PROSPECTS FOR DETERMINING NEUTRINO PARAMETERS IN LONG-BASELINE EXPERIMENTS

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Assume 3 $\nu$'s

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

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

CP Violation

- $P(\nu_e \rightarrow \nu_\mu) \neq \overline{P}(\nu_e \rightarrow \nu_\mu)$ in vacuum
- Matter affects $\nu$ and $\bar{\nu}$ differently
  $P(\nu_e \rightarrow \nu_\mu) \neq \overline{P}(\nu_e \rightarrow \nu_\mu)$ even if no intrinsic CPV
- $\delta$ = mass splittings
  $\delta_3$ enhances $P$; $\delta_1$ enhances $\overline{P}$
- Detection of CPV not easy
  Can use matter effect to determine mass ordering

Both intrinsic CPV and matter effects require $\delta_{13} \neq 0$
Measuring CPV in long baseline experiments

Approximated expressions in matter

\[ P(\nu_e \rightarrow \nu_e) = B \left( \cos \delta \cos \Delta - \sin \delta \sin \Delta \right) + C \]
\[ \Delta \approx \begin{cases} \delta m_{31}^2 > 0 \\ \delta m_{31}^2 < 0 \end{cases} \]

\[ P(\nu_x \rightarrow \nu_e) = \overline{B} \left( -\cos \delta \cos \Delta - \sin \delta \sin \Delta \right) + \overline{C} \]

\[ \Delta = \frac{18 m_{31}^2 \cdot L}{4 E} = 1.27 \frac{\delta m_{31}^2}{E^2} \left( \frac{L}{m_{ee}} \right) \left( \frac{E}{\text{GeV}} \right) \]

- \( B, \overline{B}, C, \overline{C} \) depend on \( \nu \) mixing angles
- \( B, \overline{B} \) enhanced in matter
- \( C, \overline{C} \) suppressed in matter
- Intrinsic CPV from \( \sin \delta \) term
- Matter-induced CPV from \( B \neq \overline{B}, C \neq \overline{C} \)

Measure \( P \) and \( \overline{P} \) at one \( L \) and \( E \) (e.g., with a conventional narrow band \( \nu \) beam)

=> determine 2 unknowns \( \theta_{13} \) and \( \delta \) (in principle)

Problem: Three possible 2-fold parameter degeneracies

- Can mix CP conserving and CP violating solutions

Fix \( \theta_{13} \), plot \( P \) vs. \( \overline{P} \) as \( \delta \) varies \( \Rightarrow \) ellipse

- \( (\delta, \theta_{13}) \) ambiguity
- Ellipses for different \( \theta_{13} \) overlap
- \( (\delta, \theta_{13}) \) and \( (\delta', \theta_{13}') \) give same \( P + \overline{P} \)
- \( \theta_{13} \) and \( \theta_{13}' \) can be very different
- Large CPV/CPC confusion possible

Syn (\( \delta m_{31}^2 \)) ambiguity

- Ellipses for \( \delta m_{31}^2 > 0 \) and \( \delta m_{31}^2 < 0 \) overlap
- Different due to matter effects
- \( \theta_{13} \) and \( \theta_{13}' \) are somewhat different
- Large CPV/CPC confusion possible

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

- Only \( \sin^2 2\theta_{23} \) measured in \( \nu_x \rightarrow \nu_x \)
- 2 solutions \( (\theta_{23} < \frac{\pi}{4}, \theta_{23} > \frac{\pi}{4}) \)
- \( \theta_{13} \) and \( \theta_{13}' \) 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

$(\delta, \delta_{13})$ ambiguity

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

$\text{sgn}(\delta_{13})$ ambiguity

- $\delta_{13}$ uncertainty is small
- large CPV/CPC confusion can remain
- ambiguity avoided:
  - for $\delta_{13} > 0$ if $\delta \sim \frac{\pi}{2}$
  - for $\delta_{13} < 0$ if $\delta \sim \frac{\pi}{2}$

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

- $\sin^2 \theta_{13} \simeq \sin \theta_{13} \tan \theta_{23}$
- (for $\sin^2 \theta_{23} \approx 0.9$)
- $\sin^2 \theta_{13} \simeq \frac{1}{2} \sin^2 \theta_{13}$
- CPV/CPC confusion small
- Vanishes for $\theta_{23} \approx \frac{\pi}{4}$

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

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

$\Rightarrow$ $\text{sgn}(\delta_{13})$ determined if $\theta_{13}$ large enough

- small CPV/CPC confusion for any $\theta_{23}$
- residual $(\delta, \Pi - \delta)$ ambiguity
- $\theta_{13}$ uniquely determined if $\theta_{23} \approx \frac{\pi}{4}$
Super JHF to Hyper-K
$L = 300 \text{ km}$, $E = 0.7 \text{ GeV}$

\[ \Delta \approx \frac{\pi}{2} \text{ reduces } (\delta, \theta_{13}) \text{ ambiguity to simple } (\delta, \pi - \delta) \text{ ambiguity} \]

$L = 300 \text{ km}$ not long enough to always resolve $\text{sgn}(\delta m_{31}^2)$

$\theta_{13}$ ambiguity still possible

What else can be done?

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

- One $\nu$ and one $\bar{\nu}$ measurement $\Rightarrow$ degeneracies exist over wide areas of $(\delta, \theta_{13})$ parameter space
- Additional measurements needed to eliminate degeneracies
- $3^{rd}$ measurement reduces region where degeneracies occur to lines in $(\delta, \theta_{13})$ plane
- $4^{th}$ measurement reduces degeneracies to isolated points

\[ \nu, \bar{\nu} @ \Delta = \frac{\pi}{2} \text{ Area between solid lines} \]
\[ \nu @ \Delta = \frac{\pi}{3} \text{ Along dashed curves} \]
\[ \bar{\nu} @ \Delta = \frac{\pi}{3} \text{ Boxes only} \]

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 longer L reduce degeneracies
(larger matter effects help resolve \(\text{sgn}(\Delta m^2_{31})\) ambiguity)

\[
\begin{align*}
\nu @ \Delta &= \frac{\pi}{2} \text{ and } \frac{\pi}{3} \\
\bar{\nu} @ \Delta &= \frac{\pi}{2} \text{ and } \frac{\pi}{3}
\end{align*}
\]

Measurements at different 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 \(\theta_{13}\) than 4 at a single L

How can this be put into practice?

**Off-axis Beams**

- 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 \(E\nu\)

\[
E\nu \propto \frac{1}{1 + \gamma \theta_{0A}^2} \quad \bar{E}\nu \propto \frac{E\nu}{L^2}
\]

Multiple detectors (detector cluster) allow more than one measurement at a time
Combine data from different experiments

Realistic scenario: (Superbeams)

- JHF to Super-K
  - 4 MW (5 x original JHF)
  - 2 yrs \( \nu \), 6 yrs \( \bar{\nu} \)
  - \( L = 245 \text{ km} \), \( E_{\nu} = 0.70 \text{ GeV} \)
  - (near peak for \( \delta m^2_{31} \approx 3 \times 10^{-3} \text{ eV}^2 \))
  - \( 22.5 \) kt

- FNAL aimed at SOUDAN
  - 1.6 MW (4x original) NuMI
  - 2 yrs \( \nu \), 5 yrs \( \bar{\nu} \)
  - \( \theta_{13} \approx ? \) (\( L \approx ? \), \( E_{\nu} \approx ? \))
  - \( 20 \) kt

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

What is best \( \theta_{13} \) (\( \Rightarrow L, E_{\nu} \)) for NuMI, when used in conjunction with JHF?

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

Assume: \( |\delta m^2_{31}| = 3 \times 10^{-3} \text{ eV}^2 \), \( \sin^2 2\theta_{13} = 1.0 \)
\( \delta m^2_{21} = 8 \times 10^{-5} \text{ eV}^2 \), \( \sin^2 2\theta_{12} = 0.8 \)
Good compromise (?) between $\text{sgn}(\delta m^2_{31})$ and CPV sensitivities:

- **JHF** @ 295 km + **NuMI** @ $\theta_{13} = 0.2 - 0.8^\circ$, $L = 400$ km
  - both on peak
  - leave $(\delta, \pi - \delta)$ ambiguity for a future measurement

⇒ Same **NuMI** parameters as in Breazeale, DeGouvea, Szleper, Vasco
(maximized for $\theta_{13}$ CPV sensitivity)

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

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

Measurements at different $L$ greatly reduces $\delta m^2_{21}$ effect
Higher peaks ($\Delta = \frac{3\pi}{2}, \frac{5\pi}{2}, \ldots$)

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

$\Rightarrow$ loss of $\Delta m^2_{31}$ sensitivity for $n > 1$

$\sin^2 \theta_{13}$ reach for no overlap of $\delta m^2_{21} > 0$ and $\delta m^2_{31} < 0$
Other possibilities for measuring neutrino parameters

Huber, Lindner, Winter
- Even narrow spectrum beams have some energy info - can help resolve degeneracies at larger $\theta_{13}$
- $\nu$ factory (see talk by Geer)

Burguet-Castell et al.
- Combine superbeam and $\nu$ factory data

Donini, Meloni, Migliozzi
- $\bar{\nu}$ over and $\nu$ factory ("silver channel")
- Helps $(\delta, \theta_{23})$ and $(\theta_{23}, \delta - \theta_{23})$ ambiguities

Diwan et al. (BNL)
- Single wide band $\nu$ beam
- $\nu$ energy discrimination $\Rightarrow$ many measurements at different $E_{\nu}$
- May need to supplement with $\bar{\nu}$ beam (especially for $\delta m^{2}_{31} < 0$)
- Energy resolution + background discrimination essential

Minakata, Nunokawa, Parke
- $P(\text{JHF})$ vs. $P(\mu\text{MI})$
- $P(\text{JHF})$ vs. $\bar{P}(\mu\text{MI})$
  Similar to $P$ vs. $\bar{P}$ at a single machine

\begin{align*}
P(\text{JHF}) & \text{ vs. } P(\mu\text{MI}) \\
\delta m^2_{31} > 0 \text{ separated from } \delta m^2_{31} < 0 \\
\text{Substantial ambiguity in } \delta \text{ and } \theta_{13}
\end{align*}
SUMMARY

- Any two narrow-band appearance measurements not enough to completely determine $\delta$ and $\theta_{13}$

- $\bar{\nu}_e$ vs. $\nu_e$ on peak at longer $L$ can determine $\text{sgn}(\delta m^2_{31})$
  - unambiguous test of CPV
  - unambiguous measurement of $\theta_{13}$ if $\theta_{23} \approx \pi/4$

- $P_2$ vs. $P_1$ separates $\delta m^2_{31} > 0$ from $\delta m^2_{31} < 0$, but has large uncertainty in $\delta$ and $\theta_{13}$

- $P_{\nu_{\mu}}$ at two different $L$ (e.g. JHF and NuMI) can also determine $\text{sgn}(\delta m^2_{31})$ if $\theta_{13}$ is not too small (combined experiments less bothered by large $\delta m^2_{21}$)

- Wide-band beam offers theoretical possibility of determining $\text{sgn}(\delta m^2_{31})$, $\theta_{13}$ and $\delta$ in one measurement (if $\theta_{23} \approx \pi/4$)
  - must have good energy resolution and control of backgrounds

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

- Best way to resolve $(\theta_{23}, \pi/2 - \theta_{23})$ ambiguity, if it exists, is via $\nu_e \rightarrow \nu_\tau$ in $\nu$ factory