Mass Hierarchy in Future Long-baseline Experiments

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Including Neutrino 2012 data!

\[
\begin{align*}
\sin^2 \theta_{13} &= 0.0241 \text{ (NH)} \quad 0.0193 - 0.0290 \\
\sin^2 \theta_{13} &= 0.0244 \text{ (IH)} \quad 0.0194 - 0.0291
\end{align*}
\]

G.L. Fogli et al., arXiv: 1205.5254v3

\[
\begin{align*}
\sin^2 \theta_{13} &= 0.0246 \text{ (NH)} \quad 0.019 - 0.030 \\
\sin^2 \theta_{13} &= 0.0250 \text{ (IH)} \quad 0.020 - 0.030
\end{align*}
\]

D.V. Forero et al., arXiv: 1205.4018v3

Relative Precision ~ 10%

\[\sin^2 2\theta_{13} \neq 0 @ 10\sigma\]
Missing Link in $\nu$ Oscillation: Neutrino Mass Ordering

The sign of $\Delta m^2_{31}$ ($m_3^2 - m_1^2$) is not known

Neutrino mass spectrum can be normal or inverted hierarchical

We only have a lower bound on the mass of the heaviest neutrino

$\sqrt{2.5 \cdot 10^{-3} \text{eV}^2} \sim 0.05$ eV

We currently do not know which neutrino is the heaviest

Why do we care about Neutrino Mass Ordering?

- Dictates the structure of ν mass matrix
- Can give vital clues towards the underlying theory of ν masses and mixing
- Acts as a powerful discriminator between various ν mass models

Albright and Chen, hep-ph/0608137
Connection between $0\nu\beta\beta$ and Neutrino Mass Ordering

If hierarchy is inverted, and yet no $0\nu\beta\beta$ is observed in the very far future, strong hint that neutrinos are not Majorana particles

Neutrino Oscillations in Matter

- Interactions in matter modify the oscillation probability significantly
- Coherent forward elastic scattering of neutrinos with matter particles
- Charged current interaction of $\nu_e$ with electrons creates a potential for $\nu_e$

\[ A = \pm 2\sqrt{2}G_F \cdot E \cdot n_e \]

$n_e = \text{electron number density and } + (-) \text{ for neutrinos (anti-neutrinos)}$

Creates an additional phase for $\nu_e$ and changes the oscillation probability even if $\delta = 0$, causes fake CP asymmetry

Resonant conversion – the MSW effect

Resonance occurs for neutrinos (anti-neutrinos) if $\Delta m^2$ is positive (negative)

\[ \Delta m^2 \sim A \iff E_{\text{Earth}}^{\text{res}} = 6 - 8 \text{ GeV} \]

\begin{tabular}{|c|c|}
  \hline
  $\nu$ & $\bar{\nu}$ \\
  \hline
  $\Delta m^2 > 0$ & MSW & - \\
  $\Delta m^2 < 0$ & - & MSW \\
  \hline
\end{tabular}

Platinum Channel ($P_{\mu e}$)

The appearance probability ($\nu_\mu \rightarrow \nu_e$) in matter, up to second order in the small parameters $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$ and $\sin 2\theta_{13}$,

$$P_{\mu e} \simeq \frac{\sin^2 2\theta_{13} \sin^2 \theta_{23}}{0.05} \cdot \frac{\sin^2[(1 - \hat{A})\Delta]}{(1 - \hat{A})^2}$$

$\theta_{13}$ Driven

$$- \frac{\alpha \sin 2\theta_{13} \xi \sin \delta_{CP} \sin(\Delta) \sin(\hat{A}\Delta)}{0.0096} \frac{\sin[(1 - \hat{A})\Delta]}{(1 - \hat{A})}$$

CP odd

$$+ \frac{\alpha \sin 2\theta_{13} \xi \cos \delta_{CP} \cos(\Delta) \sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 - \hat{A})\Delta]}{(1 - \hat{A})}$$

CP even

$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$

Solar Term

where $\Delta \equiv \Delta m_{31}^2 L/(4E)$, $\xi \equiv \cos \theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$, and $\hat{A} \equiv \pm (2\sqrt{2}G_F n_e E)/\Delta m_{31}^2$

Cervera et al., hep-ph/0002108
Freund et al., hep-ph/0105071
Transition Probability ($P_{\mu e}$)

Normal vs. Inverted Hierarchy and $\sin^2 2\theta_{13} = 0.1$

Agarwalla, Choubey, Raychaudhuri, hep-ph/0610333

Adding data from T2K and NOvA is useful to kill the intrinsic degeneracies

55% CP coverage @ 90% C.L. and 45% CP coverage @ 95% C.L. for MH discovery
Add a small LArTPC (5 to 10 kt) in the NOvA Beamline taking data simultaneously

100% CP coverage @ 90% C.L. and 64% CP coverage @ 95% C.L. w/ 5 kt LArTPC

Agarwalla, Prakash, Raut, Uma Sankar, arXiv:1208.3644
What large $\theta_{13}$ buys for us?

- Newly discovered large value of $\theta_{13}$ enhanced the chances of present generation experiments to provide a strong hint of mass hierarchy discovery around $2\sigma$

- Combining data from T2K and NOvA will be very useful to kill the clones

- To have a $>5\sigma$ direct determination of MH for all values of $\delta_{\text{CP}}$, we need next generation LBL expts ($>1000$ km) enriched with Earth Matter effects

- Thanks to large $\theta_{13}$, we do not need $\beta$-beam or $\nu$-Factory for MH discovery

- A reasonably upgraded Superbeam with a power of around 1 MW coupled with a small 10 to 20 kt LArTPC detector can do it provided the baseline is $>1000$ km

- Large $\theta_{13}$ allowed to adopt an incremental approach for next generation expts

- The determination of MH can be considered as a first step towards the Leptonic CP violation discovery which is quite tough even for large value of $\theta_{13}$
Option for Next Generation LBL Expts (Baselines < 1000 km)

1) CERN to Frejus : 130 km (1st Osc. Max = 0.26 GeV)
   Beam: 4.5 GeV, 4 MW, $56 \times 10^{21}$ POT/yr, 2 yrs $\nu + 8$ yrs $\bar{\nu}$
   Detector: 500 kton Water Cherenkov (MEMPHYS)

   See the talk by Thomas Patzak

2) J-PARC to Kamioka : 295 km (1st Osc. Max = 0.6 GeV)
   Beam: 30 GeV, 1.66 MW, $5 \times 10^{21}$ POT/yr, 1.5 yrs $\nu + 3.5$ yrs $\bar{\nu}$
   Detector: 560 kton Water Cherenkov (Hyper-Kamiokande)

   See the talk by Masato Shiozawa

3) CERN to Canfranc : 630 km (1st Osc. Max = 1.27 GeV)
   Beam: 50 GeV, 1.6 MW, $3 \times 10^{21}$ POT/yr, 5 yrs $\nu + 5$ yrs $\bar{\nu}$
   Detector: 500 kton Water Cherenkov

   See the talk by Lucia Votano

4) CERN to Gran Sasso : 730 km (1st Osc. Max= 1.47 GeV)
   Beam: 50 GeV, 1.6 MW, $3 \times 10^{21}$ POT/yr, 5 yrs $\nu + 5$ yrs $\bar{\nu}$
   Detector: 500 kton Water Cherenkov

Earth Matter effect is not enough at these baselines to provide $> 5\sigma$ discovery of MH
for 100% values of $\delta_{CP}$ even with high power beam and very large detector

See the talk by Silvia Pascoli

Option for Next Generation LBL Expts (Baselines > 1000 km)

1) FNAL to Homestake : 1300 km (1st Osc. Max = 2.52 GeV)

Beam: 120 GeV, 0.7 MW, $6 \times 10^{20}$ POT/yr, 5 yrs $\nu + 5$ yrs $\bar{\nu}$
Detector: 10 kton LArTPC (on surface)

LBNE proposal: See the talk by Kate Scholberg

2) CERN to Phyasalmi : 2300 km (1st Osc. Max = 4.54 GeV)

Beam: 400 GeV, 0.77 MW, $1.5 \times 10^{20}$ POT/yr, 5 yrs $\nu + 5$ yrs $\bar{\nu}$
Detector: 20 kton LArTPC (deep underground, 4000 m.w.e)

LBNO proposal: See the talk by Andre Rubbia

3) CERN to Kamioka : 8770 km (Probability Max = 6.5 GeV)

Beam: 400 GeV, 0.77 MW, $1.5 \times 10^{20}$ POT/yr, 5 yrs $\nu$ (only rate)
Detector: 22.5 kton Water Cherenkov (existing & well understood Super-K)


These baselines are long enough to provide $> 5\sigma$ discovery of MH for 100% values of $\delta_{CP}$ even with modest power beam and small detector
MH is a discrete measurement, both 1st and 2nd Oscillation maxima are useful

CERN-Phyasalmi distance is also close to the Bimagic baseline of 2540 km

Event Spectrum at LBNE and LBNO

Wide Band Beam ➔ Higher statistics ➔ cover several L/E values ➔ kill clone solutions

LAr Detector ➔ Excellent Detection efficiency at 1st and 2nd Oscillation maxima

High L ➔ High E ➔ High cross-section ➔ Less uncertainties in cross-section at high E
A four times small LBNO can give 10σ MH discovery for 100% values of $\delta_{\text{CP}}$

LBNE as it stands now can give 5σ MH discovery for 85% values of $\delta_{\text{CP}}$
**Incremental Approach: Well suited for CERN-Phyasalmi**

\[
\sin^2 2\theta_{13}^{\text{true}} = 0.1
\]

1540 km: CERN-Slanic (Romania)
Similar to FNAL-Homestake (1290 km)

<table>
<thead>
<tr>
<th>Total exposure (\times 10^{21}) pot·kt</th>
<th>NH true</th>
<th>IH true</th>
</tr>
</thead>
<tbody>
<tr>
<td>2290 km</td>
<td>32 (80)</td>
<td>50 (158)</td>
</tr>
<tr>
<td>1540 km</td>
<td>158 (502)</td>
<td>250 (627)</td>
</tr>
</tbody>
</table>

Exposure needed to achieve MH discovery with 100% coverage in \(\delta_{CP}\)

\[
240 \times 10^{21}\text{ pot.kt with }50\text{ GeV HPPS2} = 30 \times 10^{21}\text{ pot.kt with }400\text{ GeV SPS}
\]

Agarwalla, Li, Rubbia, arXiv:1109.6526 [hep-ph]

Equal sharing of neutrino & anti-neutrino running. NH requires less exposure than IH

**Mass hierarchy will be discovered at > 5\(\sigma\) with small exposure at 2300 km**
Near Resonant Matter Effect: Optimal E and L

One Mass Scale Dominance (neglect solar term)

$$P_{\mu e} = \sin^2 \theta_{23} \sin^2 2\tilde{\theta}_{13} \sin^2 \left( \frac{\Delta \tilde{m}_{31}^2 L}{4E} \right)$$

$$\Delta \tilde{m}_{31}^2 \equiv \sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} - A)^2 + (\Delta m_{31}^2 \sin 2\theta_{13})^2}$$

Constant line-averaged Earth matter potential

$$A \equiv 2\sqrt{2} G_F n_e(L) E$$

First maximize the 1-3 mixing in matter:

$$\sin^2 2\tilde{\theta}_{13} \big|_{E=E_{res}} = 1, \quad E_{res} \equiv \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2} G_F n_e}$$

Then maximize the oscillatory term at $$L = L_{\text{max}}$$

$$n_e(L) L \big|_{L_{\text{max}}} = \frac{\pi}{\sqrt{2} G_F \tan 2\theta_{13}}$$

For $$\sin^2 2\theta_{13} = 0.1$$: $$L_{\text{max}} \sim 10^4 \text{ km} \ & \ E_{\text{res}} \sim 6.6 \text{ GeV}$$

!Maximum probability: only if 1-3 mixing is large!
Mass Hierarchy Discovery with CERN-Kamioka Baseline

Send a Superbeam (average energy of 5 GeV) from CERN towards existing and well-understood Super-Kamiokande detector (L = 8770 km)

This setup can reveal the neutrino MH at 5σ in 4.5 years irrespective of the true hierarchy and CP phase with only neutrino beam from 400 GeV SPS, counting the total number of appearance events

This measurement relies on the near resonant matter effect in the $\nu_\mu$ to $\nu_e$ channel

Other Probes of Neutrino Mass Hierarchy

★ Large value of $\theta_{13}$ allows us to explore MH with atmospheric neutrinos. ICAL@INO experiment, IceCube Deepcore, PINGU are the candidates

See the talk by Srubabati Goswami, Francis Halzen

★ Supernova neutrinos can also discriminate between NH and IH

See the talk by Sovan Chakraborty

★ Cosmology can weigh neutrinos with precision and future CMB & LSS measurements have a chance to determine the light neutrino spectrum

See the talk by Carmelita Carbone

★ Observation of $0\nu\beta\beta$ with the next generation expts would not only imply that neutrinos are Majorana, but also that the hierarchy is inverted

See the talk by Werner Rodejohann

★ High Statistics Reactor experiments at a baseline of 60 km with an exposure of $> 200$ kt GW yr and 2% energy resolution (The proposals of Daya Bay II & RENO II )

See the talk by Seon-Hee Seo and Liang Zhan
Recent discovery of large value of $\theta_{13}$ have taken us one step further in validating the 3-flavor picture of the Standard $\nu$ model with a strong footing.

Neutrino mass hierarchy is one of the fundamental unsolved issues that needs to be addressed in the present or next generation LBL expts.

To have a $> 5\sigma$ direct determination of MH for all values of $\delta_{\text{CP}}$, we need next generation LBL expts ($> 1000$ km) enriched with Earth Matter effects.

An optimized Superbeam using the existing 400 GeV SPS machine pointing towards Phyasalmi mine with a baseline of 2300 km and coupled with a 20 kt LArTPC can provide a $10\sigma$ direct determination of MH for all values of $\delta_{\text{CP}}$ within 2.5 years.

The determination of MH can be considered as a first step towards the Leptonic CP violation discovery!

Thank you!
We consider the existing and well understood Super-K detector with 22.5 kt fiducial

Pre-cut efficiencies for T2KK proposal

<table>
<thead>
<tr>
<th>True $\nu$ energy</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\nu_e$ (avg)</td>
<td>QE $\nu_e$</td>
</tr>
<tr>
<td>0 - 0.35 GeV</td>
<td>95%</td>
<td>94%</td>
</tr>
<tr>
<td>0.35 - 0.85 GeV</td>
<td>87%</td>
<td>96%</td>
</tr>
<tr>
<td>0.85 GeV - 1.5 GeV</td>
<td>70%</td>
<td>95%</td>
</tr>
<tr>
<td>1.5 - 2.0 GeV</td>
<td>58%</td>
<td>91%</td>
</tr>
<tr>
<td>2.0 - 3.0 GeV</td>
<td>51%</td>
<td>91%</td>
</tr>
<tr>
<td>3.0 - 4.0 GeV</td>
<td>45%</td>
<td>90%</td>
</tr>
<tr>
<td>4.0 - 5.0 GeV</td>
<td>43%</td>
<td>90%</td>
</tr>
<tr>
<td>5.0 - 10.0 GeV</td>
<td>37%</td>
<td>86%</td>
</tr>
</tbody>
</table>

Estimated based on the criteria:

1) Events are fully contained in the fiducial volume!
2) Have a single Cerenkov ring recognized as electron-like!
3) No Michel electron present!

We only consider charged current single ring events as our signal
We only rely on total signal and background event rates
No spectral information has been used
For $\nu_e$ appearance: main NC background comes from Single-$\pi^0$ contamination
We use the true neutrino energy window of 0.5 GeV to 10 GeV
90% NC background rejection (5 – 10 GeV)
Superbeam flux

- New high power accelerator (HP-PS2)
- 50 GeV proton beam, power 1.6 MW
- $3 \times 10^{21}$ protons on target/yr (200 days/yr)
- @ flux level, 0.62% intrinsic $\nu_e$ contamination

We can also use 400 GeV proton line from SPS towards a 0.7 - 1 MW target region!

Recent optimization suggests that we can have $1.5 \times 10^{20}$ protons on target/year with 200 days/year!

We scale these fluxes to the longer $L = 8770$ km baseline, as $L^{-2}$
Signal and Background Event rates for CERN-Kamioka

Event=signal+background

Band: CP phase [0–360 degree]

<table>
<thead>
<tr>
<th>Channel</th>
<th>CERN-Kamioka (8870km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Signal</td>
</tr>
<tr>
<td>CC-1 ring</td>
<td>40</td>
</tr>
<tr>
<td>Int+Mis-id+NC</td>
<td>2</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_e$ (NH)</td>
<td>84</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_\mu$ (IH)</td>
<td>89</td>
</tr>
</tbody>
</table>

Total exposure $5 \times 10^{21}$ protons on target

This is for appearance channel!

Mass Hierarchy Discovery for different 1-3 mixing angle

CERN–Kamioka Superbeam
MH discovery (rate based analysis)

Here we take total $5 \times 10^{21}$ pot!

$\Delta \chi^2$ vs $\sin^2 2\theta_{13}^{\text{true}}$