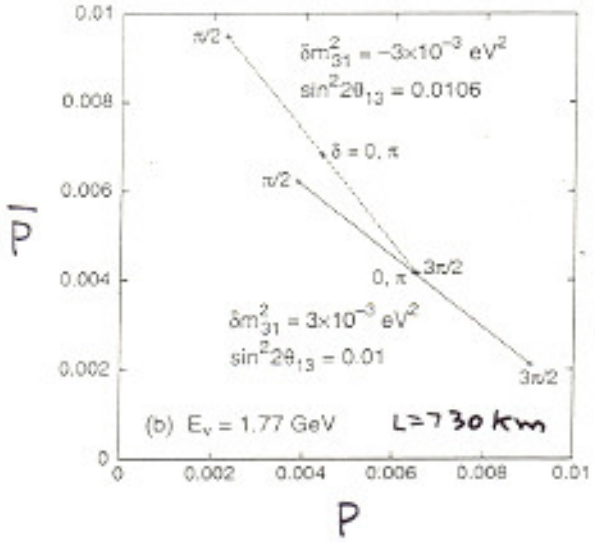
Can reduce effects of ambiguities by sitting on $\Delta \simeq (2n-1)\frac{\pi}{2}$ (on peak of leading term of vacuum oscillation)

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



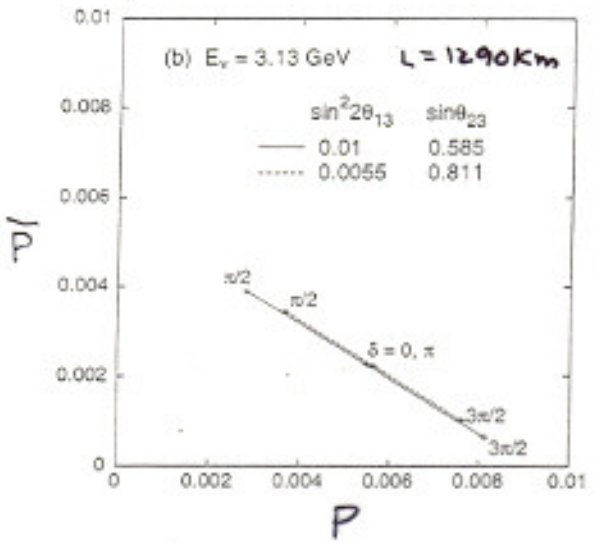
(δ, θ_{13}) ambiguity

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



Sgn (δm^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 $\delta \sim \pi/2$



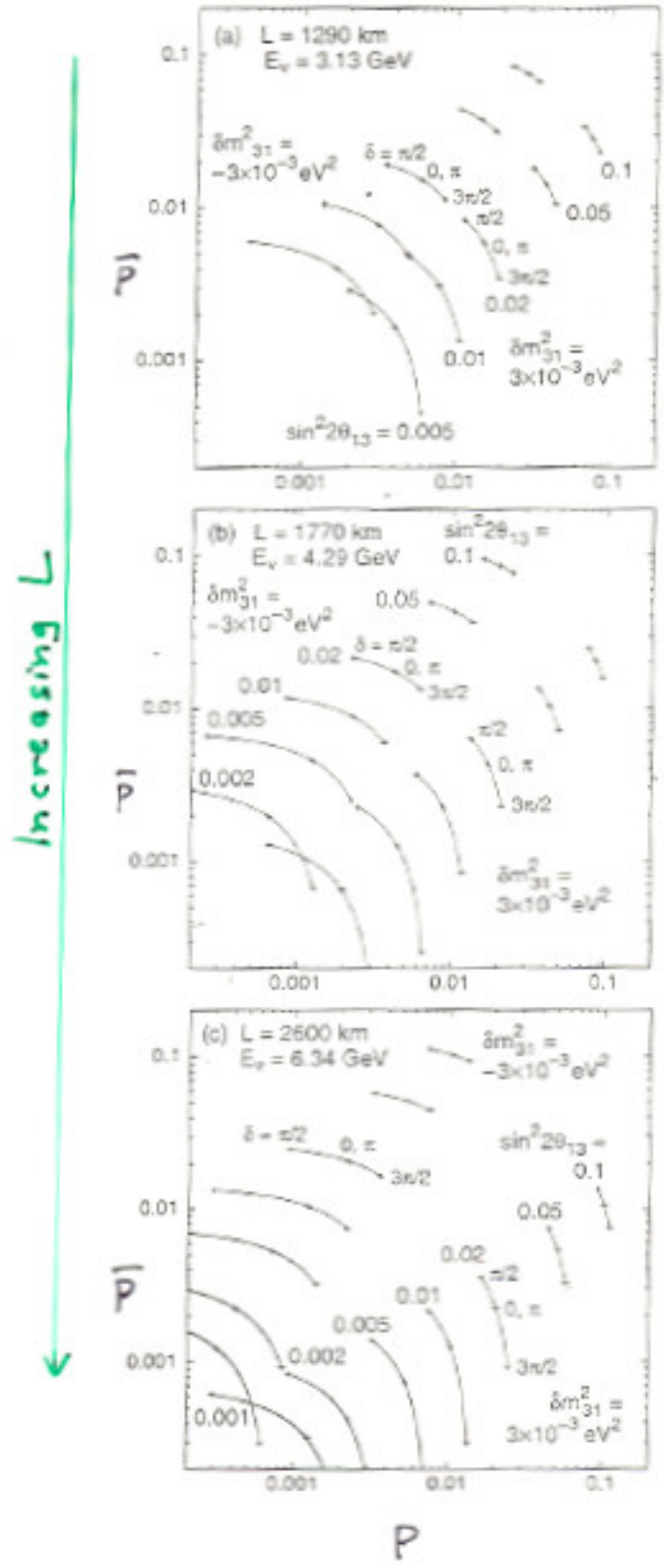
$(\theta_{23}, \frac{\pi}{2}-\theta_{23})$ ambiguity

- $\sin^2 2\theta'_{13} \simeq \sin^2 2\theta_{13} \tan^2\theta_{23}$
  (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 $\theta_{23} \simeq \frac{\pi}{4}$

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

- Choose $\Delta = \frac{\pi}{2}$ (peak) $\quad \frac{L}{E} \simeq 500 \frac{\text{km}}{\text{GeV}} \left(\frac{2.5 \times 10^{-3} \text{eV}^2}{\delta m^2_{31}} \right)$
- Choose longer L

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



Another interesting scenario :

Barger, Marfatia, KW
PRD 65, 073023 (2002)
[hep-ph/0112119]

Huber + Winter, hep-ph/0301257
(Nu Fact)

Asratyan et al., hep-ph/0303023
(superbeam)

- Choose $\sqrt{2} G_F N_e L = \pi$ $\left(L \simeq 7600 \text{ km}\right)$
  - all δ, δm^2_{21} dependence drops (for <u>any</u> $\delta m^2_{31}, \theta_{23}, \theta_{13}, E_\nu$)
  - $P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\Delta$
  - no (δ, θ_{13}) degeneracy
  - measure θ_{13} (modulo θ_{23} ambiguity)

- Combine with another baseline for δ measurement

- Decouples θ_{13} from (δ, θ_{13}) ambiguity (like reactor measurement)
  but <u>not</u> from θ_{23} ambiguity (unlike reactor measurement)

What if available experimental setups don't have $L > 1000$ km?

e.g. JHF-SuperK 300 km

NuMI-Soudan ~730 km

Neither one is sufficient ensure determination of $\mathrm{sgn}(\delta m^2_{31})$ unless θ_{13} is near CHOOZ bound (maybe not even then for large δm^2_{21})

How well can you do by combining two superbeams?

Many studies have been done...

e.g. SJHF to SuperK 4 MW, 22.5 kt

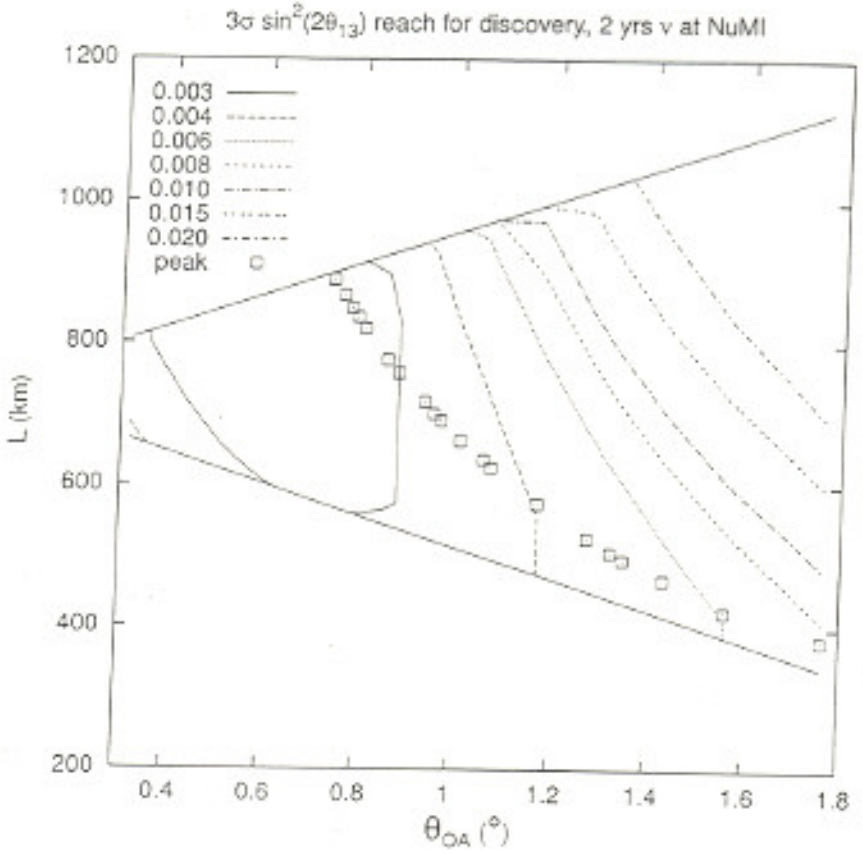
2 yrs ν, 6 yrs $\bar{\nu}$

Barger, Marfatia, Whisnant PLB 560, 75 (2003) [hep-ph/0210428]

SNuMI towards Soudan 1.6 MW, 20 kt

2 yrs ν, 5 yrs $\bar{\nu}$

Choose off-axis angle, L to optimize physics goals

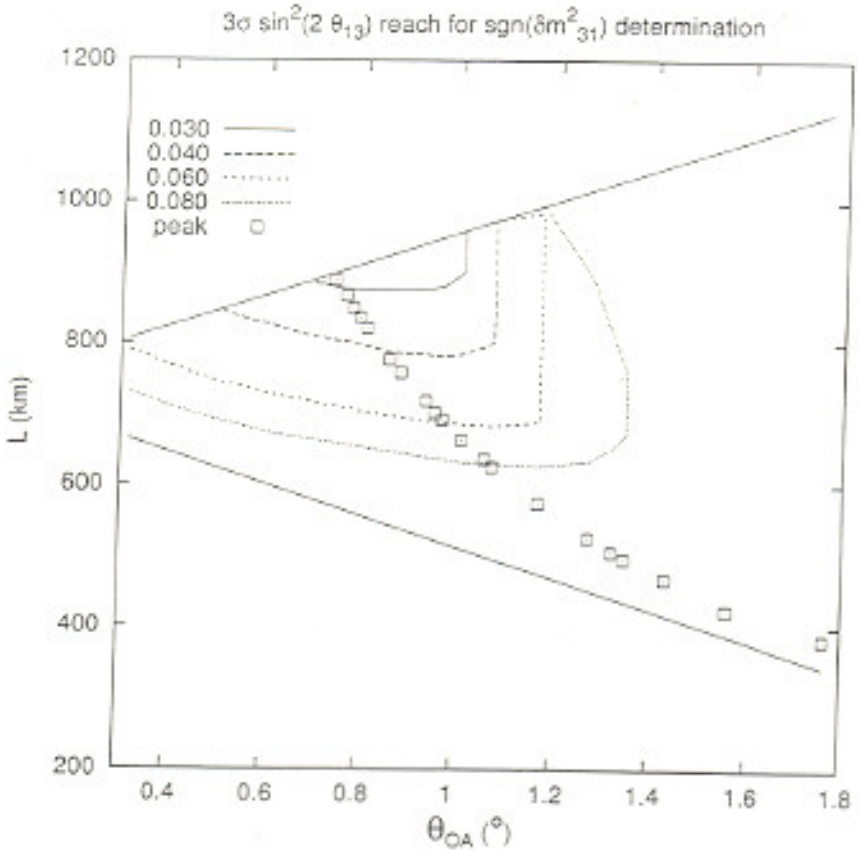


SNuMI

basic discovery reach

(2 yrs with ν beam)

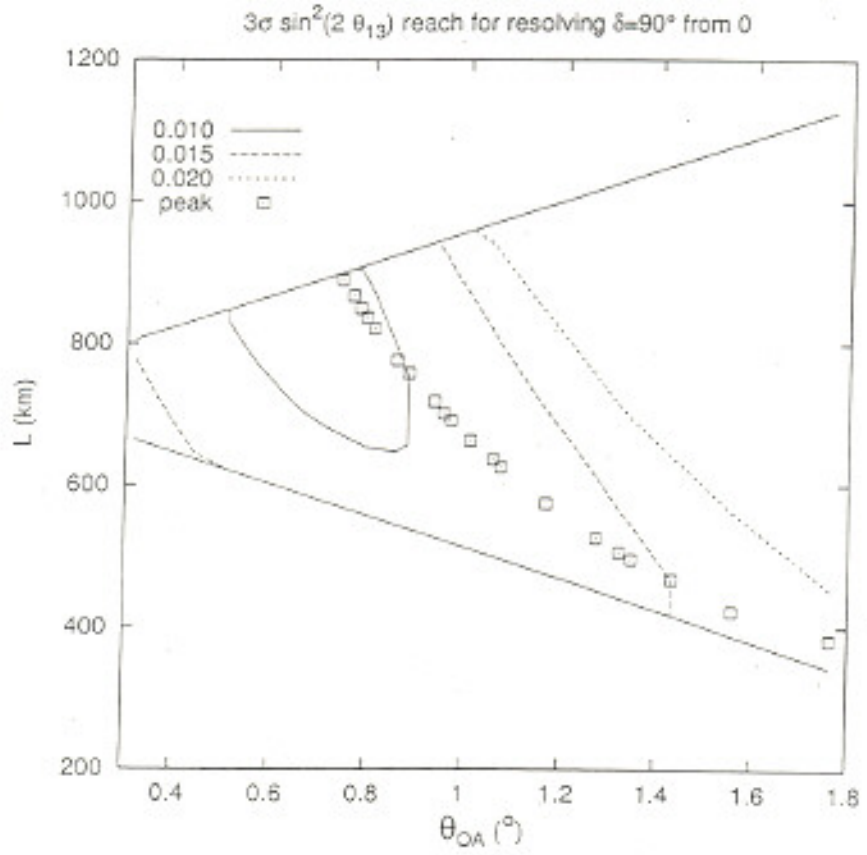
(best case; varies with δ)



SNuMI+SJHF (ν+ν̄)

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

Longer L for SNuMI is better

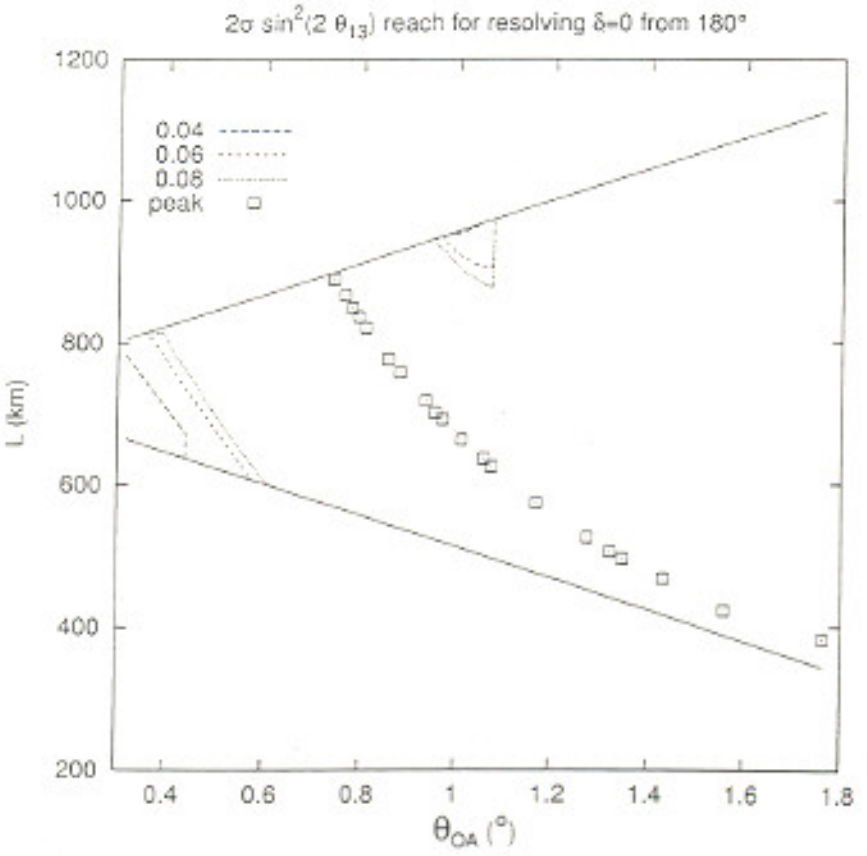


SNuMI +SJHF ($\nu+\bar{\nu}$)

CPV sensitivity

SNuMI best near peak

Larger L preferred



SNuMI +SJHF ($\nu+\bar{\nu}$)

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

SNuMI best off peak

(need some $\cos\delta$ dependence)

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

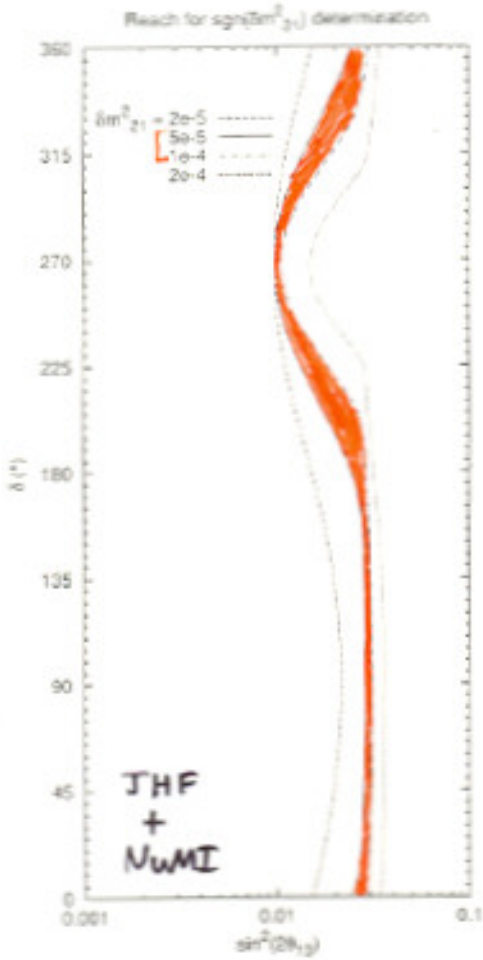
SJHF @ 295 km + SNuMI @ $\theta_{OA} = 0.7\text{-}0.8°$, $L \simeq 900$ km

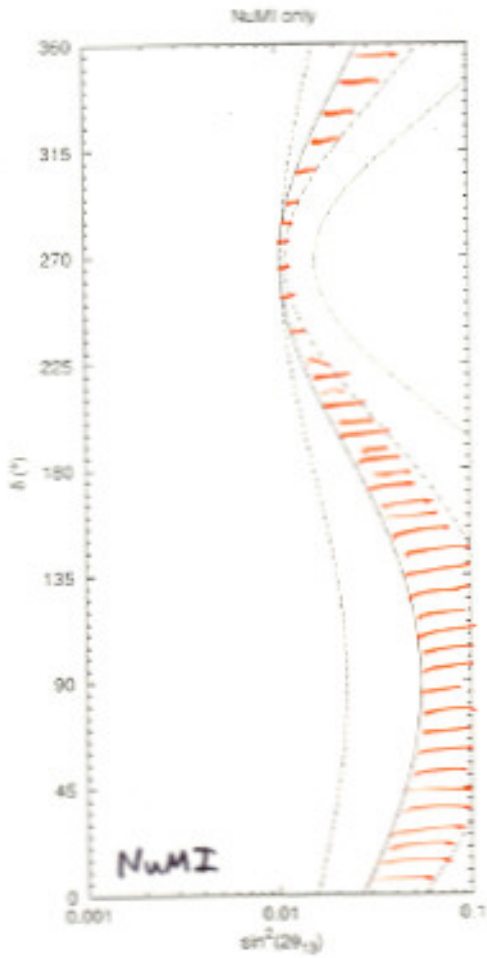
- both on peak
- leave $(\delta, \pi - \delta)$ ambiguity for a future measurement

⇒ Same NuMI parameters as in Barenboim, De Gouvea, Szleper, Velasco
(maximized for θ_{13}, CPV sensitivity)
Also good for $sgn(\delta m^2_{31})$ determination when combined w/ JHF

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

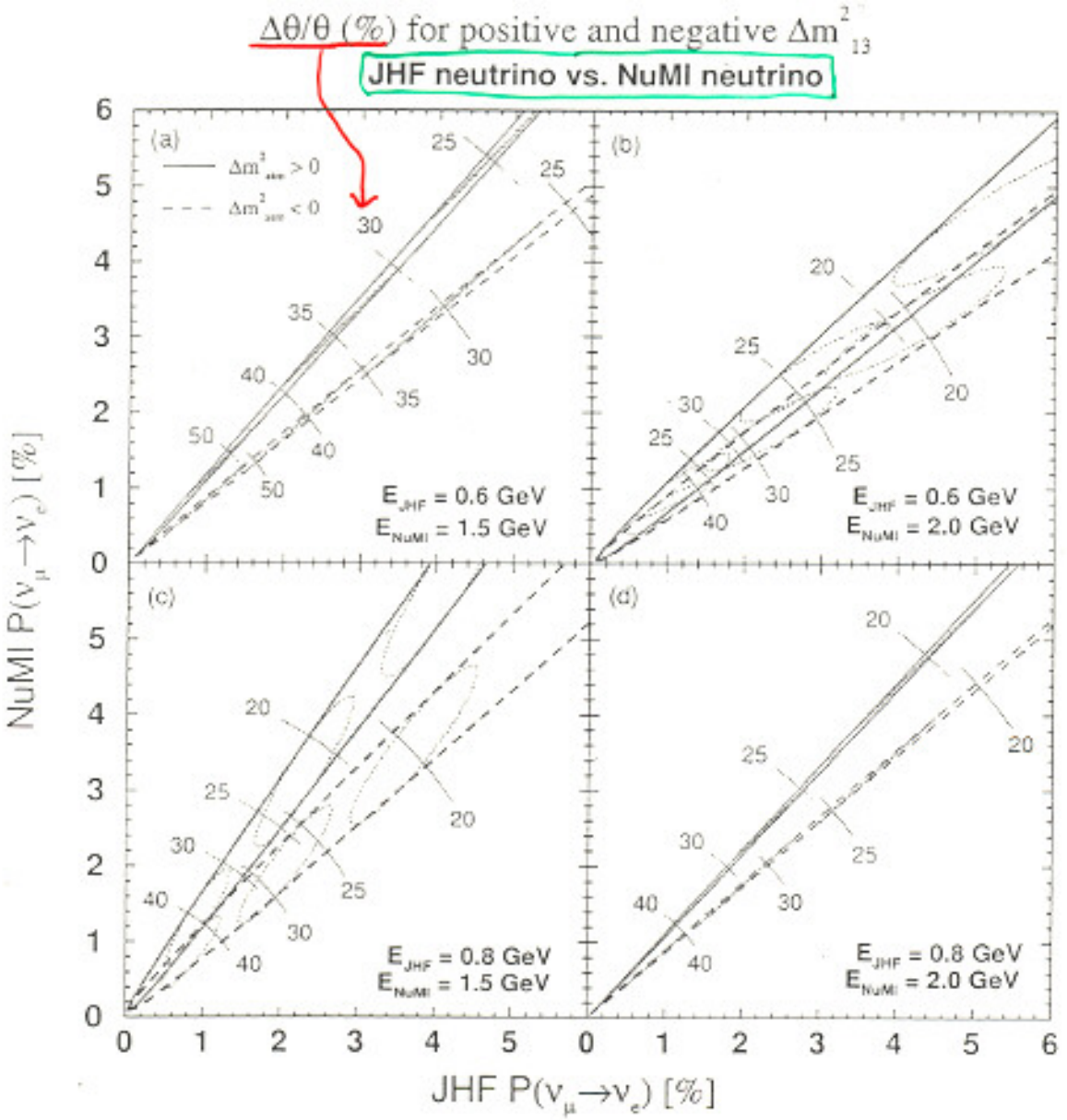
Measurements at different L greatly reduces δm^2_{21} effect





What can you do with only one measurement each at JHF + NuMI? 12

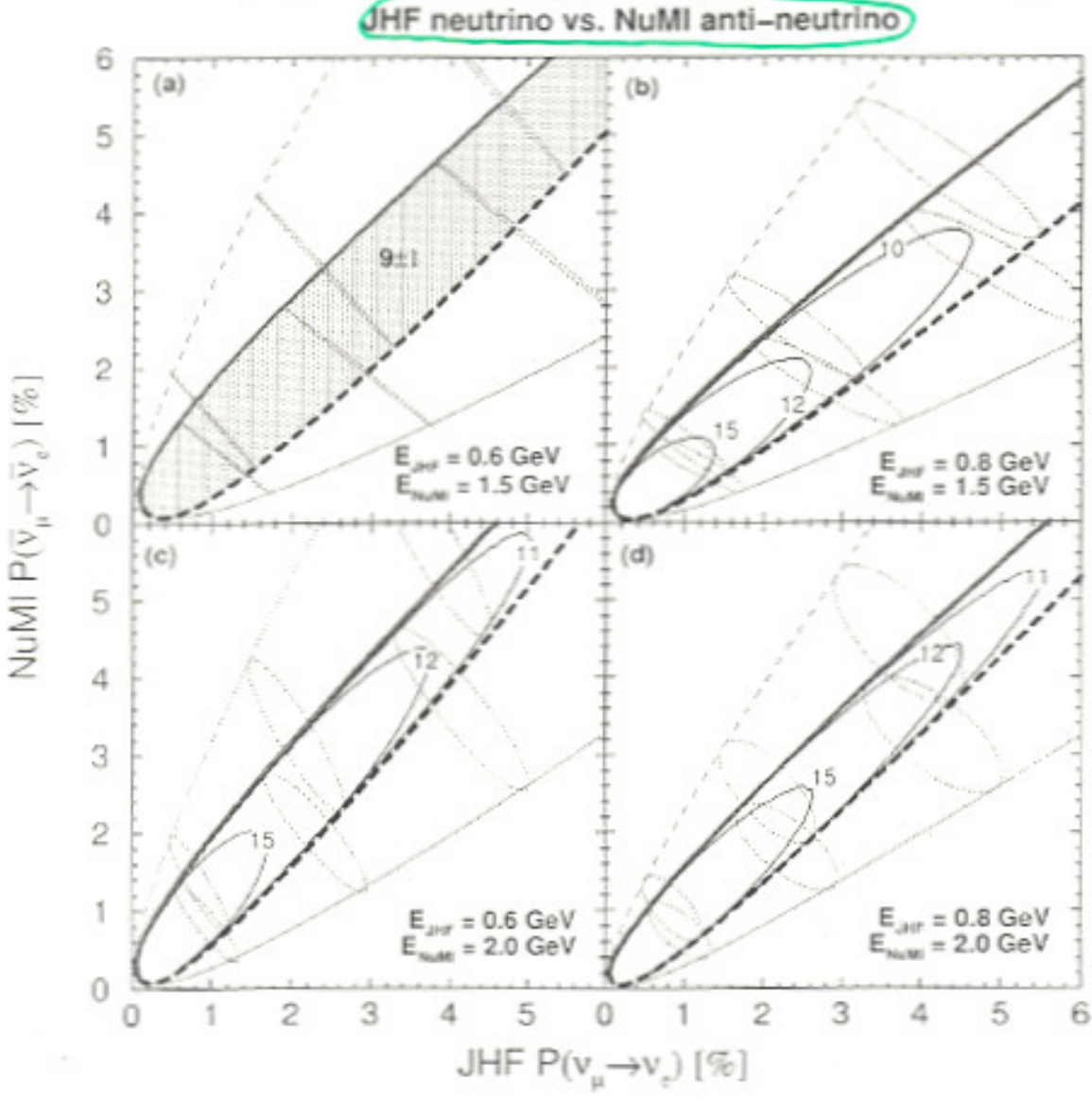
e.g. Minakata, Nunokawa + Parke
hep-ph/0301210



- Possibility to determine $\mathrm{sgn}(\delta m^2_{31})$
- However, large uncertainty in θ_{13} and δ

Minakata, Munokawa, Parke

$\Delta\theta/\theta$ [%] in the overlap region of different signs of Δm^2_{13}

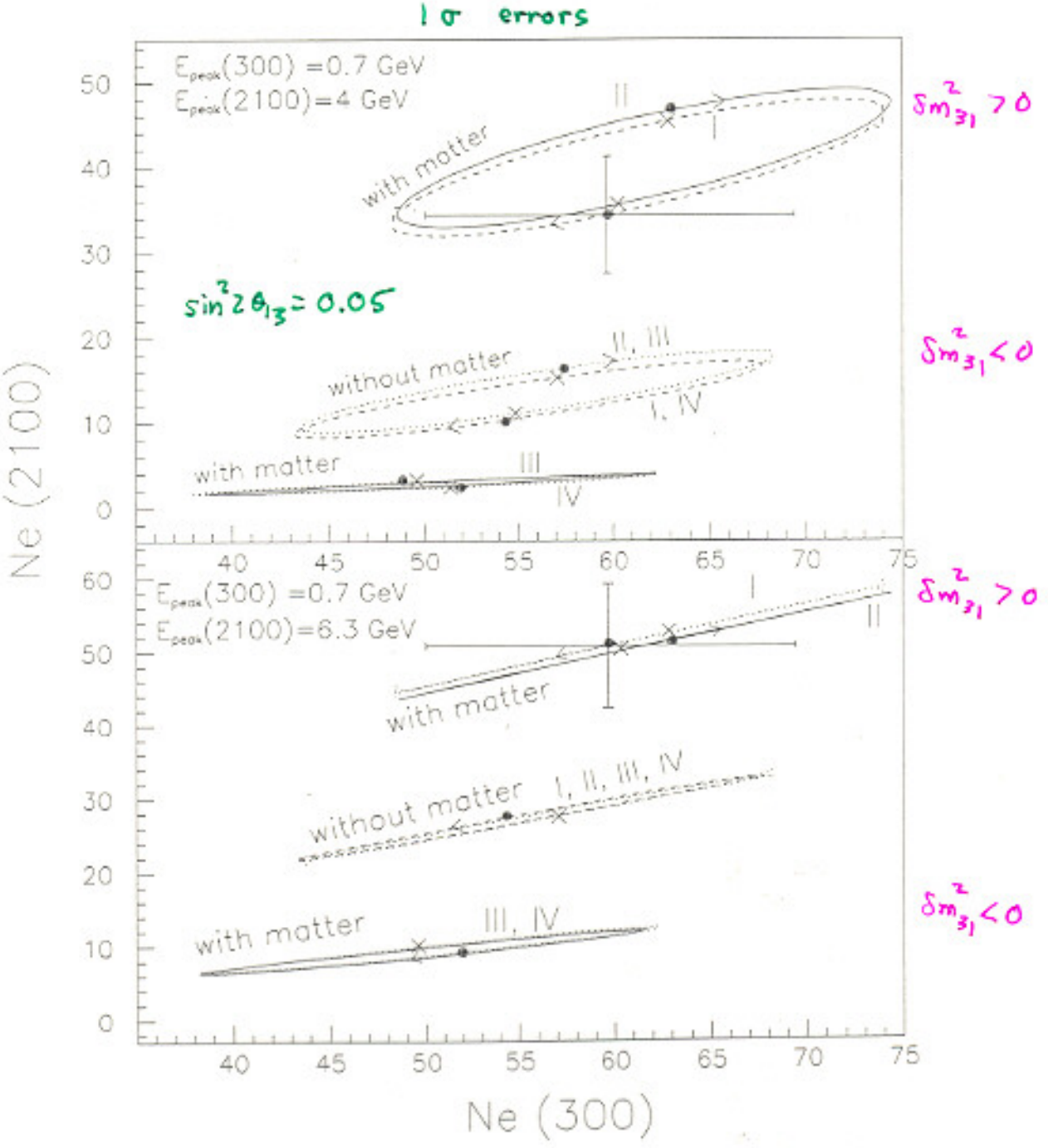


- Lose $\mathrm{sgn}(\delta m^2_{31})$ sensitivity in overlap region
- Theoretical uncertainty (due to ambiguity) of θ_{13} is 10% ($\sin^2 2\theta_{13}$ to 20%)
- $\sin\delta$ not determined if $\mathrm{sgn}(\delta m^2_{31})$ ambiguity remains
- Similar to ν and $\bar{\nu}$ at a single machine, except they can be done simultaneously

Increase 2nd baseline

Wang, KW, Xiong Yang, Young
PRD 65, 073021 (2002)
[hep-ph/0111317]

ν	JHF to Kamioka	300 km	100 kt × 5 yr	0.8 MW
ν	JHF to Beijing	2100 km	100 kt × 5 yr	0.8 MW



0.8 MW JHF, 22.5 kt, 5yrs
0.4 MW NuMI, 17 kt, 5yrs

Huber, Lindner, Winter '15
NPB 654, 3 (2003)
[hep-ph/0211300]

Sensitivity to $\mathrm{sgn}(\delta m^2)$

	No.	JHF-SK ν	JHF-SK $\bar{\nu}$	JHF-SK Sensitivity	NuMI ν	NuMI $\bar{\nu}$	NuMI L [km]	NuMI Sensitivity	Combined Label	Combined Sensitivity
	1	1	0	None	1	0	712	None	$712\nu\nu$	None
*	2	1	0	None	1	0	890	None	$890\nu\nu$	Good
*	3	1	0	None	1	0	950	None	$950\nu\nu$	Good
	4	2/8	6/8	None	2/7	5/7	712	Marginal	712cc	Marginal
	5	2/8	6/8	None	2/7	5/7	890	Marginal	890cc	Poor
*	6	2/8	6/8	None	2/7	5/7	950	Marginal	950cc	Good ←
	7	1	0	None	0	1	712	None	$712\nu\bar{\nu}$	Marginal
	8	1	0	None	0	1	890	None	$890\nu\bar{\nu}$	Poor
	9	1	0	None	0	1	950	None	$950\nu\bar{\nu}$	Poor
	10	0	1	None	1	0	712	None	$712\bar{\nu}\nu$	Marginal
	11	0	1	None	1	0	890	None	$890\bar{\nu}\nu$	Poor
	12	0	1	None	1	0	950	None	$950\bar{\nu}\nu$	Poor

↑

Combining JHF + NuMI helps considerably

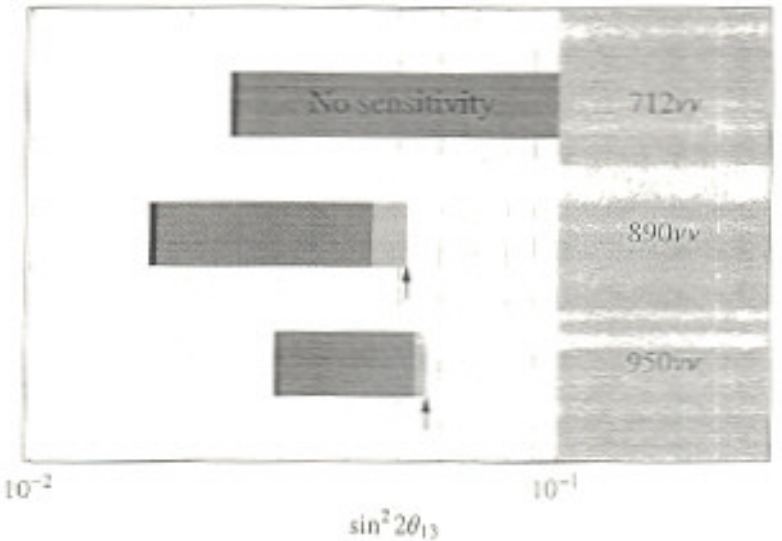
↓

Sensitivity to maximal CPV

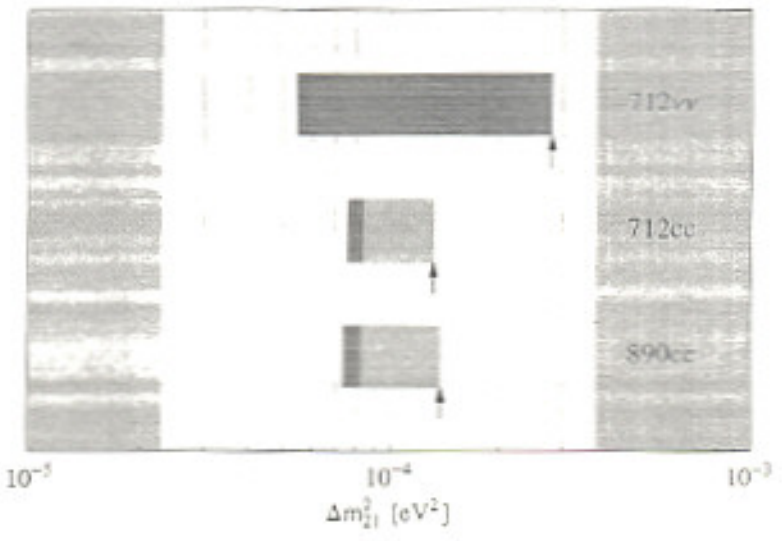
	No.	JHF-SK ν	JHF-SK $\bar{\nu}$	JHF-SK Sensitivity	NuMI ν	NuMI $\bar{\nu}$	NuMI L [km]	NuMI Sensitivity	Combined Label	Combined Sensitivity
	1	1	0	None	1	0	712	None	$712\nu\nu$	Poor
	2	1	0	None	1	0	890	None	$890\nu\nu$	Poor
	3	1	0	None	1	0	950	None	$950\nu\nu$	Poor
*	4	2/8	6/8	None	2/7	5/7	712	None	712cc	Good
*	5	2/8	6/8	None	2/7	5/7	890	None	890cc	Good
*	6	2/8	6/8	None	2/7	5/7	950	None	950cc	Suboptimal ←
*	7	1	0	None	0	1	712	None	$712\nu\bar{\nu}$	Good
*	8	1	0	None	0	1	890	None	$890\nu\bar{\nu}$	Good
*	9	1	0	None	0	1	950	None	$950\nu\bar{\nu}$	Suboptimal
	10	0	1	None	1	0	712	None	$712\bar{\nu}\nu$	Poor
	11	0	1	None	1	0	890	None	$890\bar{\nu}\nu$	Poor
	12	0	1	None	1	0	950	None	$950\bar{\nu}\nu$	Poor

Huber, Lindner, Winter

Sensitivity to sgn (Δm^2_{31}) for JHF–SK & NuMI



Sensitivity to CP violation for JHF–SK & NuMI



Summary for JHF + NuMI (without upgrades)

Huber, Lindner, Winter

- Combining JHF and NuMI gives results not achievable by one experiment alone
- For LMA-1 , sensitive to $\mathrm{sgn}(\delta m^2_{31})$ with ν running
- For LMA-2 , sensitive to CPV with $\nu + \bar{\nu}$ running

What can you do with 3 measurements?

Theoretical studies show 3 measurements can push degeneracies below $\sin^2 2\theta_{13} = 0.01$ Barger, Marfatia, KW PRD 66, 053007 (2002) [hep-ph/0206038]

e.g. Aoki, Hagiwara + Okamura
PLB 554, 121 (2003) [hep-ph/0208223]

JHF to HyperK (0.8 MW, 295 km, 1000 kt)

Narrow-band beams

$E_\nu = 0.86$ GeV	1 yr
$E_\nu = 1.29$ GeV	1 yr
$E_{\bar{\nu}} = 0.86$ GeV	4 yrs

- Good determination of θ_{13} and δ for $\sin^2 2\theta_{13} \geq 0.01$
- L too short for $\mathrm{sgn}(\delta m^2_{31}) \Rightarrow$ two (δ, θ_{13}) solutions
- Must determine $\mathrm{sgn}(\delta m^2_{31})$ elsewhere to complete the picture

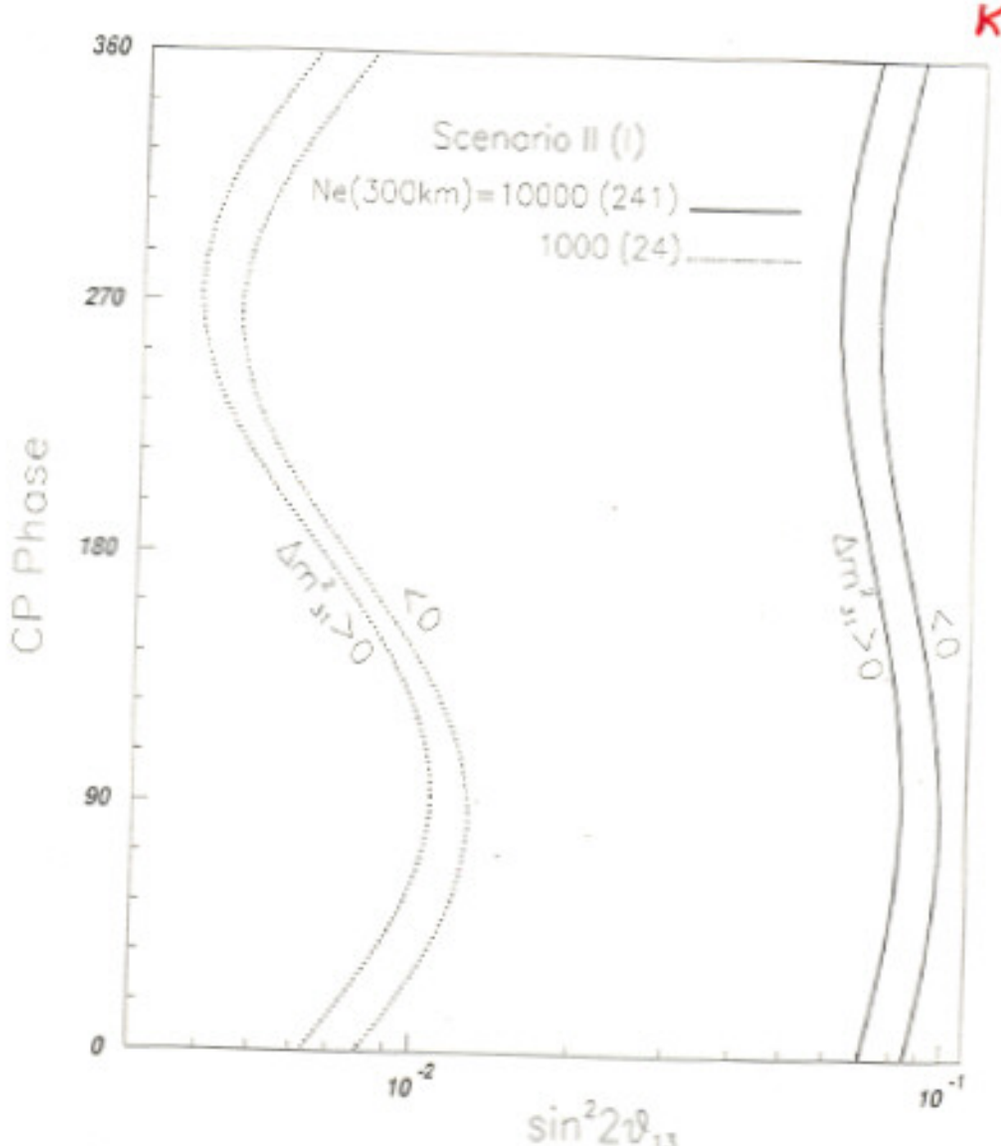
Another 3-measurement scenario

KW, Yang, Young
PRD 67, 013004 (2003)
[hep-ph/0208193]

	II	I
JHF to Kamioka	450 kt × 2 yr	(22.5 kt × 5 yr)
	4.0 MW	(0.8 MW)

Single measurement of $\nu_\mu \to \nu_e$ does not fix θ_{13}, δ, or $\mathrm{sgn}(\delta m^2_{31})$

KW, Yang, Young



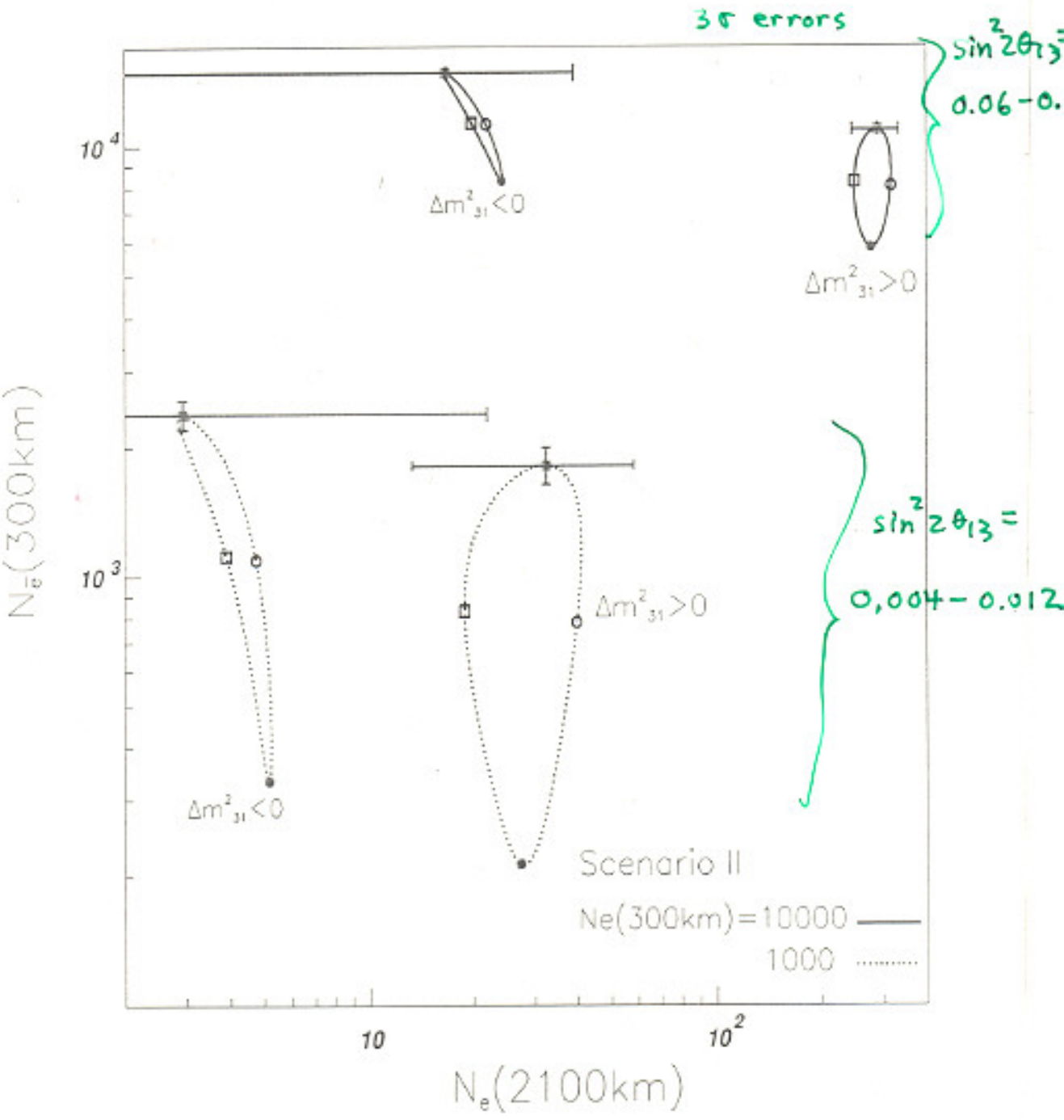
JHF to Kamioka	$\nu_\mu \to \nu_e$	450 kt × 2 yr	4 MW	0.7 GeV
	$\bar{\nu}_\mu \to \bar{\nu}_e$	450 kt × 6 yr	4 MW	0.7 GeV
JHF to Beijing	$\nu_\mu \to \nu_e$	100 kt × 5 yr	4 MW	4 GeV

Good determination of $\sin\delta$, θ_{13}

Can resolve $\mathrm{sgn}(\delta m^2_{21})$ in most cases

Can't tell δ from $\pi - \delta$

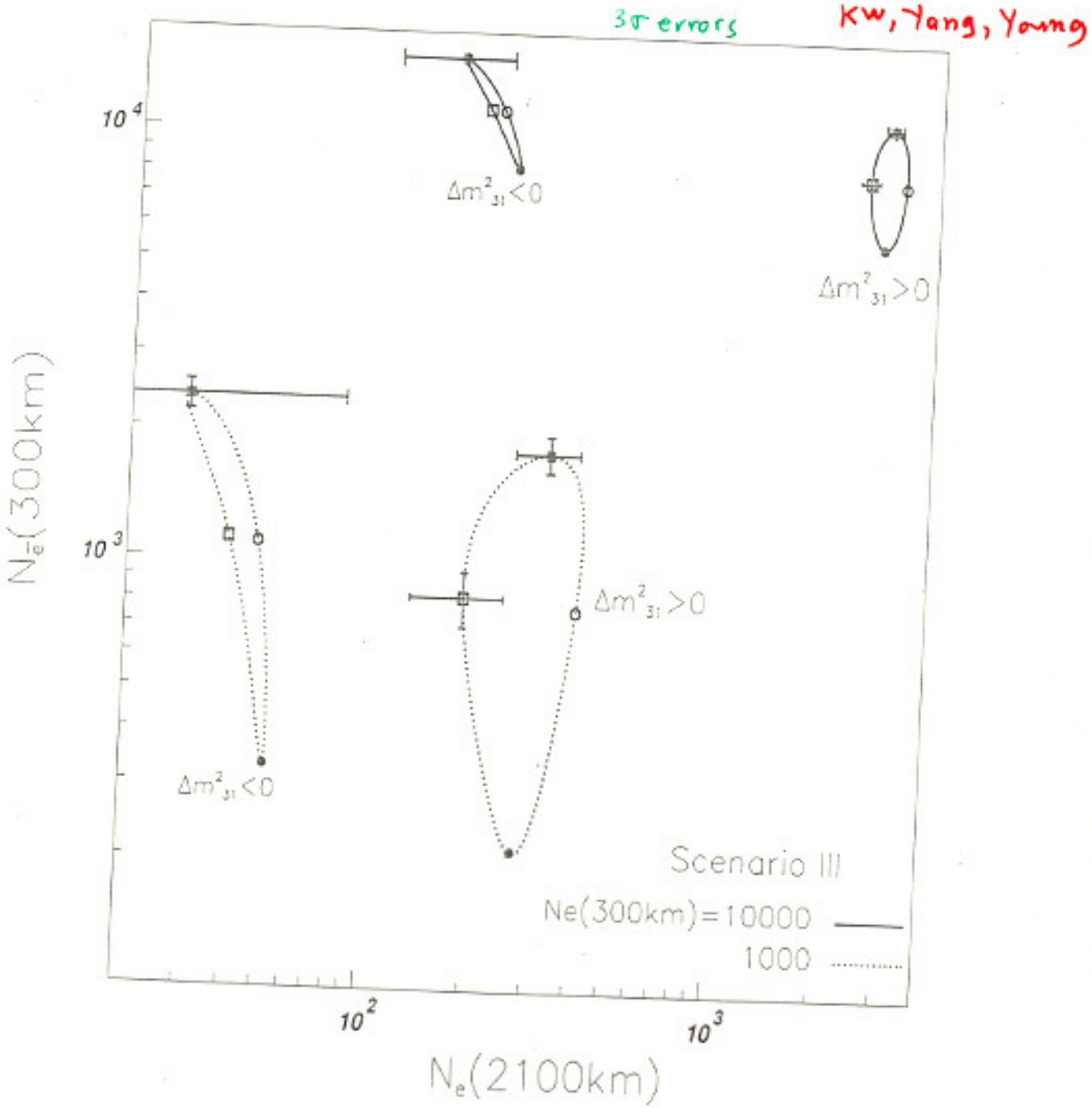
KW, Yang, Young



Now increase size of Beijing detector to 1000kt × 5yr

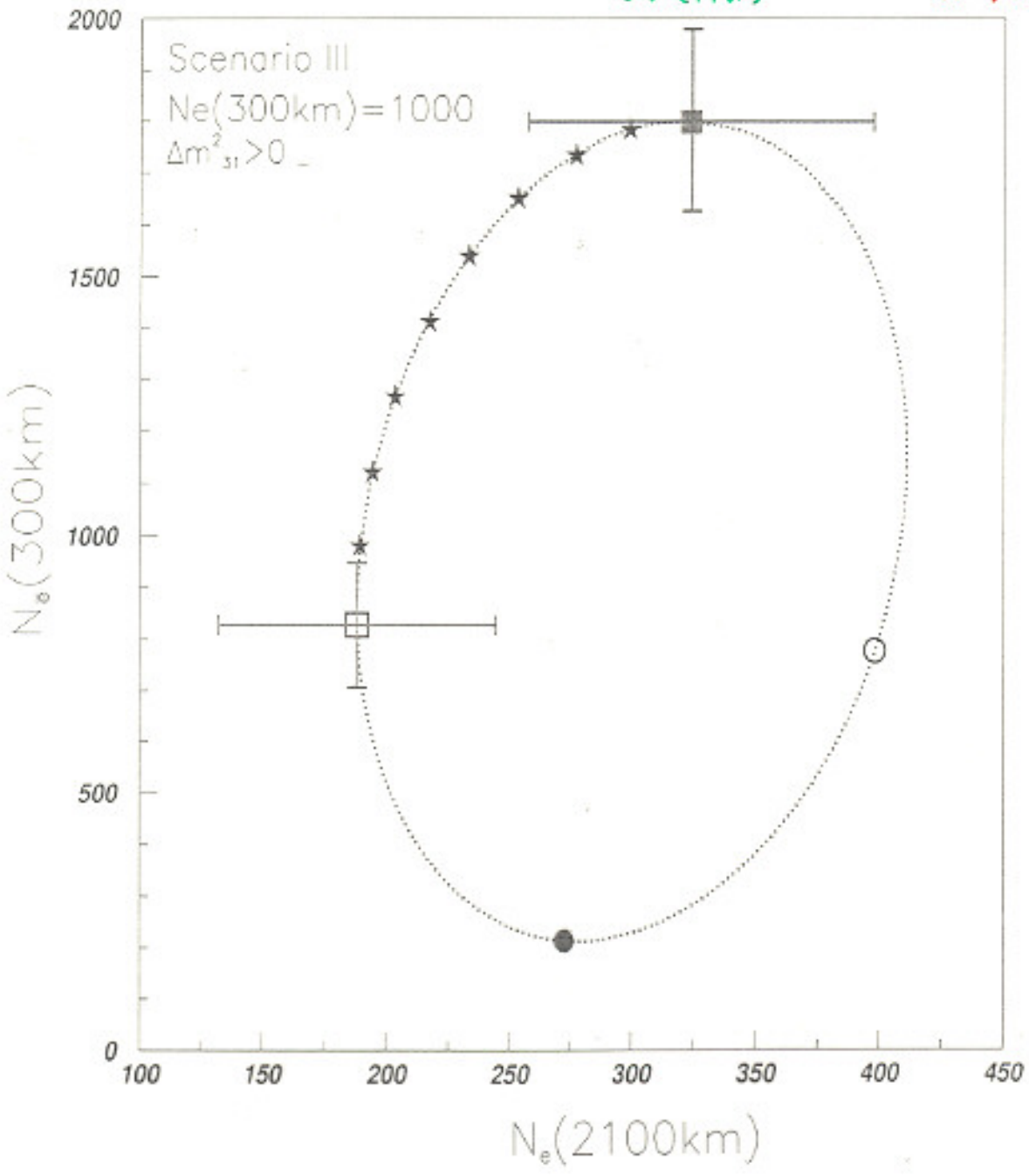
$(\delta, \pi-\delta)$ ambiguity resolved

$\delta, \theta_{13}, \mathrm{sgn}(\delta m^2_{31})$ determined



3σ errors

KW, Yang, Young



SUMMARY

- Emphasize complementarity over competition

  $1+1 > 2$ for superbeams

  Combining two superbeam experiments may be able to determine $\mathrm{sgn}(\delta m^2_{31})$ even if they can't do so separately

- Two special baselines help overcome degeneracies

  $L/E \simeq 500 \frac{\mathrm{km}}{\mathrm{GeV}} \left(\frac{2.5\times10^{-3}\mathrm{eV}^2}{\delta m^2_{31}} \right)$

  $\cos\delta$ dependence vanishes
  θ_{13} decouples from (δ, θ_{13}) ambiguity
  measure $\sin^2\theta_{23}\sin^2 2\theta_{13}$ and $\sin\delta$

  $L \simeq 7600$ km

  no δ and δm^2_{21} dependence
  measure $\sin^2\theta_{23}\sin^2 2\theta_{13}$

- Two experiments at different baselines (e.g., JHF + NuMI) may be able to determine $\mathrm{sgn}(\delta m^2_{31})$ with only ν's for $\sin^2 2\theta_{13} \geq 0.05$

- Two experiments at different baselines (e.g. SJHF + SNuMI) may be able to find CPV and determine $\mathrm{sgn}(\delta m^2_{31})$ with ν and $\bar{\nu}$ for $\sin^2 2\theta_{13} \geq 0.03$ (modulo θ_{23} ambiguity)

  - $\mathrm{sgn}(\delta m^2_{31})$ determination much less sensitive to size of δm^2_{21}
  - JHF + NuMI (no upgrade) sensitive to CPV only for LMA-2

- Measuring ν and $\bar{\nu}$ at shorter L (e.g., 300 km) and ν at longer L (e.g., 2100 km) can determine $\theta_{13}, \delta, \mathrm{sgn}(\delta m^2_{31})$ for $\sin^2 2\theta_{13} \geq 0.01$ (modulo θ_{23} ambiguity)

Final remark: Making more than the minimal number of measurements serves as a vital check