Synergies and complementarities between proposed future neutrino projects

Sushant Raut

IBS - Center for Theoretical Physics of the Universe, Daejeon, South Korea

NuFact 2017, Uppsala
28 September 2017
Neutrino Oscillations

- Standard three-flavour oscillation framework:

\[ U = U_{23} \times U_{13,\delta} \times U_{12} \]

\[ = \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 - \sin \theta_{23} & \cos \theta_{23}
\end{pmatrix} \begin{pmatrix}
\cos \theta_{13} & 0 & e^{i\delta} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\delta} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix} \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \]

- Atmospheric + LBL
- Reactor + LBL
- Solar + reactor

- Three mixing angles, two independent mass-squared differences, one CP-violating phase

\[ \Delta m^2_{31} \]

\[ \Delta m^2_{21} \]
## Known measurements

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1708.01186: de Salas, Forero, Ternes, Tortola, Valle
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NH or IH? 1708.01186: de Salas, Forero, Ternes, Tortola, Valle

LO or HO?  

$\delta_{CP}=$?
Beyond standard oscillations

$$\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}$$

Sterile neutrinos:
Additional 3 angles, 2 phases, 1 mass-squared difference

Non-standard propagation (Matter NSIs): Additional 6 amplitudes, 3 phases

$$V_{SM} \begin{pmatrix}
1 + \mathcal{E}_{ee}^m & \mathcal{E}_{e\mu}^m & \mathcal{E}_{e\tau}^m \\
\mathcal{E}_{\mu\mu}^m & \mathcal{E}_{\mu\tau}^m \\
h.c. & \mathcal{E}_{\tau\tau}^m
\end{pmatrix}$$
Beyond standard oscillations

\[
\begin{pmatrix}
\nu_e^{s/d} \\
\nu_\mu^{s/d} \\
\nu_\tau^{s/d}
\end{pmatrix}
= 
\begin{pmatrix}
1 + \mathcal{E}_{ee}^{s/d} & \mathcal{E}_{e\mu}^{s/d} & \mathcal{E}_{e\tau}^{s/d} \\
\mathcal{E}_{\mu e}^{s/d} & 1 + \mathcal{E}_{\mu\mu}^{s/d} & \mathcal{E}_{\mu\tau}^{s/d} \\
\mathcal{E}_{\tau e}^{s/d} & \mathcal{E}_{\tau\mu}^{s/d} & 1 + \mathcal{E}_{\tau\tau}^{s/d}
\end{pmatrix}
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
\]

Non-standard production/detection (Source/detector NSIs): Additional 9+9 amplitudes, 9+9 phases

Other ‘exotic’ scenarios: Decoherence, neutrino decay, extra dimensions, extra gauge interactions...
Current bounds

Sterile neutrinos:

Non-unitarity:

\[
\begin{align*}
\epsilon_{ee} &= -0.0012 \pm 0.0006 \\
|\epsilon_{\mu\mu}| &< 0.00023 \\
\epsilon_{\tau\tau} &= -0.0025 \pm 0.0017 \\
|\epsilon_{e\mu}| &< 0.7 \times 10^{-5} \\
|\epsilon_{e\tau}| &< 0.00135 \\
|\epsilon_{\mu\tau}| &< 0.00048 ,
\end{align*}
\]
Current bounds

Matter NSIs:

\[ |\varepsilon_{\alpha\beta}^\oplus| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix} \]

Source/detector NSIs:

\[ |\varepsilon_{\alpha\beta}^{ud}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ 1.8 \cdot 10^{-6} & 0.078 & 0.013 \\ 0.026 & 0.013 & 0.13 \end{pmatrix} \]

0907.0097: Biggio, Blennow, Fernandez-Martinez

Also see 1605.09284: Khan
Measuring the unknowns

\[
P_{\mu e} = 4 \sin^2 \theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1 - \hat{A})\Delta)}{(1 - \hat{A})^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(\hat{\Delta})}{\hat{\Delta}^2} \\
+ 2\alpha \sin \theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{CP}) \frac{\sin((1 - \hat{A})\Delta)}{(1 - \hat{A})} \frac{\sin(\hat{\Delta})}{\hat{\Delta}}
\]

where \( \alpha= \Delta m^2_{21}/\Delta m^2_{31} \), \( \Delta = \Delta m^2_{31} L / 4E \), \( \hat{A} = A / \Delta m^2_{31} \)

Measurements of the mass hierarchy, octant of \( \theta_{23} \) and \( \delta_{CP} \) are affected by parameter degeneracies
Why do we not know what we don’t know?

- Parameter degeneracies:
  \[ P(NH, \delta_{CP}) = P(IH, \delta_{CP}') \quad ; \quad P(\theta_{23}) = P(90-\theta_{23}) \]

See, for example:
1504.06283: Ghosh, Ghoshal, Goswami, Nath, SR
1406.2551: Coloma, Minakata, Parke
Degeneracies in neutrino parameter space

\[ \delta_{CP} \]

\[ 0^\circ \]

\[ 90^\circ \]

\[ 180^\circ \]

\[ 270^\circ \]

UHP

LHP
Degeneracies in neutrino parameter space
Degeneracies in neutrino parameter space

\[ \Delta m_{31}^2 < 0 \]

\[ \Delta m_{31}^2 > 0 \]
Degeneracies in neutrino parameter space

\[ \Delta m_{31}^2 < 0 \]

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\[ \theta_{23} > 45^\circ \]

\[ \theta_{23} < 45^\circ \]

NH, LO = IH, HO
Degeneracies in neutrino parameter space

\[ \Delta m^2_{31} < 0 \]

\[ \Delta m^2_{31} > 0 \]

- LHP: Left-Handed Neutrino
- UHP: Up-Handed Neutrino

\[ \theta_{23} > 45^\circ \]
\[ \theta_{23} < 45^\circ \]

- NH, LO = IH, HO
- NH, UHP = IH, LHP

Sushant Raut  NuFact 2017, Uppsala
Degeneracies in neutrino parameter space

\[ \Delta m^2_{31} < 0 \quad \text{for} \quad \theta_{23} > 45^\circ \]

\[ \Delta m^2_{31} > 0 \quad \text{for} \quad \theta_{23} < 45^\circ \]

- NH, LO = IH, HO
- NH, UHP = IH, LHP
- No degeneracy
Degeneracies in antineutrino parameter space

\[ \Delta m^2_{31} < 0 \]

\[ \Delta m^2_{31} > 0 \]

- \( \theta_{23} > 45^\circ \)
- \( \theta_{23} < 45^\circ \)

NH, HO = IH, LO

NH, UHP = IH, LHP

No degeneracy
Summary of degeneracies

Neutrinos

Antineutrinos
Summary of degeneracies

Neutrinos

Antineutrinos

0. If the best-fit value is in the ‘green’ area, we are lucky
1. If we end up in the yellow unshaded area, lift the octant degeneracy by collecting data with the opposite polarity
2. If we are in the shaded area, we need to resolve the hierarchy degeneracy. This can only be done in conjunction with another experiment that measures $\delta_{CP}$ or is insensitive to $\delta_{CP}$. 
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Different experiments have different L,E dependence, therefore their functional dependence on a given parameter $p$ is different.
Synergies between experiments

Different experiments have different L,E dependence, therefore their functional dependence on a given parameter p is different.

![Graph showing \( \Delta \chi^2 \) vs parameter (p) for expt 1 and expt 2, with a true solution line connecting two degenerate values for each experiment.](image)
Combined $\chi^2$ much higher than sum of the individual $\chi^2$: Synergy!
Future experiments

T2HK
T2HKK
ESSvSB
DUNE
JUNO
ICAL@INO
HK
PINGU
µDAR
MOMENT
Future experiments

- T2HK
- ESSvSB
- DUNE
- JUNO
- ICAL@INO
- HK
- PINGU

- μDAR
- T2HKK
- MOMENT

Distance intervals:
- <~20 km
- 200-2000 km
- 20-200 km
- O(1000-10000 km)
Future experiments

- T2HK
- T2HKK
- ESSνSB
- DUNE
- JUNO
- ICAL@INO
- HK
- PINGU
- μDAR
- MOMENT

- Superbeam
- Reactor
- Atmospheric μ decay
Future experiments
Future experiments

- T2HK
- T2HKK
- DUNE
- ESSνSB
- JUNO
- ICAL@INO
- HK
- PINGU
- CPV
- μDAR
- MOMENT
- mass hierarchy
- octant
Mass hierarchy

\[ P_{\mu e} = 4 \sin^2 \theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1 - \hat{A})\Delta)}{(1 - \hat{A})^2} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \]

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

Matter effects help to break the hierarchy-CP degeneracy
For favourable combinations of parameters, NOvA and T2K can determine the hierarchy very well.

1208.3644: Agarwalla, Prakash, SR, Uma Sankar

For unfavourable combinations, we need data from an expt that is either (a) insensitive to CP, (b) has more matter effects to break the degeneracy, or (c) has negligible matter effects in order to measure CP independently of the hierarchy.
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1212.1305: Choubey, Ghosh, Thakore

Also see 1203.3388: Blennow, Schwetz

1305.5539: Winter
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1307.2519: Barger et al.

1611.06118: Abe et al.
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1704.06116: Agarwalla, Ghosh, SR

See poster #64
JUNO: Mass hierarchy determination through spectral effects at L/E ~ solar mass-sq diff

1508.07166 (JUNO CDR)
Hint from T2K and NOvA for $\delta_{CP}$ around $-90^\circ$

Favourable part of the parameter space if the hierarchy is normal

Alex Sousa, at NuFact 2015 in Rio
CP violation

Synergy between NOvA and T2K helps constrain the wrong-hierarchy solution

Atmospheric neutrino expts which are typically insensitive to CP, can also improve CP measurement further by eliminating the wrong-hierarchy solution

1504.06283: Ghosh, Ghoshal, Goswami, Nath, SR
CP violation

DUNE + NOvA + T2K + atmos

1412.1744: Ghosh, Goswami, SR

T2HKK/T2HKK

1611.06118: Abe et al.

1703.07136: SR

T2HKK + DUNE
CP violation

\[
\lim_{A \to 0} \frac{dP_{\mu e}}{d\delta_{CP}} \propto \Delta \sin \Delta \sin(\Delta + \delta_{CP})
\]

CP sensitivity is greater at the second oscillation maximum ($\Delta = 3\pi/2$) than at the first one ($\Delta = \pi/2$)
CP violation

1511.02859: Blennow, Coloma, Fernandez-Martinez

1704.06116: Agarwalla, Ghosh, SR
CP violation

Combination of neutrino and antineutrino data helps in measuring $\delta_{CP}$ by breaking the degeneracy

1511.02859: Blennow, Coloma, Fernandez-Martinez

1704.06116: Agarwalla, Ghosh, SR
Octant of $\theta_{23}$

1308.5979: Ghosh, Ghoshal, Goswami, SR

Synergy in octant measurement: Note the effect of reactor data (prior on $\theta_{13}$)

\[
\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2) \\
= 4 \cos^2 \theta_{13} \sin^2 \theta_{23} (1 - \cos^2 \theta_{13} \sin^2 \theta_{23})
\]
Octant of $\theta_{23}$

DUNE

1307.2519: Barger et al.
Sterile nus

hierarchy, octant, CP measurements

CC NSIs  NC NSIs  non-unitarity  etc.
Beyond standard oscillation scenarios:
CC NSIs (production/detection),
NC NSIs (propagation),
Sterile neutrinos,
Non-unitarity, ...

Q1: How does the presence of new physics affect the measurement of the standard neutrino parameters?
Q2: Can the new physics parameters be measured?
Beyond standard oscillation scenarios:

CC NSIs (production/detection),
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Q1: How does the presence of new physics affect the measurement of the standard neutrino parameters?
Q2: Can the new physics parameters be measured?

an opportunity to probe BSM physics!
Sterile neutrinos

DUNE: Expansion of the parameter space leads to octant-$\delta_{CP}-\delta_{14}$ degeneracy

Unlike the hierarchy-$\delta_{14}$ degeneracy, the octant-$\delta_{14}$ degeneracy is more difficult to resolve, even with a combination of neutrino and antineutrino data

1605.04299: Agarwalla, Chatterjee, Palazzo

1704.04771: Ghosh, Gupta, Matthews, Sharma, Williams
Degeneracies and their possible removal at T2HKK and DUNE
To probe CC NSIs (at source and detector) without interference from the NC NSIs (in propagation), use a low-energy experiment to reduce matter effects.

**Eg. ESSnuSB**
1507.02868: Blennow, Choubey, Ohlsson, SR

**Eg. MOMENT**
1705.09500: Tang, Zhang

In preparation: Agarwalla, Ghosh, SR
NC NSIs (in propagation) are best probed with large matter effects. Eg. DUNE, T2HKK, atmospheric neutrino experiments.
Degeneracies in measuring CPV at DUNE, T2HK and T2HKK (hierarchy unknown)

1612.01443: Liao, Marfatia, Whisnant
Summary: A flowchart for the future?

- Expt data consistent with standard osc?
  - YES
    - Degeneracy?
      - NO
        - More work needed (Sterile, NSI, etc)
      - YES (Hierarchy degen)
        - Boring, but easy
      - YES (Octant degen)
        - Low energy, eg. second osc max
    - NO
      - Large matter effects: LBL or atmospheric
      - Run in nu+antinu modes
  - NO
    - More work needed
THANK YOU