Measuring the Leptonic CP Phase in Neutrino Oscillations with Non-Unitary Mixing

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NBIA PhD School: Neutrinos Underground & in the Heavens II

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Fact$^5$: 

Fact\textsuperscript{5}: Neutrinos have Mass

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And they Oscillate!

Two basis! Mass and Flavor

http://lbne.fnal.gov/

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Interaction (flavor) basis

$$\nu_\alpha, \alpha = e, \mu, \tau, 4, 5...N$$

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Mass Basis

\( \nu_i, \ i = 1, 2, 3, ...N \)

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There are two basis:

\[ \nu_\alpha = U_{\alpha i} \nu_i \]
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$U$ mixing is unitary. But parts of it not!

$U_{\alpha i}$

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If $N > 3$ and $M_h \gg E_{\text{exp}}$

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Unitary

Non-Unitary

Acessible through Oscillation

---

Fear Not: only more 6 parameters needed!

It can be shown that $^2$:

$$N = \begin{pmatrix}
\alpha_{11} & 0 & 0 \\
\alpha_{21} & \alpha_{22} & 0 \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{pmatrix}.U_{PMNS}$$

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Total: 6 more parameters. 3 of them are real.
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Total: 6 more parameters. 3 of them are real.

Only 3 ($\alpha_{11}, \alpha_{22}$ and $\alpha_{21}$) are accessible through $\nu_{e(\mu)} \rightarrow \nu_{\mu(e)}$

In unitary: Probability add to 1

Neutrino Source

Unitary Propagation:

Neutrino Detector
In non-unitary: Probability Don’t add to 1

Unitary Propagation:

Non-Unitary Propagation:
Non-unitary basis is not Orthogonal!

Unitary

\[
\begin{align*}
\hat{x} & \quad \hat{y} \\
\hat{y} & \quad \hat{z} \\
\nu_e & \quad \nu_\mu \\
\nu_\tau &
\end{align*}
\]
Non-unitary basis is not Orthogonal!

Non-Unitary

\[ \hat{x}, \hat{y}, \hat{z} \]

\[ \nu_e, \nu_\mu, \nu_\tau \]
Non-unitary basis is not Orthogonal!

The three neutrino basis is not orthogonal!
This means that you can have 0-distance ‘oscillation’ (transition):

\[ \text{F. Ge, P. Pasquini, et. al., ARXIV:1605.01670} \]
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$$\langle \nu_\alpha(0) | \nu_\beta(0) \rangle \neq 0$$

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In fact, the \(\nu_\mu \rightarrow \nu_e\) transition probability changes to\(^3\),

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New Phenomenon: 0-Distance and CP-phase

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\[
P_{\mu e}^{NU} = \alpha_{11}^2 \left( \alpha_{22}^2 P_{\mu e} + 2\alpha_{22} \text{Re}(\alpha_{21}^* S_{ee} S_{e\mu}^*) + |\alpha_{21}|^2 P_{ee} \right)
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\]

\[
(S_{\alpha\beta} = \langle \nu_\alpha^{\text{unitary}}(L) | \nu_\beta^{\text{unitary}}(L) \rangle)
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$$P_{ee}(0) = 1$$

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Survival Prob. \( P_{ee}(0) = 1 \)

Complex parameter with a **new** CP phase (\( \phi \))!

\(^3\) F. Ge, P. Pasquini, et. al., ARXIV:1605.01670
Why do we care?

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4 Miranda, O. G., et. al., ARXIV:1604.05690

Why do we care?

Non-unitary can lead to CP-phase ambiguity\textsuperscript{4}!

\textsuperscript{4} Miranda, O. G., et. al., ARXIV:1604.05690

Why do we care?

Non-unitary can lead to CP-phase ambiguity$^4$!

That’s because $|\alpha_{21}|$ can be as large as$^2 \sim 3\%$

---

$^4$ Miranda, O. G., et. al., ARXIV:1604.05690

We can see that by two plots:

From: \(^3\) F. Ge, P. Pasquini, et. al., ARXIV:1605.01670
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\[ P_{\mu e} \text{ for differents } \delta_{CP} \text{ and } \phi. \]

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The ration \( R \) between the contributions of \( \delta_{CP} \) and \( \phi \) to \( P_{\mu e} \)

From: ³ F. Ge, P. Pasquini, et. al., ARXIV:1605.01670
\( \phi \) can mimic \( \delta_{CP} \)

We can see that by two plots:

\[ \begin{align*}
P_{\mu e} & : \delta_{CP} = 0 \text{ and } \alpha_{21} = 0, \quad \delta_{CP} = 3\pi/2 \text{ and } \alpha_{21} = 0, \quad \delta_{CP} = 0 \text{ and } \alpha_{21} = 0.02 \\
R_{a} & : \alpha = 2.5\% \text{ and } R: \ c_{\phi} \text{ and } s_{\phi} \text{ and } c_{\phi+\delta} \text{ and } s_{\phi+\delta} \text{ contributions.}
\end{align*} \]

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T2(H)K experiment is awesome!

What about in Experimental Setup?

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one of T2K and T2HK goal is to measure $\delta_{CP}$

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The experiment consists of neutrinos flux from pion decay at Tokay

From: 5 Abe, K. and others, PTEP 2015, no. 4, 043C01 (2015)
Neutrinos from Pion Decay

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Another really nice technic is used:

protons

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Another really nice technic\textsuperscript{5} is used:

\begin{itemize}
\item protons
\item Graphite
\end{itemize}

\footnote{Abe, K. and others, PTEP 2015, no. 4, 043C01 (2015)}
Another really nice technic\textsuperscript{5} is used:

\textbf{Graphite}

\begin{align*}
\pi &\sim 94\% \\
K &\sim 6\%
\end{align*}

\textsuperscript{5} Abe, K. and others, PTEP \textbf{2015}, no. 4, 043C01 (2015)
T2(H)K experiment is awesome!

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Size: 50 kton (560 kton) and Base Line: 295 km

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T2K and T2HK says they can measure the $\delta_{CP}$:

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Or can they?

We performed the analysis on T2K and T2HK considering non-unitary:

From: 5 Abe, K. and others, PTEP 2015, no. 4, 043C01 (2015)
T2K and T2HK cannot measure $\delta_{CP}$

The effect of including non-unitarity at T2K [$\delta_{trueCP} = -90^\circ$, NH]

- Unitary
- Non-Unitary
- Non-Unitary + Prior

The effect of including non-unitarity at T2HK [$\delta_{trueCP} = -90^\circ$, NH]

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Should we give up on T2(H)K $\delta_{CP}$?

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So what happens to the $\delta_{CP}$ sensibility?

From: \textsuperscript{6} J. Evslin at. al., JHEP 02, 137 (2016)
Should we give up on T2(H)K $\delta_{CP}$?

The effect of including non-unitarity at T2K+$\mu$SK [$\delta_{CP}^{true} = -90^\circ$, NH ]

The effect of including non-unitarity at T2HK+$\mu$HK [$\delta_{CP}^{true} = -90^\circ$, NH ]

From: 6 J. Evslin at. al., JHEP 02, 137 (2016)
Non-unitary can mimic $\delta_{CP}$
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T2K and T2HK suffer from this and loses sensibility.
Non-unitary can mimic $\delta_{CP}$

T2K and T2HK suffer from this and loses sensibility.

It is possible to recover T2(H)K sensibility by couple it to $\mu$DAR
Using a very near detector (20 m) to probe $P_{\mu e}(0) = |\alpha_{21}|^2$
Model Dependent Couplings

\[ |\alpha_{11} \alpha_{21}| \]

\[ M \text{ [GeV]} \]
DUNE Sensibility?

![Graph showing event rates and resolution for DUNE and T2K experiments.]

- **DUNE (1300 km)**
  - 3 σ Resolution
  - \( L/E = 550 \)

- **T2K (12y on \( \nu_e \)) [L=295 km]**
  - Event Rate \([\text{MeV}^{-1}]\)