Neutrino oscillations at long-baseline experiments

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Current status in neutrino oscillations

Current allowed regions at $3\sigma$:

- $\theta_{12} : 31.3^\circ \rightarrow 35.9^\circ$
- $\theta_{13} : 7.8^\circ \rightarrow 9.1^\circ$
- $\theta_{23} : 38.3^\circ \rightarrow 53.3^\circ$
- $\delta : 0 \rightarrow 360^\circ$

$$\Delta m_{21}^2 : (7.02 \rightarrow 8.09) \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{\text{atm}}^2 : \begin{bmatrix} 2.3 & \rightarrow & 2.6 \\ -2.6 & \rightarrow & -2.3 \end{bmatrix} \times 10^{-3} \text{ eV}^2$$

Gonzalez-Garcia, Maltoni, Schwetz, 1409.5439

(see also 1312.2878 and 1405.7540)

NuFIT 2.0 (2014)
Neutrino tasks for the next 20 years

- is there CP violation in the leptonic sector? What is the value of $\delta$?
- what is the ordering of neutrino masses?
- which flavor of neutrinos dominates the third mass eigenstate?
- why is the mixing in the leptonic sector so different from the mixing in the quark sector? does the flavour of the SM obey a certain pattern? (flavour puzzle)
- are there more than three neutrino species?
- are neutrinos Majorana particles?
- why are neutrinos so light with respect to the charged leptons?
- what is the value of the lightest neutrino mass?
- are there non-standard neutrino interactions?
- ...
CP violation

$\delta \neq 0, \pi$ ?
Why CP violation?

• In the νSM, there are three possible sources of CP violation:
  - Quark mixing → large
  - Strong CP problem → tiny!! (if any)
  - Lepton mixing → ?? (at least one extra Dirac phase, and possibly two additional Majorana)

• The CKM phase is not enough for matter-antimatter asymmetry of the Universe

Leptogenesis? → see talk by P. di Bari
CP violation searches

Three-family $\nu_e$ appearance oscillation probability:

$$P_{\mu e}^{\nu_{\text{vac}}} \simeq \sin^2 2\theta_{13} X(\theta_{23}) \sin^2 \Delta_{31}$$

$$+ \sin 2\theta_{13} \cos \theta_{13} Y(\theta_{23}, \theta_{12}) \Delta_{21} \sin \Delta_{31} \cos(\delta + \Delta_{31})$$

$$+ Z(\theta_{23}, \theta_{12}) \Delta_{21}^2$$

Cervera et al, hep-ph/0002108
(see also e.g., Freund, hep-ph/0103300,
Akhmedov et al, hep-ph/0402175, and Asano,
Minakata, 1103.4387)

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E}$$

$$\epsilon \equiv \frac{\Delta_{21}}{\Delta_{31}}$$
1\textsuperscript{st} vs 2\textsuperscript{nd} oscillation maxima

Figure from Coloma and Fernandez-Martinez, 1110.4583 [hep-ph].

P. Coloma - $\nu$ oscillations
$1^{\text{st}}$ vs $2^{\text{nd}}$ oscillation maxima

Figure from Coloma and Fernandez-Martinez, 1110.4583 [hep-ph].
Long-baseline exps in the market

Slide adapted from Messier's talk at NuPhys14
Prospects for CP violation searches

DISCLAIMER: Plot for illustration purposes only: an accurate comparison depends on many factors!
Current hint for CP violation

The combination of current T2K and reactor experiments seems to indicate that CP is violated in the lepton sector:

P. Coloma - Neutrino oscillation phenomenology
Current hint for CP violation

Elevant, Schwetz, 1506.07685
(see also Gonzalez-Garcia, Maltoni and Schwetz, 1409.5439; Schwetz, hep-ph/0612223; Blennow, Coloma, Fernandez-Martinez, 1407.3274)
Ordering of neutrino masses
Why the mass ordering?

Why the mass ordering?

Giunti and Zavanin, 1505.00978 (see also Bilenky et al, hep-ph/0104218, or Blennow et al, 1005.3240, among others)
Reactor experiments at medium baselines

\[ P_{ee} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) \]

\[ - \sin^2 2\theta_{13} \left[ c_{12}^2 \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) + s_{12}^2 \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right) \right] \]

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Matter effects

In two-families:

$$P = \sin^2 2\theta_M \sin^2 \left( \frac{\Delta m^2_L L}{4E} \right)$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - A)^2} \ ; \ A = \frac{2EV}{\Delta m^2}$$

Wolfenstein ('78), Barger et al ('80), Mikheev and Smirnov ('85)
Matter effects in disappearance

- PINGU: 1401.2046
  see also Mena, Mocioiu, Razzaque, 0803.3044 and Akhmedov, Razzaque, Smirnov, 1205.7071

- ORCA @ KM3NET
  see e.g. 1402.1022 [astro-ph.IM]

- Hyper-Kamiokande
  1309.0184

- INO @ ICAL
  see e.g. Ghosh and Choubey, 1306.1423

- 50 kt LAr detector
  Barger et al, 1203.6012

Petcov, hep-ph/9805262
Akhmedov, hep-ph/9805272
Prospects for mass ordering

Blennow, Coloma, Huber and Schwetz, 1311.1822
(see also Blennow, 1311.3183, and Vitells, Read, 1311.4076)
Precise measurement of mass splittings

The ordering of neutrino masses may as well come from a global fit to different data.

Blennow, Schwetz, 1306.3988 [hep-ph]
(see also Li et al, 1303.6733 [hep-ph], for instance)
Precision

$\delta$ ?
Why precision?

Ballett, King, Luhn, Pascoli, Schmidt, 1410.7573 [hep-ph]
(see also, e.g., Ballett et al, 1503.07543, Girardi et al, 1410.8056 and 1504.00658, and Meloni, 1308.4578)
Precision in delta

\[
\begin{align*}
\Delta \delta & = 1 \sigma \\
\delta & \text{[°]}
\end{align*}
\]

T2K+NOvA

CKM precision

Future facilities

DISCLAIMER: Plot for illustration purposes only: the comparison depends on many factors!

See also Coloma, Donini, Fernandez-Martinez, Hernandez, 1203.5651
Cross section systematics

Coloma, Huber, Kopp and Winter, 1209.5973
(see also Huber, Mezzetto and Schwetz, 0711.2950, Day McFarland, 1206.6745)
Neutrons and missing E

Neutrons will be invisible even in Liquid Argon detectors

They carry away a significant fraction of energy in neutrino events
Conclusions

• The neutrino picture is far from being complete

• We are entering the precision Era in oscillations
  - systematics need to be under control!

• The ordering of neutrino masses will probably be the next milestone

• A strong CP violating signal may take longer to achieve. Again, systematics will be an issue here
Thank you!
Backup slides
Main ways to determine the MO

Interference in vacuum

Matter effects

Zhan et al, 0807.3203

Petcov, Piai, hep-ph/01102074
Choubey, Petcov, Piai, hep-ph/0306017

Wolfenstein ('78), Barger et al ('80), Mikheev and Smirnov ('85)