Sensitivity to CP Violation in Lepton Sector with T2K-II and NOνA Experiments

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In cooperation with Dr. Cao Son (KEK)
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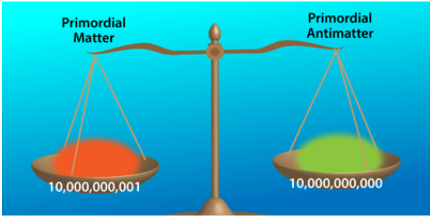
Windows on the Universe, Quy Nhon, August 7, 2018

Outline

Introduction

- At the early universe (Big Bang) the amounts of matter and antimatter are supposed to be equal
- Observed universe: matter-antimatter asymmetry



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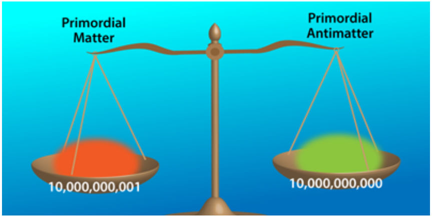

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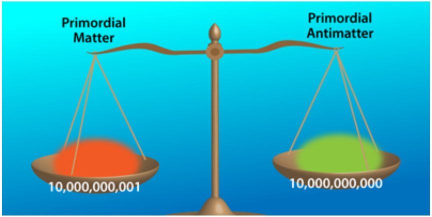

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- In quark sector, small CPV strength $\mathcal{O}(10^{-5})$ leads to small matter-antimatter asymmetry $\mathcal{O}(10^{-18})$ compared to observed value $\mathcal{O}(10^{-10})$

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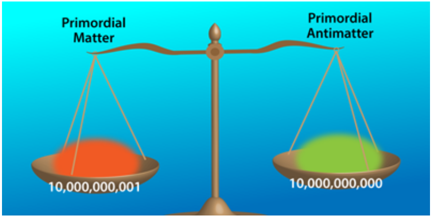

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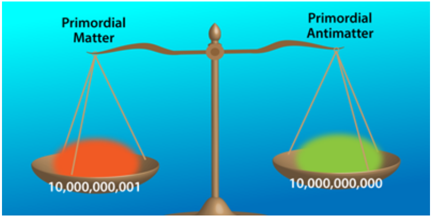

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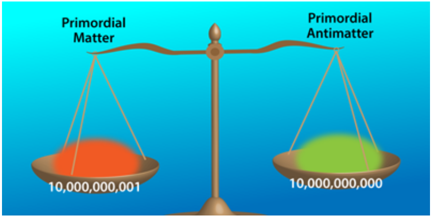

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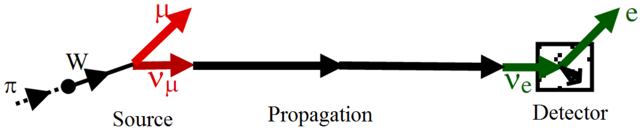
CP violation in lepton sector

- **Neutrino oscillation** phenomenon may provide new source of CPV in lepton sector



- 3-flavor neutrino oscillation model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates — PMNS matrix — mass eigenstates

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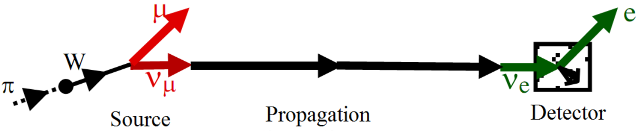

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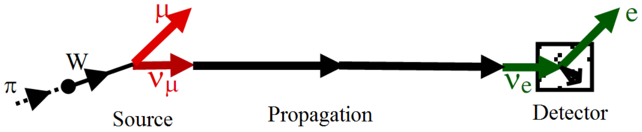

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Measurements at long baseline ν oscillation experiments

- Disappearance channels $P(\nu_\mu \to \nu_\mu)$, $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$: sensitive to θ_{23} and Δm^2_{32}
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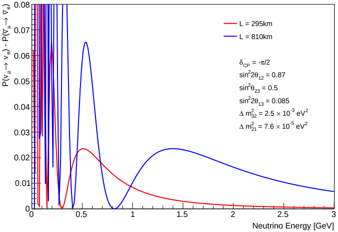
$$\begin{aligned}\mathscr{A}_{\mathrm{CP}} &= P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \\ &= -16 s_{12} s_{13} s_{23} c_{12} c_{13}^2 c_{23} \sin\delta_{CP} \sin\Delta_{21} \sin\Delta_{31} \sin\Delta_{32}\end{aligned}$$



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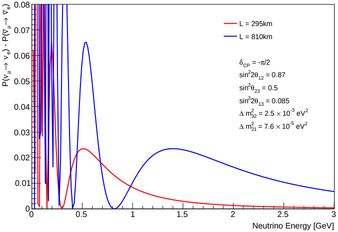
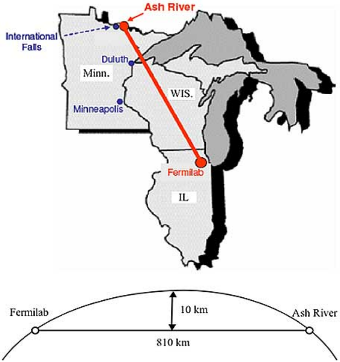


T2K(-II) and NOvA experiments

Off-axis long baseline neutrino oscillation experiments



T2K(-II): Tokai to Kamioka

NOvA: NuMI Off-axis ν_e Appearance

T2K(-II) and NOvA experiments

- Current central goals:
  - measure δ_{CP}
  - define mass hierarchy (sign of Δm^2_{32})
- T2K(-II) is proposed to run up to 2026 :
  - collect total 20×10^{21} POT
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	$\sin^2 2\theta_{12}$	$\sin^2 2\theta_{13}$	$\sin^2 \theta_{23}$	$\Delta m^2_{21}(eV^2/c^4)$	$\Delta m^2_{32}(eV^2/c^4)$
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Experiment setup in GLoBES

For T2K-II

http://inspirehep.net/record/1478189?ln=en

- Update: flux, operation years, ...
- Efficiencies:
  - ν_e sample signal: 66.3%; $\bar{\nu}_e$ sample signal: 69.7%
  - ν_μ sample signal: 72.6%; $\bar{\nu}_\mu$ sample signal: 80.2%
- Sys. uncertainties: 4% for all signal samples

For NOvA

http://inspirehep.net/record/1516801?ln=en

- Efficiencies:
  - ν_e sample signal: 60.0%; $\bar{\nu}_e$ sample signal: 71.5%
  - ν_μ sample signal: 31.9%; $\bar{\nu}_\mu$ sample signal: 38.0%
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Sensitivity to CP violation

T2K-II event rates

- The appearance event rates in T2K-II far detector with 10×10^{21} POT ν-mode: 10×10^{21} POT $\bar{\nu}$-mode at three different values of $\delta_{CP} = -\pi/2$, 0, $+\pi/2$.

	δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode ν_e sample	$-\pi/2$	558.8	448.6	2.8	73.3	1.8	32.3
	0	466.3	354.9	4.0	73.3	1.8	32.3
	$+\pi/2$	370.9	258.6	4.9	73.3	1.8	32.3
$\bar{\nu}$-mode $\bar{\nu}_e$ sample	$-\pi/2$	115.8	19.8	52.3	29.2	0.4	14.1
	0	134.6	16.2	74.7	29.2	0.4	14.1
	$+\pi/2$	149.3	11.8	93.8	29.2	0.4	14.1

Result from GLoBES

Sensitivity to CP violation

NOvA event rates

- The appearance event rates in NOvA far detector with 36×10^{20} POT ν-mode: 36×10^{20} POT $\bar{\nu}$-mode at three different values of $\delta_{CP} = -\pi/2$, 0, $+\pi/2$.

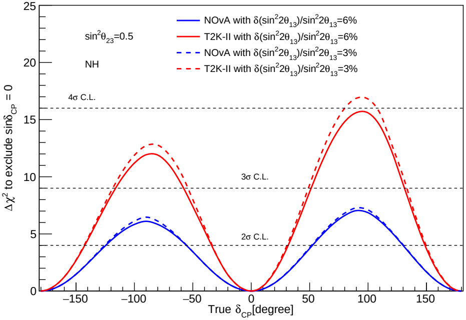
	δ_{CP}	Total	Signal	ν_μ beam CC	ν_μ beam NC +cosmic	ν_e beam
ν-mode ν_e sample	$-\pi/2$	266.1	192.4	5.7	39.5	28.5
	0	239.4	165.7	5.7	39.5	28.5
	$+\pi/2$	195.6	121.9	5.7	39.5	28.5
$\bar{\nu}$-mode $\bar{\nu}_e$ sample	$-\pi/2$	63	33.8	2.1	13	14.1
	0	78.9	49.7	2.1	13	14.1
	$+\pi/2$	87.5	58.3	2.1	13	14.1

Result from GLoBES

Sensitivity to CP violation

Constraint on θ_{13} from reactor

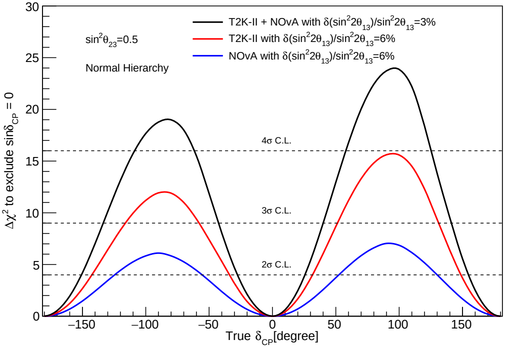
- Reduce θ_{13} uncertainty from 6% to 3%, fractional region of δ_{CP} values to exclude $\sin\delta_{CP} = 0$:
  - At 3σ C.L. for T2K-II: increases from 39.9% to 42.0%
  - At 2σ C.L. for NOvA: increases from 40.8% to 41.4%



Sensitivity to CP violation

Combined T2K-II and NOvA

- T2K-II + NOvA + constraint on θ_{13} from reactor: $\sin\delta_{CP} = 0$ can be excluded at 4σ C.L. with fractional region of δ_{CP} values up to 32.4%

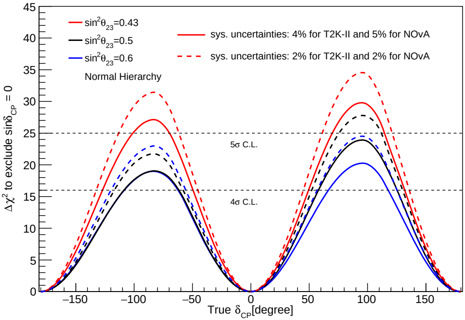


Sensitivity to CP violation

Reduction in systematic uncertainties

- Systematic uncertainties: 2% for both T2K-II and NOvA, CPV can be observed at 5σ C.L. with fractional region of δ_{CP} values:

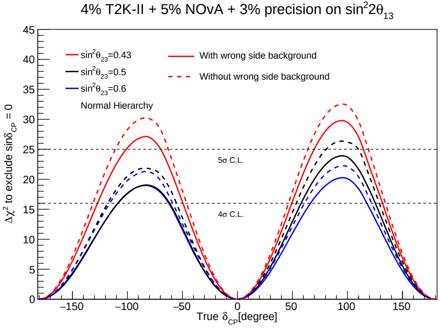
- 31.2% if $sin^2\theta_{23} = 0.43$
- 10.4% if $sin^2\theta_{23} = 0.50$
- 0.0% if $sin^2\theta_{23} = 0.60$



Sensitivity to CP violation

Removal of wrong-sign backgrounds

- If the wrong-sign backgrounds in ν_e and $\bar{\nu}_e$ samples are removed completely: The sensitivity to CPV at 5σ C.L. with fractional region of δ_{CP} values increases:
  - for $\sin^2\theta_{23} = 0.50$: from 0.0% to 8.1%
  - for $\sin^2\theta_{23} = 0.43$: from 21.4% to 28.6%



Conclusion

- With a combined analysis of T2K-II and NOvA at the end of their runs with ultimate constraint on θ_{13}, CP violation can be observed at 4σ C.L. if $\delta_{CP} \sim -\pi/2$.
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