Upgraded experiments with super neutrino beams

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Outline

- Status quo
- Origin of neutrino mass
- Key measurements
- Neutrino oscillation
- Experimental strategies
  - T2KK
  - WBB
  - NO$\nu$A*
- Comparison & robustness
- Summary
Status quo

- Conversion of $\nu_e$ from the Sun into $\nu_\mu + \nu_\tau$
- Disappearance of $\bar{\nu}_e$ from nuclear reactors at a distance of $\sim 200$ km
- Disappearance of $\nu_\mu$ from the Atmosphere
- Disappearance of $\nu_\mu$ from a neutrino beam
- No disappearance of $\bar{\nu}_e$ from nuclear reactors at a distance of $\sim 1$ km
Status quo

A common framework for all the neutrino data is oscillation.

- $\Delta m_{21}^2 \sim 8 \cdot 10^{-5} \text{ eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m_{31}^2 \sim 2.5 \cdot 10^{-3} \text{ eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \lesssim 0.15$

This implies a lower bound on the mass of the heaviest neutrino

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

but we currently do not know which neutrino is the heaviest.
Status quo

Quarks

\[ U_{CKM} = \begin{pmatrix}
1 & 0.2 & 0.005 \\
0.2 & 1 & 0.04 \\
0.005 & 0.04 & 1 \\
\end{pmatrix} \]

Neutrinos

\[ U_\nu = \begin{pmatrix}
0.8 & 0.5 & ? \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7 \\
\end{pmatrix} \]

Why are neutrino mixings so large?
Status quo
Mass hierarchy in the SM

What makes neutrinos so much lighter?

\[ \Delta m^2_{\text{atm}} \]

\[ \Delta m^2_{\text{sun}} \]

\[ \Delta m^2_{31} > 0 \quad \Delta m^2_{31} < 0 \]
Origin of neutrino mass

Neutrinos in the Standard Model (SM) are strictly massless, *ie.* there is no way to write a mass term for neutrinos with only SM fields which is gauge invariant and renormalizable.

Neutrinos are massive in reality – thus neutrino mass requires physics beyond the standard model.
Origin of neutrino mass

The SM is an effective field theory, *ie.* at some high scale $\Lambda$ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \ldots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda} (LH)(LH) \rightarrow \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_\nu \nu \nu$$

Thus studying neutrino masses is the most sensitive probe for new physics at high scales.
Origin of neutrino mass

One example is the seesaw mechanism

$$\mathcal{L}_\nu = m_D \overline{\nu}_L N_R + \frac{1}{2} m_R \overline{N}_L^c N_R + h.c$$

$N_R$ is a heavy right handed neutrino, \textit{i.e.} a singlet under the SM gauge group.

The light neutrino mass is the given by

$$m_\nu \approx \frac{m_D^2}{m_R}$$

Identifying $m_D \sim 100 \text{ GeV}$ and $m_R \sim m_{GUT} \sim 10^{15} \text{ GeV}$ yields $m_\nu \sim 10^{-2} \text{ eV}$
Origin of baryons

At the same time $N_R$ can provide a mechanism for creating the observed tiny surplus of matter over anti-matter.

Leptogenesis requires the temperature of the Universe to be high enough that there is a thermal population of $N_R$. Their subsequent out-of-equilibrium decays are a new source of CP violation and lepton number

$$\Gamma(N_R \rightarrow LH) - \Gamma(N_R \rightarrow \overline{L}H^*) \neq 0$$

which later on is converted to baryon number by non-perturbative processes.
Key measurements

In the context of GUT scale right handed neutrinos it is very difficult to establish a one-to-one correspondence between high and low-energy observables.

A given model, however, usually has generic predictions for low energy observables. Therefore studying neutrinos allows to gain considerable insight into phenomena which otherwise would be inaccessible.

Colliders can not probe this kind of physics, since any effects in scattering amplitudes are suppressed by $m_{GUT}$, at LHC this would be effects of $\mathcal{O}(10^{-10})$!
## Key measurements

| Case | Texture | Hierarchy | $|U_{e3}|$ | $|\cos 2\theta_{23}|$ | Solar Angle |
|------|---------|-----------|-----------|----------------|-------------|
| A    | $\sqrt{\Delta m_{13}^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$ | Normal | $\sqrt{\frac{\Delta m_{12}^2}{\Delta m_{13}^2}}$ | $\sqrt{\frac{\Delta m_{23}^2}{\Delta m_{13}^2}}$ | $O(1)$ |
| B    | $\sqrt{\Delta m_{13}^2} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}$ | Inverted | $\frac{\Delta m_{12}^2}{|\Delta m_{13}^2|}$ | $\frac{\Delta m_{23}^2}{|\Delta m_{13}^2|}$ | $O(1)$ |
| C    | $\sqrt{\frac{\Delta m_{12}^2}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}}$ | Inverted | $\frac{\Delta m_{12}^2}{|\Delta m_{13}^2|}$ | $\frac{\Delta m_{23}^2}{|\Delta m_{13}^2|}$ | $\sim \frac{\Delta m_{23}^2}{|\Delta m_{13}^2|}$ |
| Anarchy | $\sqrt{\Delta m_{13}^2} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$ | Normal | $> 0.1$ | – | $O(1)$ |

**Caveat:** Assumes diagonal lepton mass matrix!
Key measurements

The most sensitive low energy observables are

- Majorana vs Dirac mass – $0\nu\beta\beta$
- Absolute $m_\nu$ – Katrin, Cosmology
- How large is $\theta_{13}$? – Oscillation
- Which one is the heaviest neutrino? – $0\nu\beta\beta$, Katrin, Oscillation
- Is $\theta_{23}$ maximal? – Oscillation
- Is there leptonic CP violation? – Oscillation
- Are there only 3 light neutrinos? – Oscillation
One example

![Predictions of All 63 Models](chart)

**Albright, Chen, 2006.**
Neutrino oscillations

The mass eigenstates are related to flavor eigenstates by $U_\nu$, thus a neutrino which is produced as flavor eigenstate is a superposition of mass eigenstates. These mass eigenstates propagate with different velocity and a phase difference is generated. This phase difference gives rise to a finite transition probability

$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sum_{ij} U_{\alpha j} U_{\beta j}^* U_{\alpha i}^* U_{\beta i} e^{-i \frac{\Delta m_{ij}^2 L}{2E}} \sim \sin^2 2\theta \sin^2 \frac{\Delta m_{ij}^2 L}{4E}$$

Neutrino oscillation is a quantum mechanical interference phenomenon and therefore it is uniquely sensitive to extremely tiny effects.
Neutrino oscillations – CP viol.

Like in the quark sector mixing can cause CP violation

\[ P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0 \]

The size of this effect is proportional to

\[ J_{CP} = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \delta \]

The experimentally most suitable transition to study CP violation is \( \nu_e \leftrightarrow \nu_\mu \), which is only available in beam experiments.
Neutrino oscillation – matter

The charged current interaction of $\nu_e$ with the electrons creates a potential for $\nu_e$

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

where $+$ is for $\nu$ and $-$ for $\bar{\nu}$.

This potential gives rise to an additional phase for $\nu_e$ and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0$$

even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.
Neutrino oscillation – matter

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

\[ \Delta m^2 \sim A \]

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

<table>
<thead>
<tr>
<th>( \Delta m^2 )</th>
<th>( \nu )</th>
<th>( \bar{\nu} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta m^2 &gt; 0 )</td>
<td>MSW</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta m^2 &lt; 0 )</td>
<td>-</td>
<td>MSW</td>
</tr>
</tbody>
</table>
\[ P(\nu_\mu \rightarrow \nu_e) \]

Two-neutrino limit – \( \Delta m^2_{21} = 0 \)

\[ \approx \sin^2 2\theta_{13} \quad \sin^2 \theta_{23} \quad \frac{\sin^2(\hat{A} - 1)\Delta}{(\hat{A} - 1)^2} \]
\( P(\nu_{\mu} \rightarrow \nu_{e}) \)

Three flavors – \( \Delta m^2_{21} \neq 0 \)

\[
\approx \sin^2 2\theta_{13} \quad \sin^2 \theta_{23} \quad \frac{\sin^2((\hat{A} - 1)\Delta)}{(\hat{A} - 1)^2} \\
\pm \alpha \sin 2\theta_{13} \quad \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)}{\hat{A}(1 - \hat{A})} \\
+ \alpha \sin 2\theta_{13} \quad \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta) \sin(\hat{A}\Delta) \sin((1 - \hat{A})\Delta)}{\hat{A}(1 - \hat{A})} \\
+ \alpha^2 \quad \cos^2 \theta_{23} \sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\]
\[ P(\nu_\mu \rightarrow \nu_e) \]

Small quantities – \( \alpha := \Delta m^2_{21} / \Delta m^2_{31} \) and \( \sin 2\theta_{13} \)

\[
\approx \sin^2 2\theta_{13} \quad \sin^2 \theta_{23} \quad \frac{\sin^2((\hat{1} - 1)\Delta)}{\hat{1}^2}
\]

\[
\pm \alpha \sin 2\theta_{13} \quad \sin \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta) \sin(\hat{1}\Delta) \sin((1 - \hat{1})\Delta)}{\hat{1}(1 - \hat{1})}
\]

\[
+ \alpha \sin 2\theta_{13} \quad \cos \delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta) \sin(\hat{1}\Delta) \sin((1 - \hat{1})\Delta)}{\hat{1}(1 - \hat{1})}
\]

\[
+ \alpha^2 \quad \cos^2 \theta_{23} \sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{1}\Delta)}{\hat{1}^2}
\]
Eight-fold degeneracy

- intrinsic ambiguity for fixed $\alpha$
Eight-fold degeneracy

- intrinsic ambiguity for fixed $\alpha$
- Disappearance determines only $|\Delta m_{31}^2| \Rightarrow$

$T_s := \Delta m_{31}^2 \rightarrow -\Delta m_{31}^2$
Eight-fold degeneracy

• intrinsic ambiguity for fixed $\alpha$

• Disappearance determines only $|\Delta m_{31}^2| \Rightarrow \mathcal{T}_s := \Delta m_{31}^2 \rightarrow -\Delta m_{31}^2$

• Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow \mathcal{T}_t := \theta_{23} \rightarrow \pi/2 - \theta_{23}$
Eight-fold degeneracy

- intrinsic ambiguity for fixed $\alpha$
- Disappearance determines only $|\Delta m^2_{31}| \Rightarrow \mathcal{T}_s := \Delta m^2_{31} \rightarrow -\Delta m^2_{31}$
- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow \mathcal{T}_t := \theta_{23} \rightarrow \pi/2 - \theta_{23}$
- Both transformations $\mathcal{T}_{st} := \mathcal{T}_s \oplus \mathcal{T}_t$
## Setups

Detector mass $[Mt] \times$ target power $[MW] \times$ running time $[10^7 s]$.

<table>
<thead>
<tr>
<th>Setup</th>
<th>$t_\nu$ [yr]</th>
<th>$t_\bar{\nu}$ [yr]</th>
<th>$P_{Target}$ [MW]</th>
<th>$L$ [km]</th>
<th>Detector technology</th>
<th>$m_{Det}$ [kt]</th>
<th>$\mathcal{L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO$\nu$A*</td>
<td>3</td>
<td>3</td>
<td>1 ($\nu$)</td>
<td>810</td>
<td>Liquid argon TPC</td>
<td>100</td>
<td>1.02</td>
</tr>
<tr>
<td>WBB</td>
<td>5</td>
<td>5</td>
<td>1 ($\nu$) + 2 ($\bar{\nu}$)</td>
<td>1290</td>
<td>Water Cherenkov</td>
<td>300</td>
<td>7.65</td>
</tr>
<tr>
<td>T2KK</td>
<td>4</td>
<td>4</td>
<td>4 ($\nu$)</td>
<td>295+1050</td>
<td>Water Cherenkov</td>
<td>270+270</td>
<td>17.28</td>
</tr>
</tbody>
</table>

- 5% systematics for all setups
- LArTPC based on numbers from B. Fleming
- WBB-WC based on Yanagisawa et al.
- T2KK performance based on LOI
- hep-ex/0106019
- NuMI fluxes from M. Messier’s website
CP fraction

- reduces 2D plot to 3 points
- allows unbiased comparison
- allows risk assessment
- CPF = 1, worst case – guaranteed sensitivity
- CPF = 0, best case
Comparison

- $\sin^2 2\theta_{13}$ performances are very similar
- T2KK clearly best for CPV
- WWB clearly best for mass hierarchy
Where to put NO$\nu$A*
On vs off-axis
On vs off-axis
Summary

- Neutrinos have mass
- New Physics
- Many candidates
- Oscillation can provide many of the key measurements
- Complementary to the energy frontier
Summary

- Exposure is the key factor – money and physics
- Detector technology plays a big role
- Off vs On-axis decision requires careful analysis
- NO$\nu$A* can be a competitive experiment
- Short distances ($< 500 \text{ km}$) are disfavoured
- Every strategy requires MW beams, 0.1 Mt detectors, 10 years of running

$500,000,000 \text{ $$}}$
More NO$\nu$A options

**True value of $\sin^2 2\theta_{13}$**

- **Mass hierarchy**
  - LAr
  - $+40.0 \times 10^{20}$
  - $+10.5 \times 10^{25}$
  - $+18.0 \times 10^{980}$
  - $+12.0 \times 10^{810}$
  - $+1/2 \times 12.0 \times 10^{810}$
  - $+1/2 \times 18.0 \times 10^{980}$

- **CP violation**
  - No data points

**Fraction of $\delta_{CP}$**

- **True value of $\sin^2 2\theta_{13}$**
The Jump

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

\[ \sin^2 2\theta_{13} \]