Complementarity of T2K/HK with Other Longer Baseline Experiments

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The purpose of this talk is to motivate to enforce the synergetic activities among the future long baseline (LBL) experiments.

The speaker is not a member of LBL experiments. Therefore, an objective view may be provided as a bystander.

The discussion is conceptual one and the used parameter values are rough. There might be errors or misunderstandings.
Flow of this talk

* Purpose of this talk
* Example of a successful synergy
* \( P(\nu_\mu \to \nu_e) \) and \( A_{\text{CP}} \) with matter effect
* Possible synergies
* Conclusion
An example of successful synergy:

The complementarity between Accelerator and Reactor

\[ P(\nu_\mu \rightarrow \nu_e; \Phi_{31} = \pi/2) \sim \frac{\sin^2 2\theta_{13}}{2 \left(1 - \left(L/L_0\right)\right)^2} - 0.043 \frac{\sin 2\theta_{13}}{1 - \left(L/L_0\right)} \sin \delta\]

The plot shows the probability \( P(\nu_\mu \rightarrow \nu_e) \) as a function of the reactor distance, with different lines representing different values of \( \sin^2 \delta \) and \( \sin^2 2\theta_{23} \). The T2K Baseline is indicated on the graph.
The synergy of Reactor and Accelerator has given us hints of large $\sin \delta$ & Normal hierarchy,

\[ P(\nu_\mu \rightarrow \nu_e; \Phi_{31} = \pi/2) \sim \frac{\sin^2 2\theta_{13}}{2 \left(1 - \left(L/L_0 \right) \right)^2} - 0.043 \frac{\sin 2\theta_{13}}{1 - \left(L/L_0 \right)} \sin \delta \]
\[ P_{31}(\nu_\mu \rightarrow \nu_e; \Phi_{31} = \pi/2) \sim \frac{\sin^2 2\theta_{13}}{2(1 - (L/L_0))^2} - 0.043 \frac{\sin 2\theta_{13}}{1 - (L/L_0)} \sin \delta \]

An example of successful synergy:

The complementarity between Accelerator and Reactor

By the way ...
The center value is in the unphysical region now.

**T2K**: Please shrink the error.

**Nova**: What is your result?
**Double Chooz** will check the DB & RENO results soon with the near detector.

\[ \Rightarrow \text{Redundancy is important} \]
* Difference between $P(\nu_\alpha \rightarrow \nu_\beta)$ and $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$

* Experimentally:

\[
A_{CP}(\Phi_{31} = \pi/2) = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}
\]

\[
\sim - \left| \frac{\Delta m_{12}^2}{\Delta m_{31}^2} \right| \frac{\pi \sin 2\theta_{12}}{\tan \theta_{23} \sin 2\theta_{13}} \sin \delta \sim -0.29 \sin \delta
\]

Thanks to the all experiments, this coefficients can be calculated now. (synergies!)

* However, the matter effect introduces a fake $A_{CP}$
Matter (MSW) Effect

Only $\nu_e$ and $\bar{\nu}_e$

Effective Weak Potential

$$V_W = 2\sqrt{2} E \frac{n_e G_F}{m_3^2 - m_1^2}$$

changes the coupling sign depending on $\nu$ or $\bar{\nu}$

changes sign depending on the mass hierarchy

Energy dependent
Baseline Dependence of the Matter Effect

At the oscillation maximum;

$$\Phi_{31} = \left| \Delta m_{31}^2 \right| \frac{L}{4E_\nu} = \frac{\pi}{2}$$

the weak potential can be expressed by using the baseline \( L \),

$$V_W = \frac{2\sqrt{2} E_\nu G_F \bar{n}_e}{m_3^2 - m_1^2} = \pm \frac{L}{\pi/\sqrt{2} G_F \bar{n}_e} = \pm \frac{L}{L_0} \sqrt{\frac{\nu}{\nu'}}$$

Reference Baseline: \( L_0 = \frac{\pi G_F}{\sqrt{2}} \int_0^L n_e \, dl \sim \pm 5,500 \text{km} \) 
\( (\rho=3[\text{g/cm}^3]) \)

<table>
<thead>
<tr>
<th>( L [\text{km}] )</th>
<th>( V_W (=L/L_0) )</th>
</tr>
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<tbody>
<tr>
<td>T2K/HK</td>
<td>295</td>
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<td>1,300</td>
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Main effect of the weak potential on the oscillation:

\[
\sin \Phi_{31} \rightarrow \frac{\sin (1 - V_W) \Phi_{31}}{1 - V_W}
\]

At oscillation maximum

\[
\sin (1 - V_W) \frac{\pi}{2} \sim 1 - \frac{\pi^2}{8} V_W^2 \sim 1
\]

Then, the appearance probability with the matter effect is,

\[
P(\nu_\mu \rightarrow \nu_e; @ \Phi_{31}) \sim \frac{s_{23}^2 \sin^2 2\theta_{13}}{(1 - V_W)^2} \pm \frac{\pi}{2} \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \frac{\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}}{(1 - V_W)} \sin \delta
\]
Oscillation probabilities for various cases

\[
\begin{align*}
P_{NH}\left(\nu_\mu \rightarrow \nu_e; @ \Phi_{31}\right) & \sim s_{23}^2 \frac{0.09}{\left(1-L/|L_0|\right)^2} - \frac{0.013}{\left(1-L/|L_0|\right)} \sin \delta \\
 & \sim s_{23}^2 \frac{0.09}{\left(1+L/|L_0|\right)^2} + \frac{0.013}{\left(1+L/|L_0|\right)} \sin \delta \\
P_{IH}\left(\nu_\mu \rightarrow \nu_e; @ \Phi_{31}\right) & \sim s_{23}^2 \frac{0.09}{\left(1-L/|L_0|\right)^2} + \frac{0.013}{\left(1-L/|L_0|\right)} \sin \delta \\
 & \sim s_{23}^2 \frac{0.09}{\left(1+L/|L_0|\right)^2} - \frac{0.013}{\left(1+L/|L_0|\right)} \sin \delta
\end{align*}
\]
Baseline Dependence of $\nu_e$ Appearance Prob.

$$P\left(\nu_\mu \rightarrow \nu_e; @ \Phi_{31}\right) \sim \frac{s_{23}^2 \sin^2 \theta_{23}}{\left(1 \pm L/|L_0|\right)^2} \left(\frac{0.09}{1 \pm L/|L_0|}\right) - \left(\frac{0.013}{1 \pm L/|L_0|}\right) \sin \delta$$

$\sin \delta = -1$, $\sin^2 2\theta_{23} > 0.98$

uncertainty from $\theta_{23}$ degeneracy

$\sin \delta = -1$
$\sin \delta = 0$
$\sin \delta = +1$

T2K/HK  MINOS   NOVA   LBNF

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

$\sin \delta = -1$, $\sin^2 2\theta_{23} > 0.98$

$0 \leq L [\text{km}] \leq 1400$

N.H.

I.H.
Baseline Dependence of $\nu_e$ Appearance Prob.

\[ P(\nu_\mu \rightarrow \nu_e; @ \Phi_{31}) \sim s_{23}^2 \frac{0.09}{(1 \pm L/|L_0|)^2} - \frac{0.013}{(1 \pm L/|L_0|)} \sin \delta \]

T2K+NOVA may enforce the hint on M.H. and $\sin \delta$ or may give us tension.

\[ P(\nu_\mu \rightarrow \nu_e) \]

L[km]

T2K/HK MINOS NOVA LBNF

\[ \sin \delta = -1, \sin^2 2\theta_{23} > 0.98 \]

\[ \sin \delta = 0 \]

\[ \sin \delta = +1 \]
Baseline Dependence of $\bar{\nu}_e$ Appearance Prob.

$$P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e; \Theta \Phi_{31}\right) \sim s_{23}^2 \frac{0.09}{\left(1 + L/\left|L_0\right|\right)^2} + \frac{0.013}{\left(1 + L/\left|L_0\right|\right)} \sin \delta$$

Graph showing baseline dependence with different values of $\sin \delta$ and $\sin^2 \theta_{23}$.
**CP asymmetry with the matter effect**

\[ A_{CP}(\Phi_{13}) = \frac{P - \bar{P}}{P + \bar{P}} \sim -\pi \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \frac{\sin 2\theta_{12}}{t_{23} \sin 2\theta_{13}} \sin \delta_{CP} \pm 2 \left( \frac{L}{L_0} \right) \]

\[ \sim -0.29 \sin \delta_{CP} \pm A_{FK} \]

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**Error of the \(\sin \delta\) measurement**

\[ \delta(\sin \delta_{CP}) = 3.4 \sqrt{\left( \delta A_{CP} \right)^2 + \left( A_{FK} \left( \delta \bar{n}_e / \bar{n}_e \right) \right)^2} \]
Baseline Dependence of CP asymmetry

\[ A_{CP} \sim -0.29 \sin \delta \pm 2 \left( \frac{L}{L_0} \right) \]

- \( \sin \delta = +1 \)
- \( \sin \delta = 0 \)
- \( \sin \delta = -1 \)

- \( \sin^2 \theta_{23} > 0.98 \)
Will evaluate the sensitivity by $3\sigma$ error of $\sin\delta_{CP}$ assuming $\delta_{CP} = 0$. 

\[ \sigma_{\sin\delta} \sim 0.5 \]
May be possible to limit $\delta_{CP}$ by $2\sigma$ but not $3\sigma$. 

$A_{CP} \sim -0.29 \sin \delta \pm 2 \left( \frac{L}{L_0} \right)$

$\sin \delta = -1, \sin^2 2\theta_{23} > 0.98$
HK case

\[ \delta_{\text{CP}} \text{ sensitivity} \]

\[ 3\sigma_{\sin\delta} \sim 0.33 \]
If $\sin \delta = 0$ & N.H. and HK measured the expected value.

If $\sin \delta = 0$ & N.H. and HK measured the expected value.

$\sin \delta = +1$

$\sin \delta = 0$

$\sin \delta = -1, \sin^2 2\theta_{23} > 0.98$

If $\text{M.H. is known}$, $|\sin \delta| < 0.33(3\sigma)$ can be obtained.
If M.H. is not known, there are two solutions. 

\(\sin\delta = 0\) cannot be confirmed.  

\(\sin\delta = -1, \sin^22\theta_{23} > 0.98\) 

\(\sin\delta = +1\) 

\(\Rightarrow\) M.H. is necessary.
LBNF case

arXive: 1307.7335

$3 \sigma_{\sin \delta} \sim 0.3$
This case, M.H. is determined to be N.H.
LBNF case

T2K/HK  MINOS NOVA  LBNF

sin δ = -1

sin δ = 0

sin δ = +1

sin^2 2θ_{23} > 0.98

Then extrapolate to L = 0 to obtain sin δ_{CP}.

\[ \delta (\sin \delta_{CP}) = 3.4 \sqrt{\left( \delta A_{CP} \right)^2 + \left( A_{FK} \left( \delta n_e / n_e \right) \right)^2} \]

what is the error of the average density?
HK+LBNF case

Improvement of $\sin \delta$ accuracy

* $\delta \sin \delta_{HK} = 0.1$ & $\delta \sin \delta_{LB} = 0.1$

$\Rightarrow \delta \sin \delta_{HK+LB} = 0.071??$ (common error?)
If $\delta \sin \delta_{CP} \sim 0.1 \Rightarrow \delta \sin \delta_{CP} \sim 0.1/\sqrt{2}$ by combining with LBNF.

HK+LBNF case

$\delta_{CP}$ sensitivity

Need not this proviso
**HK+LBNF case**

**Improvement of \( \sin \delta \) accuracy**

- \( \sin \delta = -1 \)
- \( \sin \delta = 0 \)
- \( \sin \delta = +1 \)

\[ \sin^2 2\theta_{23} > 0.98 \]

* MSW error independent analysis is possible.

\[
\sin \delta = 3.4 \frac{L_{HK} A_{LB} - L_{LB} A_{HK}}{L_{LB} - L_{HK}}
\]
HK+LBNF case

Strict test of the standard neutrino scheme and MSW effect.

This indicates a new physics or failure of the standard MSW.
Energy dependence of the oscillation

\[
\sin\left(1 - V_W \right) \Phi_{31} = \sin\left(\Phi_{31} - \frac{n_e G_F}{\sqrt{2}} L\right)
\]

Constant phase shift (\(\Delta \Phi\)) at given \(L\)

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\[
\Delta \Phi_{LB} - \Delta \Phi_{HK} = \frac{G_F}{\sqrt{2}} \left(\bar{n}_{e}^{LB} L_{LB} - \bar{n}_{e}^{HK} L_{HK}\right) \sim 0.29?
\]

Strong test of MSW with the same osc. mode.
Any merit compared with using \(\Phi_{31}\) from the \(\nu_\mu\) disappearance?
On the complementarity of Hyper-K and LBNF

* Enhance the sensitivity of CPV
* Solving $\theta_{23}$ degeneracy
* Improve precision of oscillation parameters. (not only $\delta_{CP}$ .)
* Search for non standard phenomena: different L and E
* Nucleon decay: different channel
* Supernova: flavor separated measurements

The last sentence of this report.

The benefit that will accrue from the parallel implementation of these complementary experiments should be quantified at an early stage.

⇒ A concrete benefit: Proposals will become stronger ....
Conclusion

Be Bosons;

\[ |1+1|^2 = 4, \]

Rather Incoherence;

\[ |1|^2 + |1|^2 = 2, \]

No Fermions;

\[ |1-1|^2 = 0. \]