Long-baseline neutrino oscillation sensitivity with Theia

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Neutrino mixing and oscillation

PMNS matrix:

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

$$P(\nu_\mu\to\nu_e)-P(\bar\nu_\mu\to\bar\nu_e)=$$

ME $\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$ ← Small

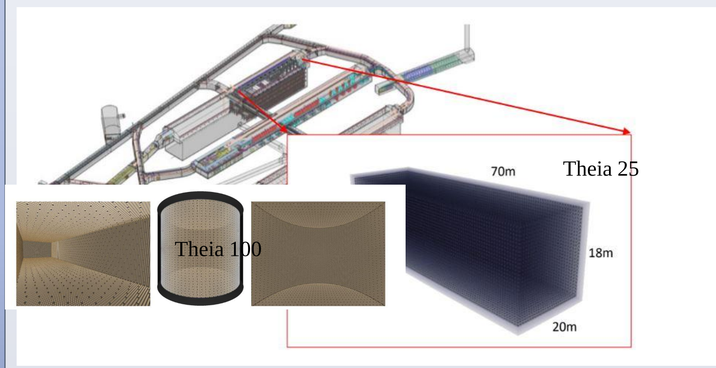
ME $-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$ ← Proportional to L

CPV $-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta\,s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$ ← What we want

with $A=2\sqrt{2}G_F n_e E=7.6\times10^{-5}\,\mathrm{eV}^2\cdot\frac{\rho}{\mathrm{g\,cm^{-3}}}\cdot\frac{E}{\mathrm{GeV}}$

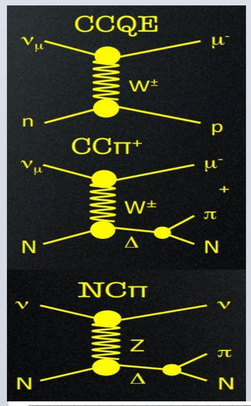
- A non-zero Θ_{13} has been measured.
- Different appearance probability between ν and anti-ν indicates the CP phase.

Theia detector

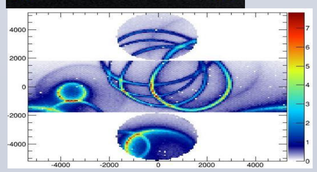


Theia has proposed two possible masses of 25 kt and 100 kt with features:
- large-scale water-based liquid scintillator
- Advanced photo-sensor technology with improvements in time resolution, light collection, spatial granularity etc.
- Multiple complementary and advanced reconstruction techniques

Neutrino detection and reconstruction

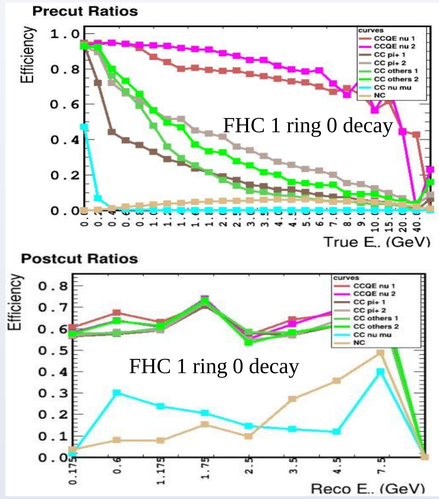


- Main neutrino interaction channels at GeV:
  - CCQE: ν_e 0 decay electrons ; ν_μ typically 1 decay electron
  - CCπ+ : 1, 2 or 3 rings; ν_e 1 decay electron ; ν_μ 2 decay electrons
  - NC π : NCπ0 can be mis-ided as an electron ; NC π+ can be mis-ided as either μ or e.
- As a reconstruction package, FiTQun is now exclusively used for all T2K oscillation analysis
- For any hypothesis of final state particles, predict the charge and hit recorded by every PMT



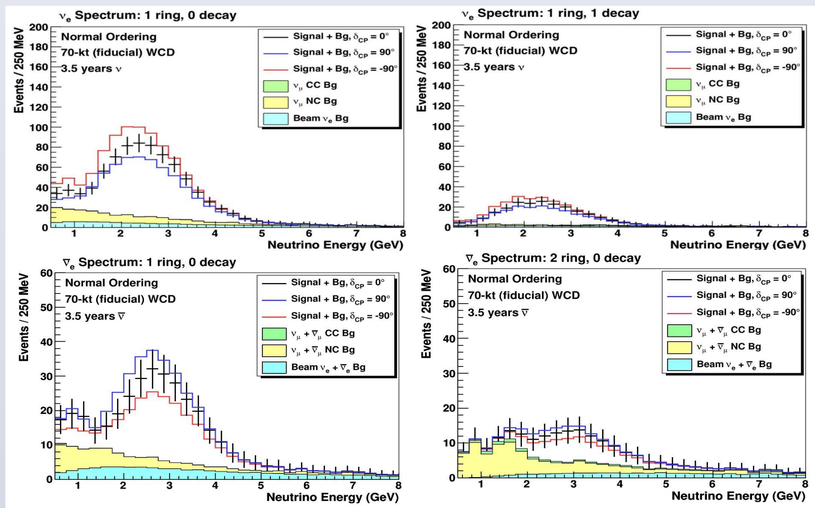
- FiTQun can handle any number of reconstructed tracks in the water detector
- Event hypotheses are distinguished by comparing best-fit likelihoods.

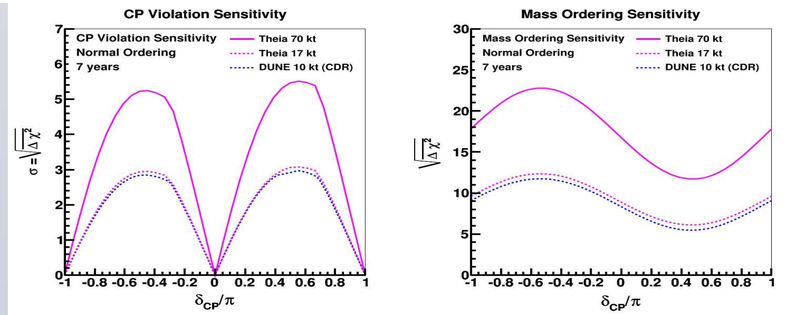
Background reduction



- BDT has been used for the background reduction for each i-ring j-decay sample (i from 1-3, j from 0-1).
- T2K-like fully contained fiducial volume cuts have been applied as pre-cuts.
- Variables with FiTQun after the pre-cuts:
  - vertex, distance to wall, direction
  - pi0 fit momenta, likelihood, angle, mass
  - 1-ring fit: momenta, likelihood
  - 2-ring fit: kinematics, differences between the best fit likelihoods of each combination (e-like or pi-like)
  - 3-ring fit: similar to the 2 ring case, with all possible differences between the best fit likelihood of each combination (e-like and pi-like)
- Energy-dependent BDT cuts are applied to the samples after the pre-cuts.

Long-baseline sensitivity





- There are totally 9 samples included in the sensitivity study.
  - FHC:
    - 1-ring, 0 or 1-decays
    - 2-rings, 0 or 1-decays
    - 3-rings, 0 or 1-decays
  - RHC:
    - 1-ring, 0-decay
    - 2-rings, 0-decay
    - 3-rings, 0-decay
- Full set of spectra: Eur. Phys. J. C 80, 416 (2020). https://doi.org/10.1140/epjc/s10052-020-7977-8
- The CP and mass hierarchy sensitivities with a 25 kt (fiducial) Theia module are comparable to a 10 kt (fiducial) DUNE module.

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