Neutrino Oscillation and Resolving the Neutrino Mass Ordering

D. Jason Koskinen
Standard Model & Neutrinos

Quarks
- u
- c
- t
- d
- s
- b

Leptons
- e
- \( \nu_e \)
- \( \mu \)
- \( \nu_\mu \)
- \( \tau \)
- \( \nu_\tau \)

Atoms

Bosons
- Y
- \( Z^0 \)
- W
- g
- H
Standard Model & Neutrinos

Quarks
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- c
- t
- d
- s
- b

Leptons
- e
- μ
- τ

Bosons
- γ
- Z^0
- W
- g
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Atoms

Light X-Rays
Gamma rays
CMB
Standard Model & Neutrinos

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Atoms

More numerous than atoms

Light
X-Rays
Gamma rays
CMB
Standard Model & Neutrinos

**Quarks**
- u
- c
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- s
- b

**Leptons**
- e
- μ
- τ
- ν_e
- ν_μ
- ν_τ

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Standard Model & Neutrinos

Quarks
- u
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Leptons
- e
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\( \nu_e \), \( \nu_\mu \), \( \nu_\tau \)
Standard Model & Neutrinos

Quarks
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- c
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- e
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ν_e
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Standard Model & Neutrinos

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- e
- \(\nu_e\)
- \(\mu\)
- \(\nu_\mu\)
- \(\tau\)
- \(\nu_\tau\)

**Bosons**
- \(Y\)
- \(Z^0\)
- W
- g
- H
Neutrino Admixture

Flavor Eigenstate

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle
\end{pmatrix}
= \mathcal{U}_{\text{PMNS}}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle
\end{pmatrix}
\]

Mass Eigenstate

\[
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\]

- Neutrinos are produced/detected in ‘flavor’ states but move through space as a composition of ‘mass’ states.
Measuring Parameters

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{pmatrix}
= \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} \\
\end{pmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle \\
\end{pmatrix}
\]

underlying nature of weak mixing

\[
C_{12} = \cos\theta_{12} \quad S_{12} = \sin\theta_{12}
\]

\[
\begin{pmatrix}
|\nu_e\rangle \\
|\nu_\mu\rangle \\
|\nu_\tau\rangle \\
\end{pmatrix}
= \begin{bmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\
-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\
s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \\
\end{bmatrix}
\begin{pmatrix}
|\nu_1\rangle \\
|\nu_2\rangle \\
|\nu_3\rangle \\
\end{pmatrix}
\]

Experimentally measured values

Three angles and one Charge-Parity phase
What Is Being Measured?

Mark Ross-Lonergan -- IPPP, Durham University

KamLAND
$\bar{v}_e$ Disappearance

SNO
Solar CC/NC ratio

Daya Bay
$\bar{v}_e$ Disappearance

MINOS/T2K
$\nu_e$ Appearance

MINOS/T2K
$\nu_\mu$ Disappearance

SNO
Solar NC fluxes

OPERA and SK
$\nu_\tau$ Appearance
Fundamental Mixing

Quarks (CKM)

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} =
\begin{pmatrix}
    V_{ud} & V_{us} & V_{ub} \\
    V_{cd} & V_{cs} & V_{cb} \\
    V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

Conirms Unitarity

Leptons (PMNS)

\[
\begin{pmatrix}
    |\nu_e\rangle \\
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    |\nu_\tau\rangle
\end{pmatrix} =
\begin{pmatrix}
    U_{e1} & U_{e2} & U_{e3} \\
    U_{\mu1} & U_{\mu2} & U_{\mu3} \\
    U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
    |\nu_1\rangle \\
    |\nu_2\rangle \\
    |\nu_3\rangle
\end{pmatrix}
\]

Currently Assumes Unitarity
Fundamental Mixing

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\]

Currently Assumes Unitarity

Confirms Unitarity
Neutrino Oscillation

- The three conventional neutrino angles have been measured, but NOT all the 9 individual PMNS elements

- More data and more oscillation channels are necessary to complete even a minimally constraining PMNS ‘unitary’ triangle
Mass Ordering

\[
\nu_3, \quad \nu_2, \quad \nu_1 \quad \Delta m_{23}^2 \quad \Delta m_{12}^2 \quad \Delta m_{23}^2
\]

or

\[
\nu_2, \quad \nu_1, \quad \nu_3 \quad \Delta m_{12}^2 \quad \Delta m_{23}^2 \quad \Delta m_{12}^2
\]

\[
\nu_e, \quad \nu_\mu, \quad \nu_\tau
\]
Why? (Models)

- 86 models were identified in 2006* for lepton flavor symmetries

- 55 are now disfavored for predicting $\theta_{13} > 3 \sigma$ from measured

- A prime remaining discriminator is the predicted order Inverted/Normal

*hep-ph/0608137

<table>
<thead>
<tr>
<th>Reference</th>
<th>Hierarchy</th>
<th>$\sin^2 2\theta_{23}$</th>
<th>$\tan^2 \theta_{12}$</th>
<th>$\sin^2 \theta_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anarchy Model:</td>
<td></td>
<td></td>
<td></td>
<td>$\geq 0.011 @ 2\sigma$</td>
</tr>
<tr>
<td>dGM [18]</td>
<td>Either</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| $L_e - L_\mu - L_\tau$ Models: | | | | |
| BM [35] | Inverted | | | 0.00029 |
| BCM [36] | Inverted | | | 0.00063 |
| GMN1 [37] | Inverted | | | $\geq 0.52$ | $\leq 0.01$ |
| GL [38] | Inverted | | | 0 |
| PR [39] | Inverted | | | $\leq 0.58$ | $\geq 0.007$ |

| $S_3$ and $S_4$ Models: | | | | |
| CFM [40] | Normal | | | 0.00006 - 0.001 |
| HLM [41] | Normal | 1.0 | 0.43 | 0.0044 |
| Normal | 1.0 | 0.44 | 0.0034 |
| KMM [42] | Inverted | 1.0 | | 0.000012 |
| MN [43] | Normal | | | 0.0024 |
| MNY [44] | Normal | | | 0.000004 - 0.000036 |
| MPR [45] | Normal | | | 0.006 - 0.01 |
| RS [46] | Inverted | $\theta_{23} \geq 45^\circ$ | | 0.0025 |
| Normal | $\theta_{23} \leq 45^\circ$ | 0.93 | 0.43 | 0.0016 - 0.0036 |
| TY [47] | Inverted | | | |
| T [48] | Normal | | | |

| $A_4$ Tetrahedral Models: | | | | |
| ABGMP [49] | Normal | 0.997 - 1.0 | 0.365 - 0.438 | 0.00069 - 0.0037 |
| AKKL [50] | Normal | | | 0.006 - 0.04 |
| Ma [51] | Normal | 1.0 | 0.45 | |

| SO(3) Models: | | | | |
| M [52] | Normal | 0.87 - 1.0 | 0.46 | 0.00005 |

| Texture Zero Models: | | | | |
| CPP [53] | Normal | | | |
| Inverted | | | | |
| WY [54] | Either | | | 0.0006 - 0.003 |
| Either | | | | 0.002 - 0.02 |
| Either | | | | 0.02 - 0.15 |
• If the neutrino is a majorana particle \textit{and} the mass ordering is inverted, then current 0νββ experiments are in good shape, but if not...
Resolving the Neutrino Mass Ordering via Oscillation
Electron (anti)neutrinos pick up an ‘effective’ mass, which modifies the vacuum oscillation probability.

Oscillations in Matter
Matter

Vacuum Oscillations

\[ P_{\alpha\alpha} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E} \]

Matter Oscillations

\[ P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2 L}{4E} \]

\[
\Delta \tilde{m}^2 = \xi \cdot \Delta m^2, \quad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},
\]

\[
\xi \equiv \sqrt{\sin^2 2\theta + (\cos 2\theta - \tilde{A})^2},
\]

\[
\tilde{A} = \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2E} G_F n_e}{\Delta m^2}
\]

*W. Winter, Neutrino 2014*
Reactor Experiment Possibilities

- Long baseline reactor experiments with O(10) KTons of liquid scintillator requiring very good energy resolution

*X. Li, Windows on the Universe 2013
Reactor Neutrinos

- Proposed reactor + liquid scintillator experiments
- Neutrino ordering gives a modulation of solar oscillation parameters in reactor long-baselines

* X. Li, Windows on the Universe 2013
** J.S. Park, International Workshop on “RENO-50” 2013
Reactor Neutrinos

- Proposed reactor + liquid scintillator experiments
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**J.S. Park, International Workshop on “RENO-50” 2013**
Neutrino Mass Ordering
Neutrino Mass Ordering

$P(\nu_e \rightarrow \nu_\mu)$ with Travel Through the Earth - 10 GeV, 17'9

- Normal Hierarchy
- Inverted Hierarchy
Neutrino Mass Ordering

$P(\nu_e \rightarrow \nu_\mu)$ with Travel Through the Earth - 10 GeV, 179°

$P(\nu_\mu \rightarrow \nu_e)$ with Travel Through the Earth - 6 GeV, 126°
Neutrino Mass Ordering

- Inverted/Normal ordering has up to a 20% difference in oscillation probability for specific energies and zenith angles (baselines)
Accelerator Neutrinos for Neutrino Ordering

Others
- T2K
- Hyper-K
- ESSnuSB
- DUNE
NOvA

- First results released in early August
- Two multivariate $\nu_e$ selectors - LID & LEM
  - LID selects 6 events while LEM selects 11 (includes the 6 LID selected events)
- Ordering (hierarchy) and CP-value are intrinsically coupled for long baseline experiments
Future Atmospheric Experiments

India-Based Neutrino Observatory (INO)

Oscillation Research with Cosmics in the Abyss (ORCA)

Precision IceCube Next Generation Upgrade (PINGU)
Precision IceCube Next Generation Upgrade (PINGU)

- Use existing and familiar technology to infill IceCube/DeepCore
- Improve rejection of cosmic ray muon background
- ~40 strings deployed over 2-3 years

Letter of Intent - arXiv:1401.2046
Neutrino Ordering w/ No Magnet

- INO has magnet to separate neutrinos from anti-neutrinos, but PINGA and ORCA do not
INO has magnet to separate neutrinos from anti-neutrinos, but PINGA and ORCA do not.
Neutrino Mass Ordering by Eye

Track-Like Events (mainly CC $\nu_\mu + \bar{\nu}_\mu$)

1-year exposure

PRELIMINARY

*D. Jason Koskinen - ICNFP2015

*K. Clark, ICRC2015
Bottom Line for PINGU

σ vs. Time, at nu-fit (2014) values of θ_{23}, Δm_{31}^{2}

- Normal
- Inverted
- NMH, stat. only
- IMH, stat. only

Time [yrs]

Preliminary

*T. Arlen WIN2015
Global Combination

*Blennow & Schwetz, arXiv:1306.3988

*Ghosh, Thakore & Choubey, arXiv:1212.1305
Conclusion

- Neutrino oscillation is confirmed laboratory signal for Beyond Standard Model physics that requires more investigation than the measurement of only 3 angles and 1 cp-phase.

- Neutrino mass ordering is a major remaining target with an active current and future experimental program.

Thank You.
Backup
$\nu_\tau$ Appearance in PINGU

*J.P.A.M. de André, NuFact 2014
$\nu_\tau$ Appearance in PINGU

- Direct measure of $U_{\tau 3}$

*J.P.A.M. de André, NuFact 2014*
\( \nu_\tau \) Appearance in PINGU

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*J.P.A.M. de André, NuFact 2014*
$\nu_\tau$ Appearance in PINGU

- Direct measure of $U_{\tau 3}$
- Energy and zenith angle excess in cascade channel
- PINGU plots currently use same initial Boosted Decision Tree as NMH, but secondary selection for `cascades’
$\nu_\tau$ Appearance in PINGU

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*J.P.A.M. de André, NuFact 2014*
Measuring $\nu_\tau$ Appearance

- High statistics allow possibility to measure

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INO-ICAL

- Magnetized Iron Calorimeter (ICAL)
- Underground lab in the Theni district
- 3 modular 17 kton pieces
  - 14.4m in height x 16m length x 16m width
  - 1.5 Telsa in central region
  - 5.6cm steel w/ gap for RPC
- Resistive plate chambers
- 52 kton
ORCA

- 115 vertical lines at KM3NeT-Fr site in Mediterranean
- 6-7 strings in ORCA configuration are funded as Phase 1
- Pursuing phase 1.5 with 115 lines at French KM3NeT site which would be deployed by 2019
ORCA Cosmic Ray Muon Background

- ORCA has no current plans for an instrumented veto
- Use topological and reconstruction cuts for removal
Early estimate of significance

On-going work to include more realistic Monte Carlo physics, systematics assessment, include background, geometry optimization, etc.