Improving CP Measurement with Muon Decay at Rest

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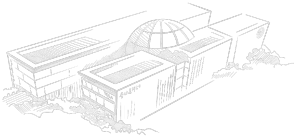
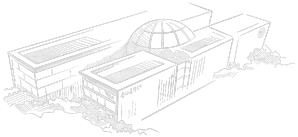
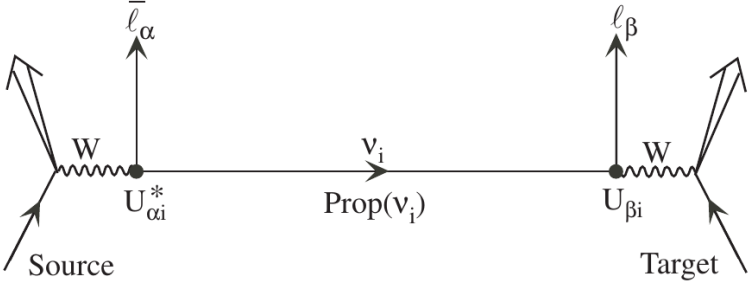


Content



Neutrino oscillation



Boris Kayser, arXiv:hep-ph/0506165

Neutrino flavor eigenstate $|\nu_\alpha\rangle \xleftrightarrow{|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle}$ Neutrino mass eigenstate $|\nu_i\rangle$

First evidence of physics beyond the Standard Model!

CP in Neutrino oscillation

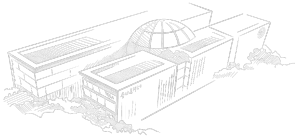
$$P_{\alpha\beta} = \delta_{\alpha\beta} \quad -4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2(\Delta m^2_{ij}\tfrac{L}{4E})$$
$$+2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\tfrac{L}{2E}\right)$$

where

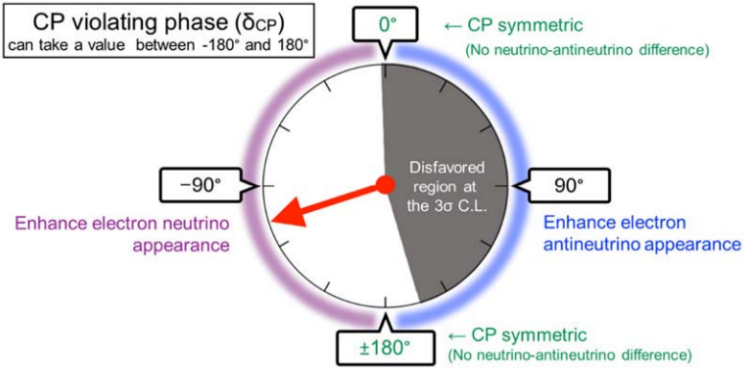
$$U_{\mathrm{PMNS}} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}s_{23} \end{bmatrix}$$

CP-sensitive oscillation channel:

$$P_{\bar{\mu}\bar{e}} - P_{\mu e} \propto \sin\delta_{CP}$$



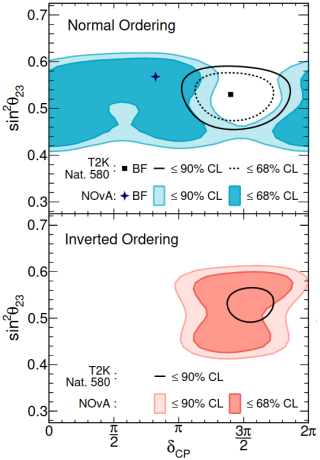
Current Status: T2K experiment



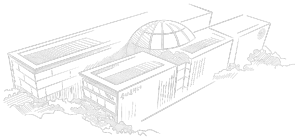
T2K experiment, https://www.kyoto-u.ac.jp/en/research-news/2020-04-21

Current Status: NOνA experiment

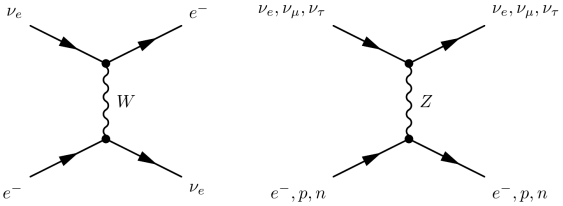
NOνA experiment, arXiv:2108.08219



- The results are in tension
- Need more precise measurement!



Matter Effect



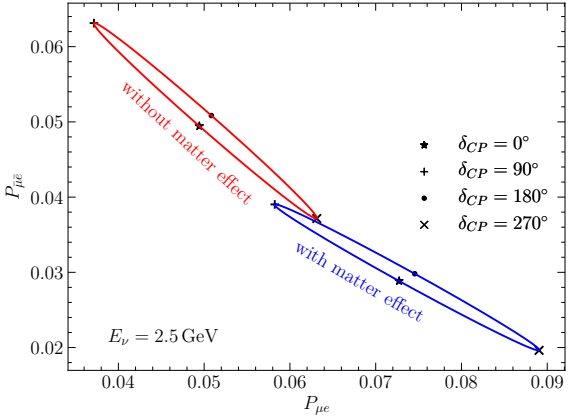
In flavor space,

$$\mathcal{H}_F = \frac{1}{2E}(U\mathbb{M}^2U^\dagger + \mathbb{A})$$

$$\mathbb{M}^2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix}, \mathbb{A} = \begin{bmatrix} 2\sqrt{2}E_\nu G_F N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

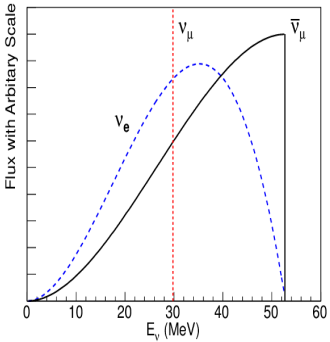
Degeneracy

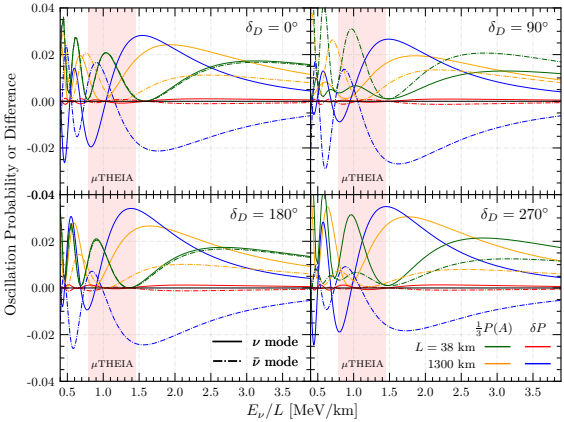
- A non-zero δ_{CP} makes $P_{\mu e} \neq P_{\bar{\mu}\bar{e}}$
- A non-zero matter effect can also make $P_{\mu e} \neq P_{\bar{\mu}\bar{e}}$ even if $\delta_{CP} = 0$



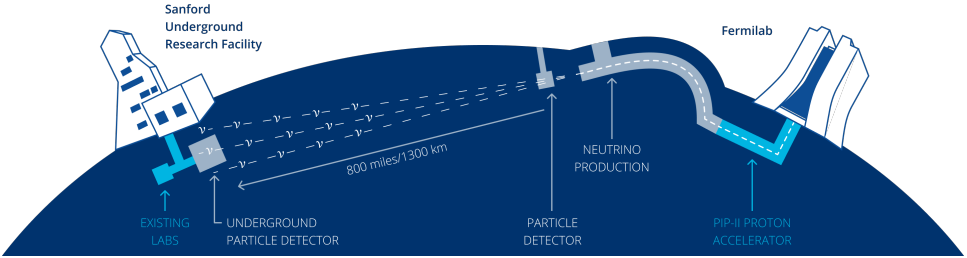
One Solution

- A low-energy neutrino beam can resolve this degeneracy
- **Neutrinos from muon decay at rest** satisfy this requirement



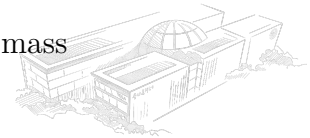


DUNE



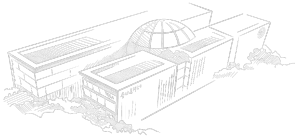
Fermilab, https://lbnf-dune.fnal.gov/how-it-works/neutrino-beam/

- A wide-band neutrino spectrum, E_ν peaks at $\sim$2.5 GeV
- Four Liquid-Argon far detectors, each has 10 kt fiducial mass
- However, it cannot detect low energy $\bar{\nu}_e$

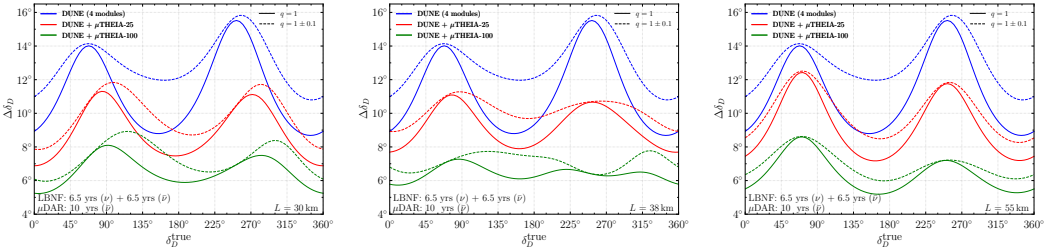


THEIA

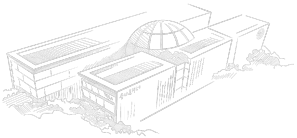
- A proposed Water-based Liquid Scintillator (WbLS)
- Locate at the same place as DUNE far detector
- **Can measure low-energy μDAR neutrinos effectively**!



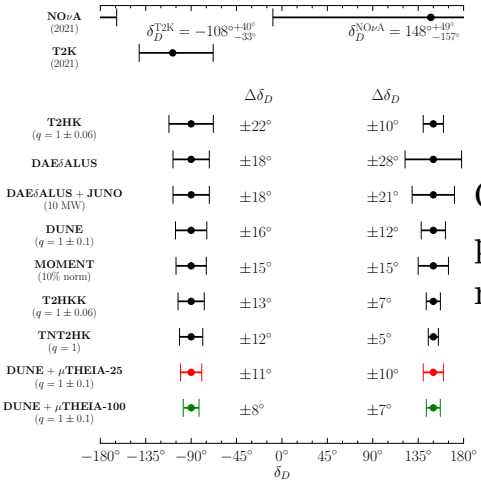
CP sensitivity



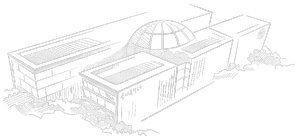
Enhance CP sensitivity significantly!



Compare with Other Experiments

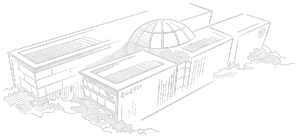


One of the most sensitive experiments for CP measurement!

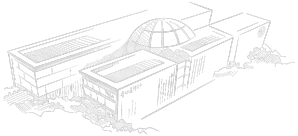


Summary

- Currently, there is still a long way to go for measuring CP
- CP sensitivity can be reduced due to matter effect
- An additional low-energy neutrino beam can resolve the degeneracy and enhance CP sensitivity significantly



Thanks



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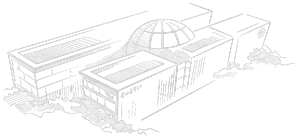

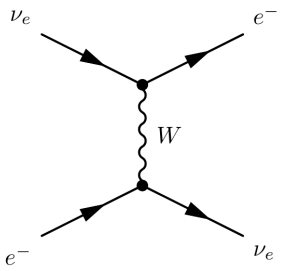

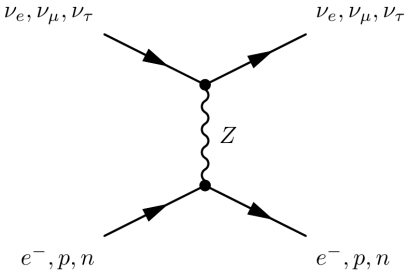

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$$
\begin{aligned}
P_{\substack{\nu_\mu \to \nu_e \\ \bar{\nu}_\mu \to \bar{\nu}_e}} &\approx \alpha^2 \sin^2 2\theta_s c_a^2 \frac{\sin^2(A\Delta_a)}{A^2} + 4 s_r^2 s_a^2 \frac{\sin^2[(1 \mp A)\Delta_a]}{(1 \mp A)^2} \\
&+ 2\alpha s_r \sin 2\theta_s \sin 2\theta_a \cos(\Delta_a \pm \delta_D) \\
&\times \frac{\sin(A\Delta_a)}{A} \frac{\sin[(1 \mp A)\Delta_a]}{(1 \mp A)}.
\end{aligned}
$$