Improving CP Measurement with Muon Decay at Rest

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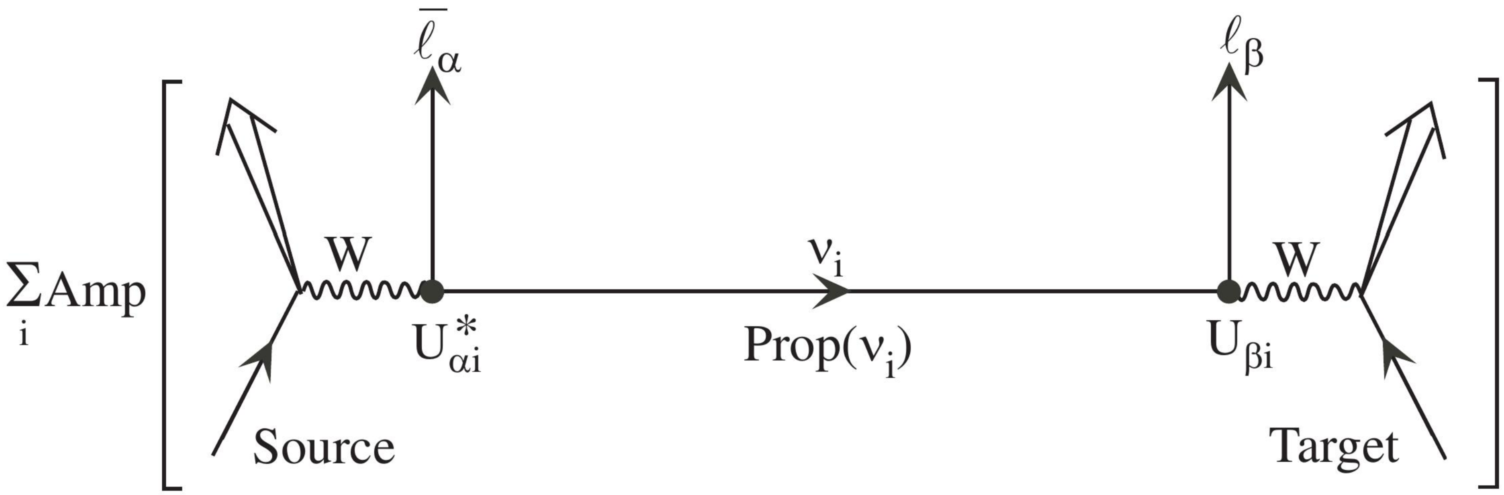
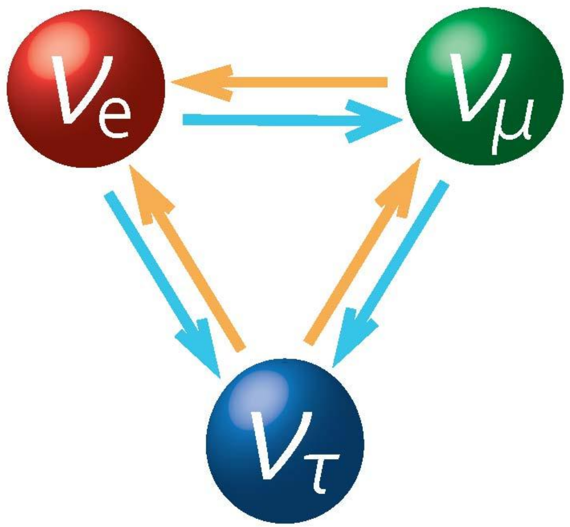
ν Here, There & Everywhere

Neutrino oscillation





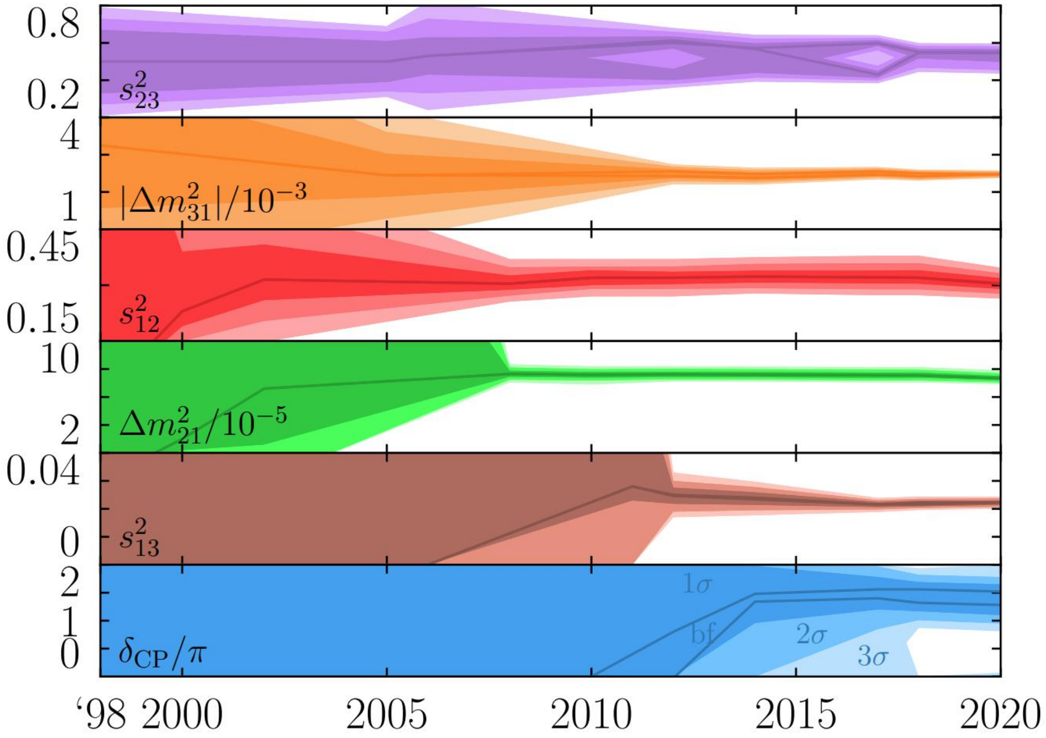
Kayser [arXiv:hep-ph/0506165]

First evidence of physics beyond the Standard Model !

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

Neutrino oscillation

three mixing angles + two squared mass differences + one Dirac CP phase



Denton et al,
[arXiv:2212.00809]

MINOS, T2K, NOvA, IceCube, SK...

MINOS, T2K, NOvA, IceCube, SK

KamLAND

KamLAND

Daya Bay, RENO, Double Chooz

T2K, NOvA →

CP in neutrino oscillation

Oscillation probability in vacuum:

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

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\beta \to \nu_\alpha)$$

CP-sensitive oscillation channel:

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

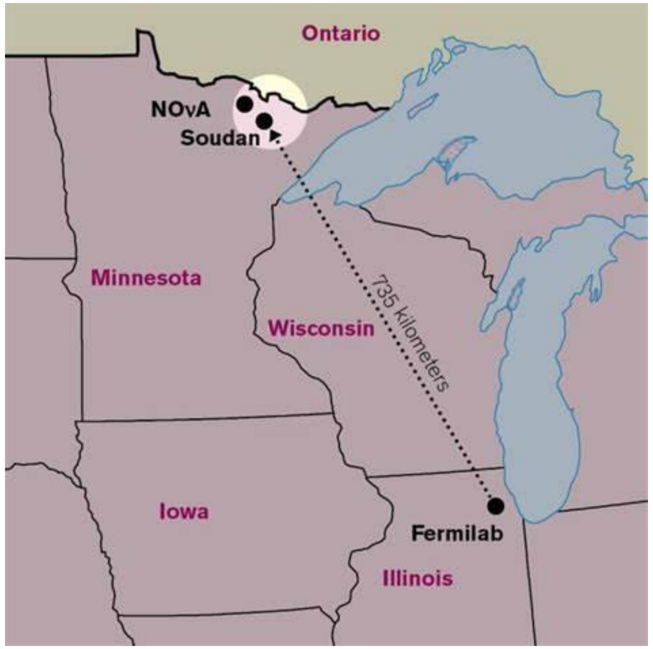
accelarator neutrino experiments

Current status of CP measurement

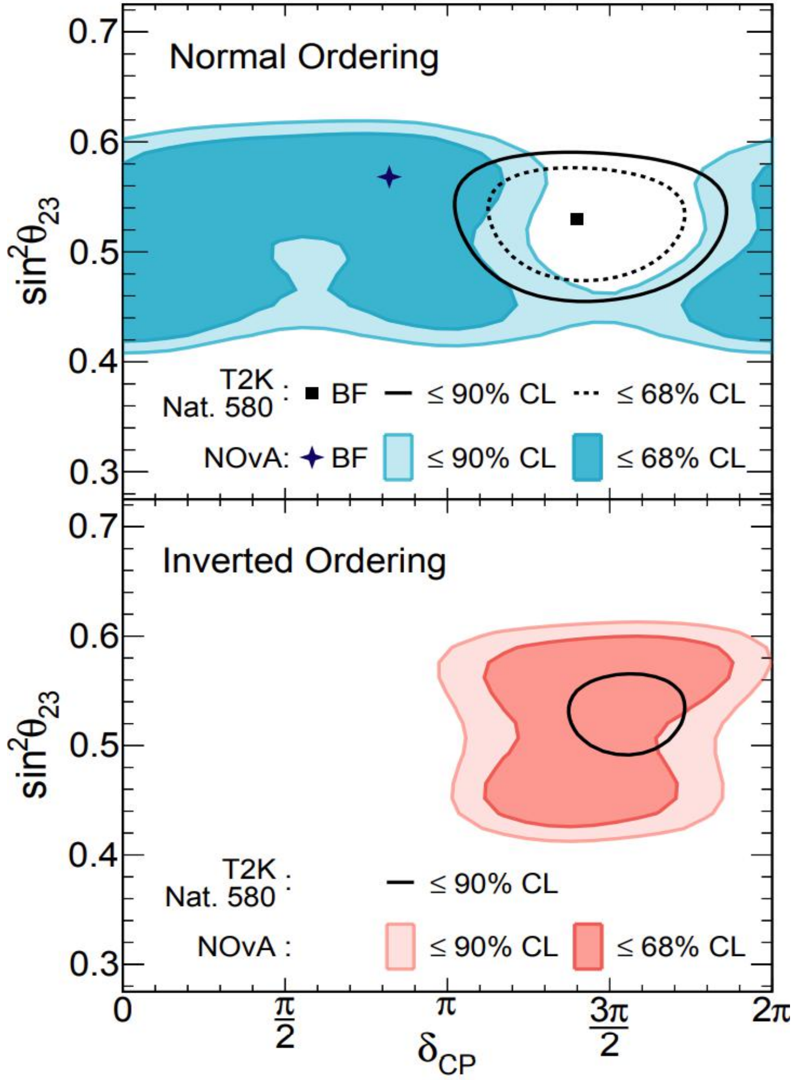
T2K

credit: APS

NOvA



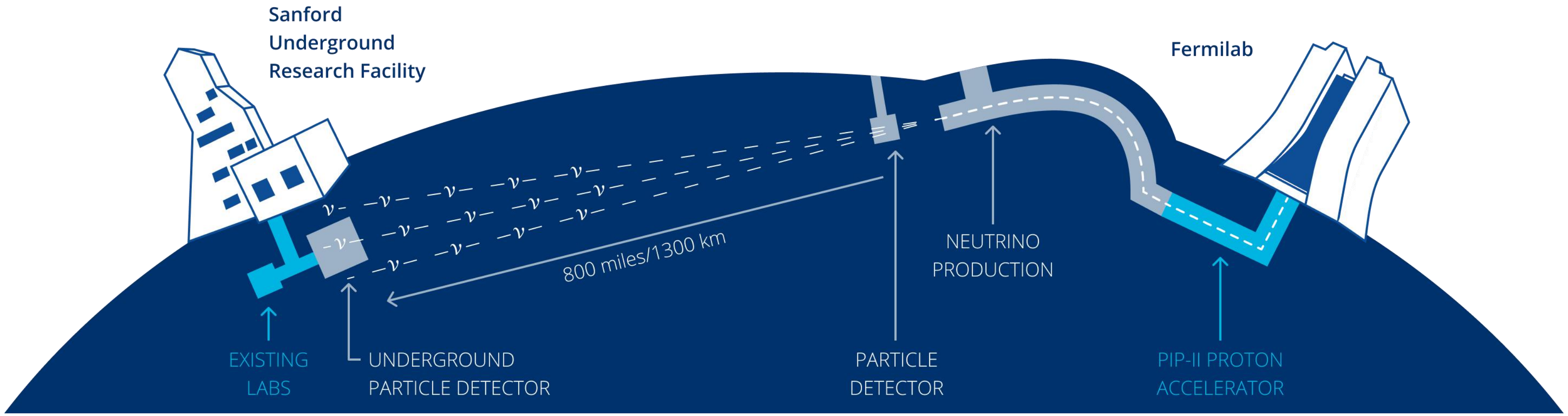
credit: livescience



NOvA Collaboration [arXiv:2108.08219]

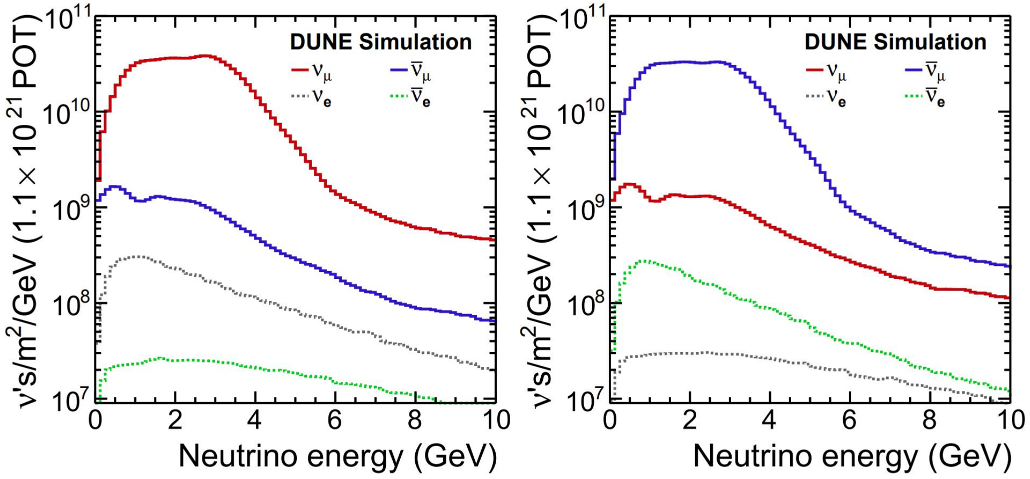
- The results are in tension
- Next-generation experiments are needed

Next-generation experiment: DUNE



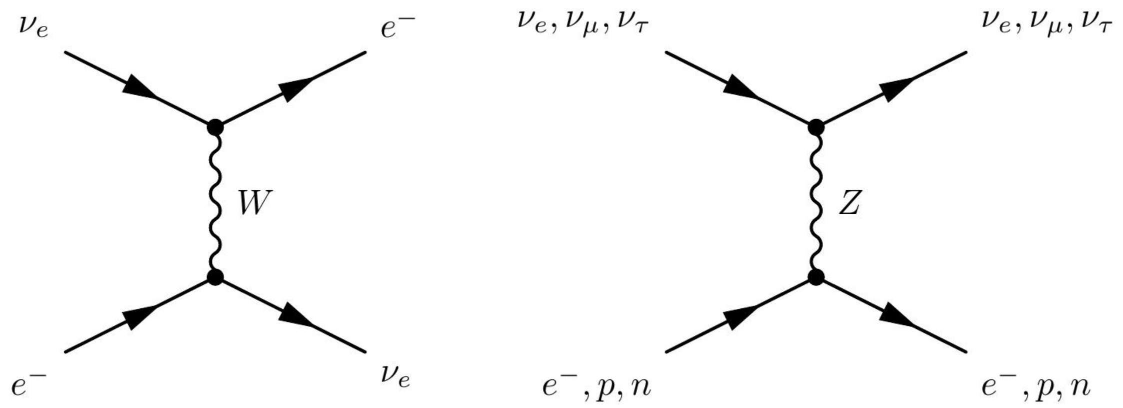
Fermilab, https://lbnf-dune.fnal.gov/how-it-works/neutrino-beam/

Neutrino source: a wide-band beam with high energy peaks at ~2.5 GeV



DUNE Collaboration [arXiv:2103.04797]

Matter effect



In flavor space,

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

with

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

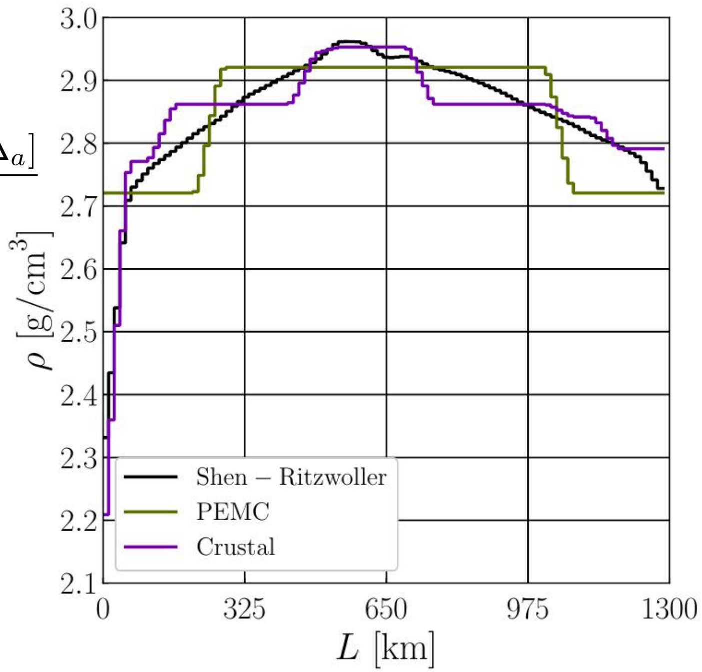
Matter effect

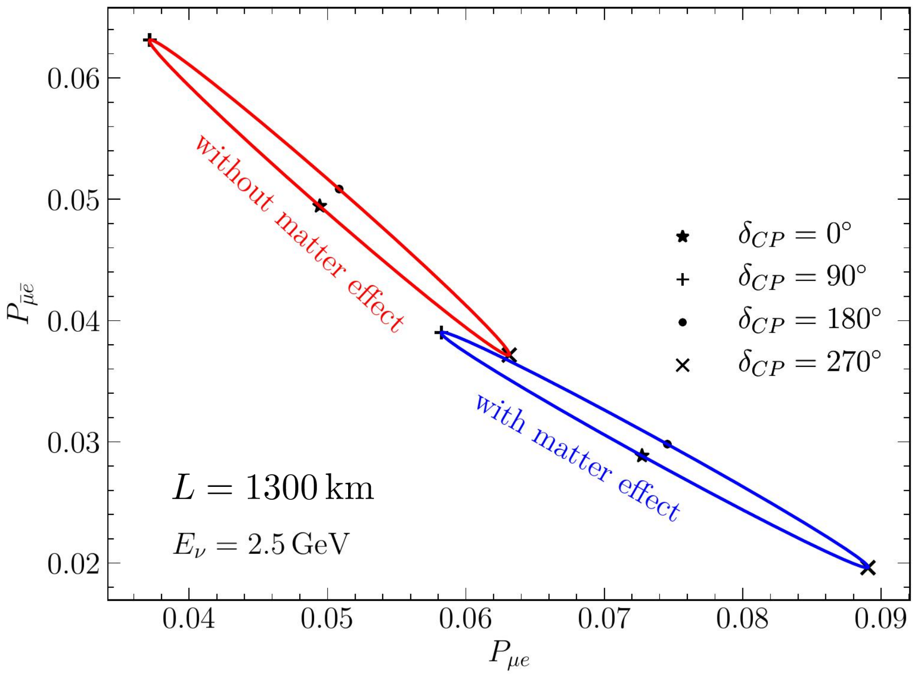
$$P_{\substack{\nu_\mu\to\nu_e \\ \overline{\nu}_\mu\to\overline{\nu}_e}} \approx \alpha^2 \sin^2 2\theta_s c_a^2 \frac{\sin^2(A\Delta_a)}{A^2} + 4s_r^2 s_a^2 \frac{\sin^2[(1\mp A)\Delta_a]}{(1\mp A)^2} + 2\alpha s_r \sin 2\theta_s \sin 2\theta_a \cos(\Delta_a \pm \delta_D) \times \frac{\sin(A\Delta_a)}{A}\frac{\sin[(1\mp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

with

$$A \approx \frac{E_\nu}{\Delta m_a^2} 7.56\times 10^{-14}\frac{\rho_e}{\mathrm{g/cm^3}}\mathrm{eV}$$

$$\Delta_a \equiv |\Delta m_a^2| L/4E_\nu$$





Kelly & Parke [arXiv:1802.06784]

Matter effect can fake CP and contaminate CP measurement

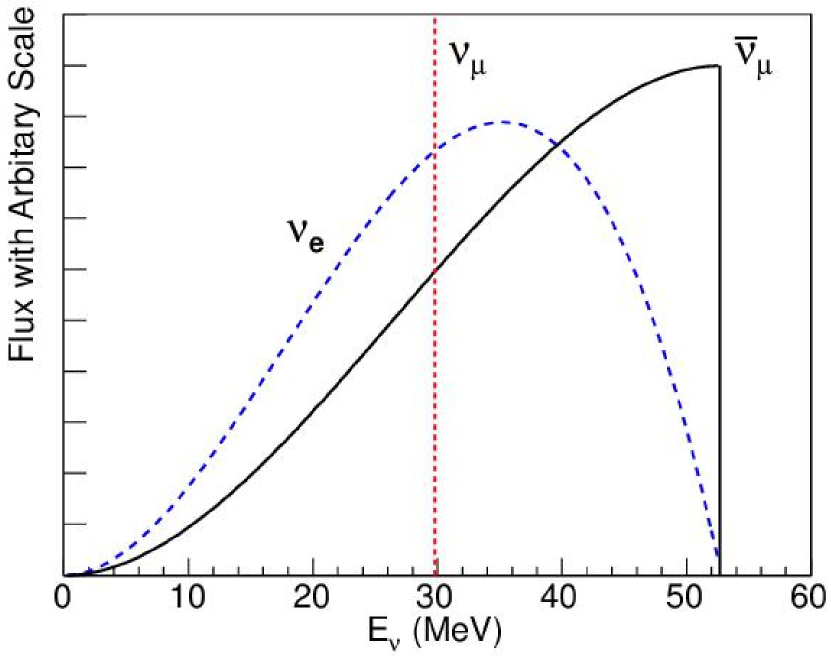
Our proposal: DUNE+muTHEIA

Low-energy neutrino beam from muon decay at rest can get rid of matter effect contamination

- Shoot protons at a target to creat pions. Negative pions are captured quickly. Positive pions remain

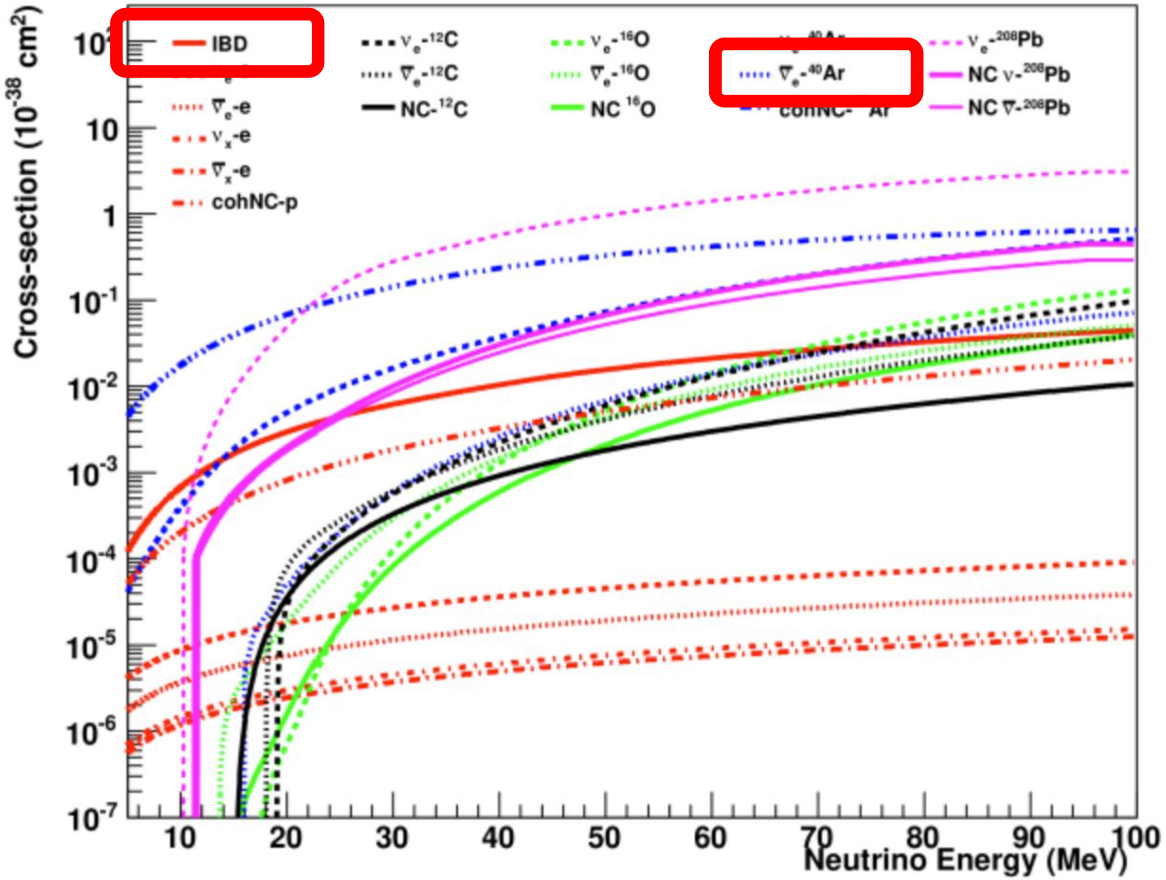
- Positive pions decay into muon neutrinos and antimuons

- Antimuons decay into positrons, electron neutrinos, and muon antineutrinos



such as DAEδALUS experiment

Our proposal: DUNE+muTHEIA

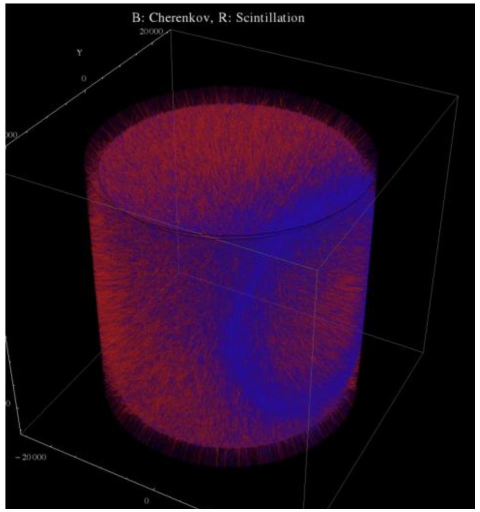


arXiv:1205.6003

neutrino cross sections

The event rate at DUNE far detectors (LArTPC) is low!

Our proposal: DUNE+muTHEIA



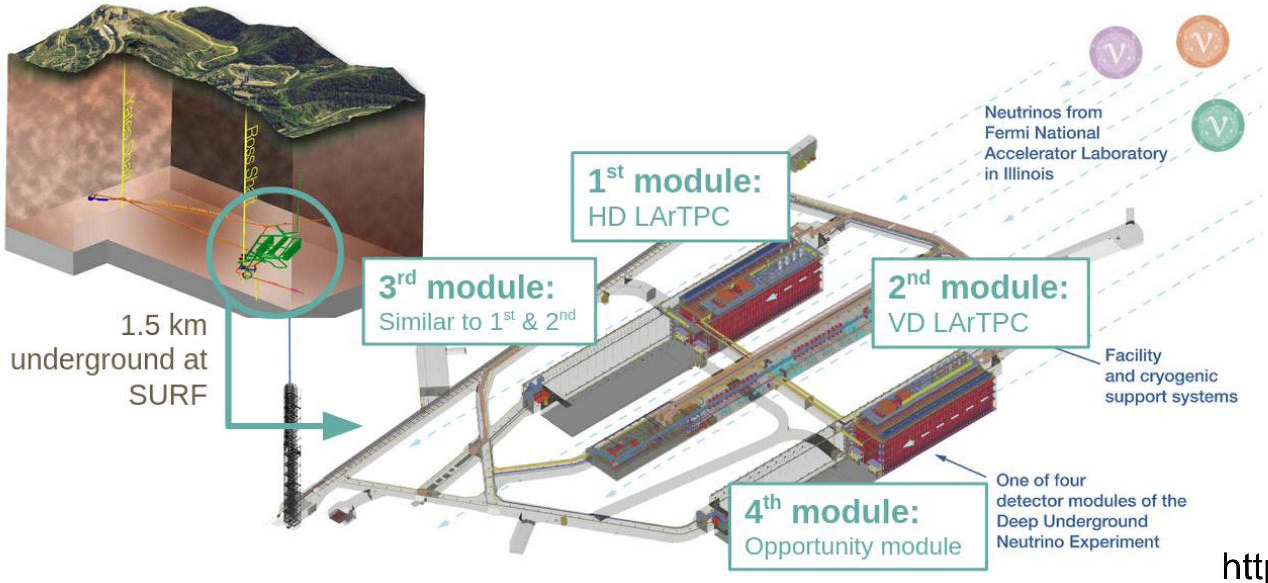
Theia Collaboration

THEIA Experiment:

- Water-based Liquid Scintillator (WbLS)
  THEIA-25: 17 kt fiducial mass
  THEIA-100: 70 kt fiducial mass

- Chrenkov light (good angular resolution)
  +
  Scintillation light (low energy threshold)

- It plans to replace one of DUNE far detectors with THEIA detector



http://neutrinos.ciemat.es/dune-en

Our proposal: DUNE+muTHEIA

Measurements

high-energy neutrinos (LBNF)

- DUNE far detectors
- THEIA detector

low-energy neutrinos (muDAR)

- THEIA detector

Results

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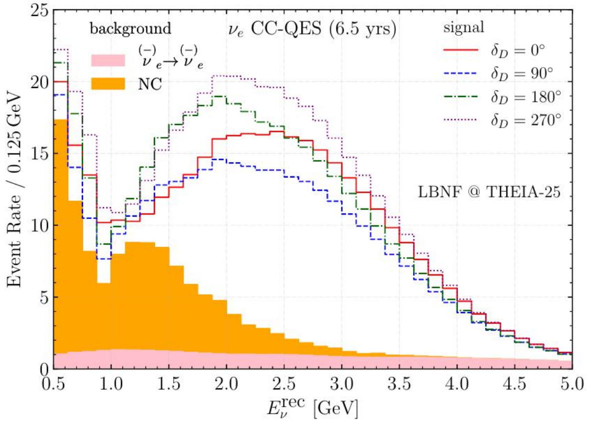
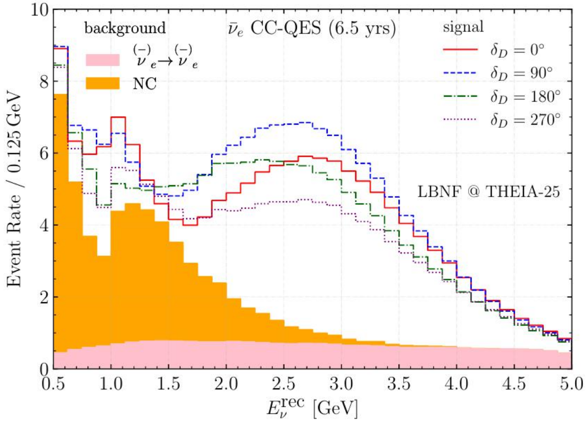
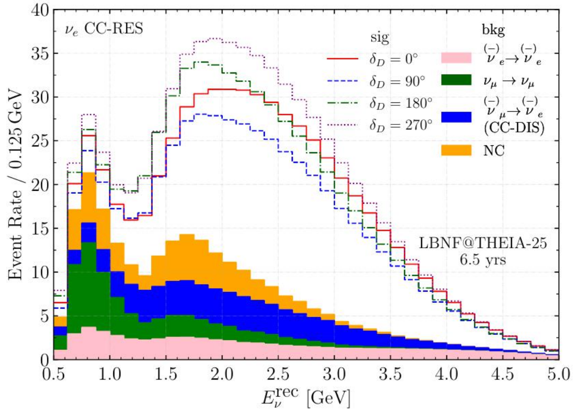
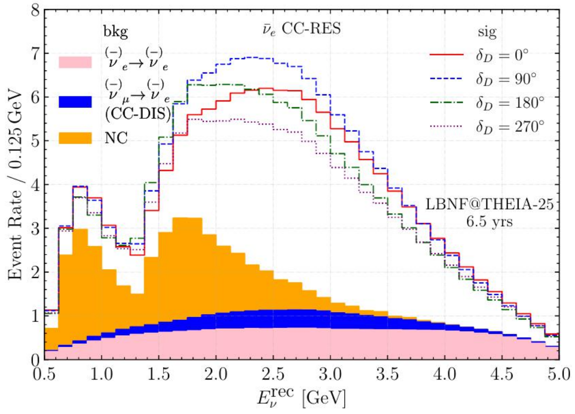
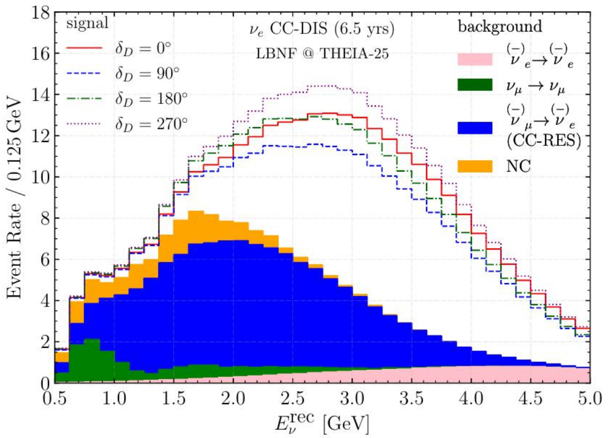
High-energy neutrinos at THEIA detector

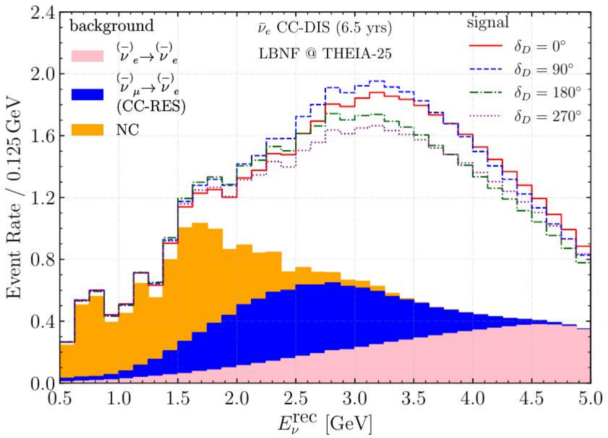








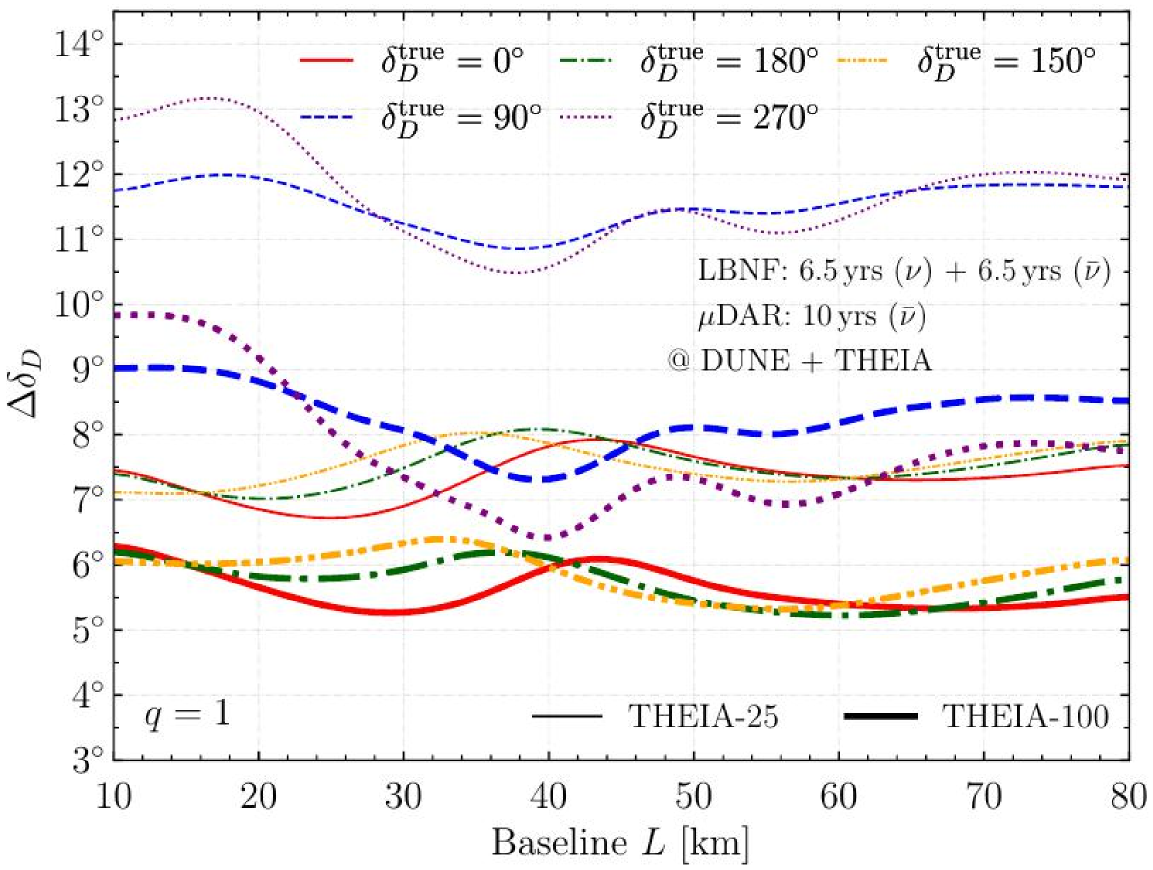


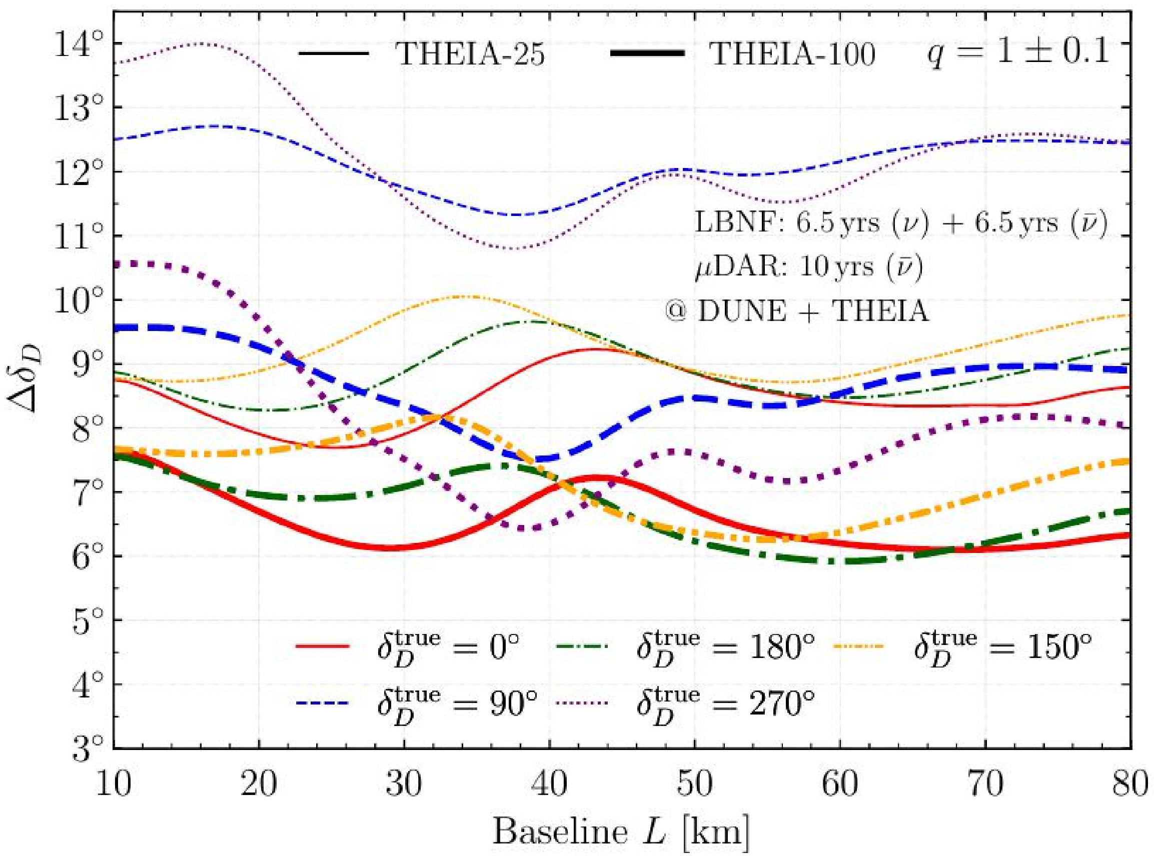


event rates

Results

Low-energy neutrinos at THEIA detector

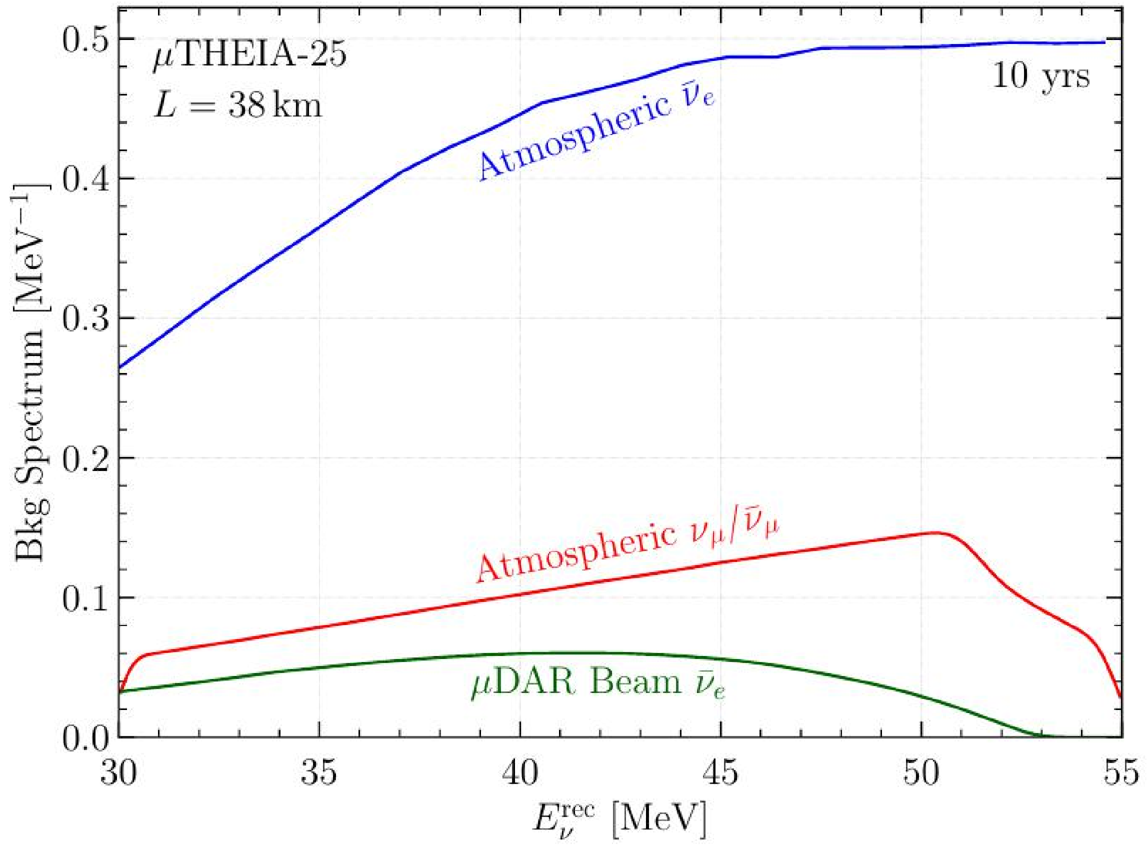


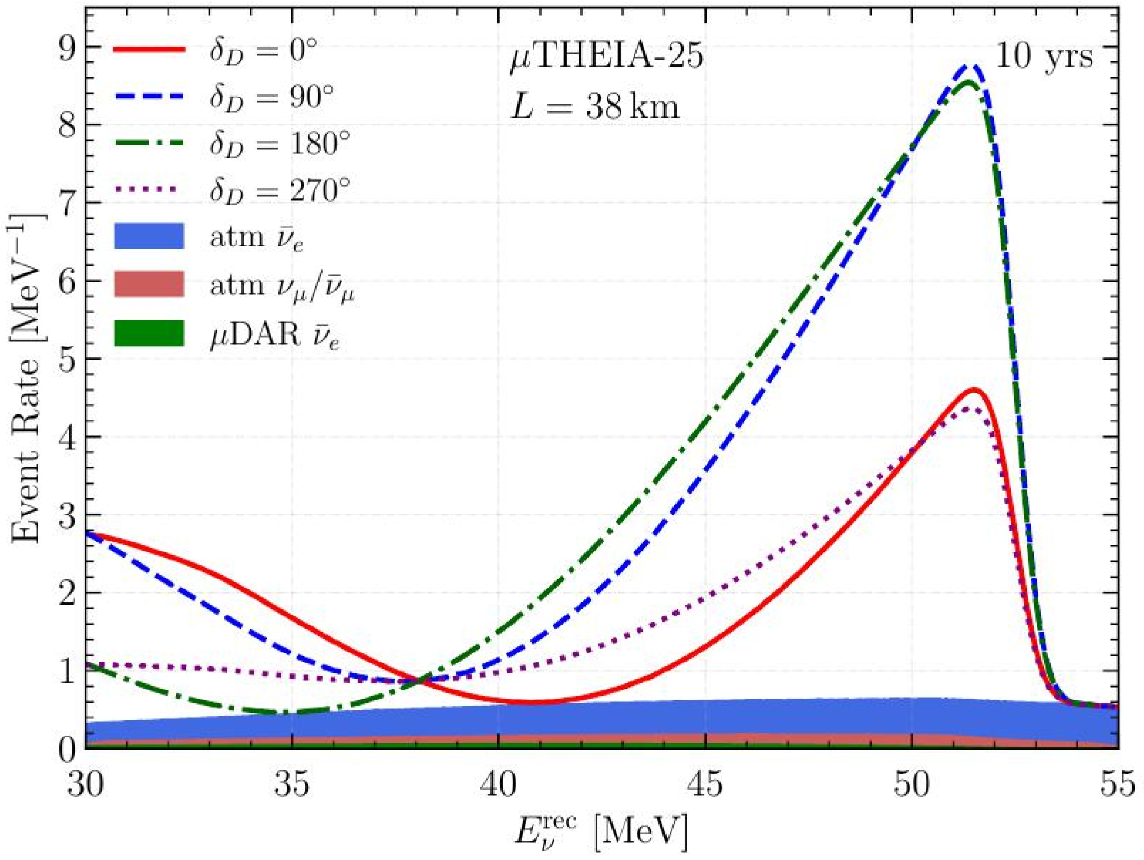


Three optimal baseline of muTHEIA choices: 30 km, 38 km, 55 km

Results

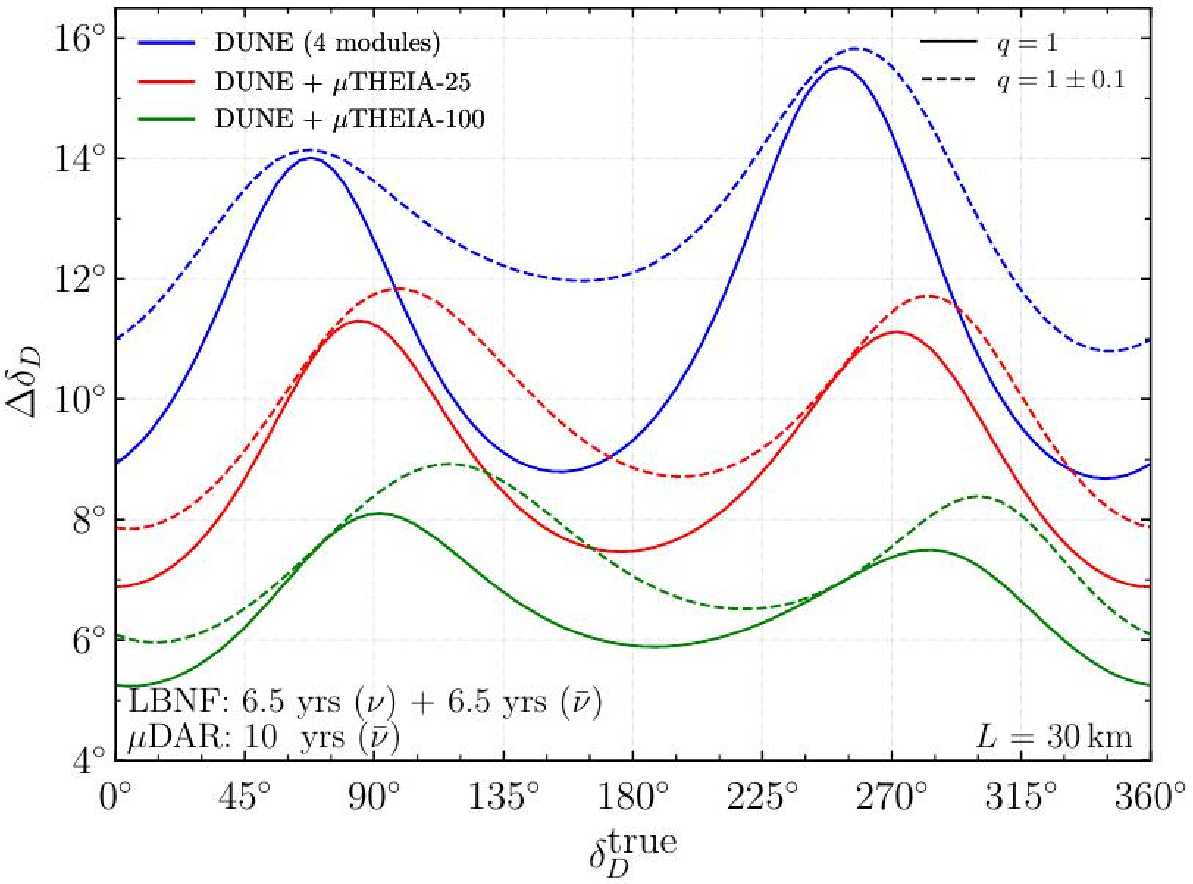
Low-energy neutrinos at THEIA detector



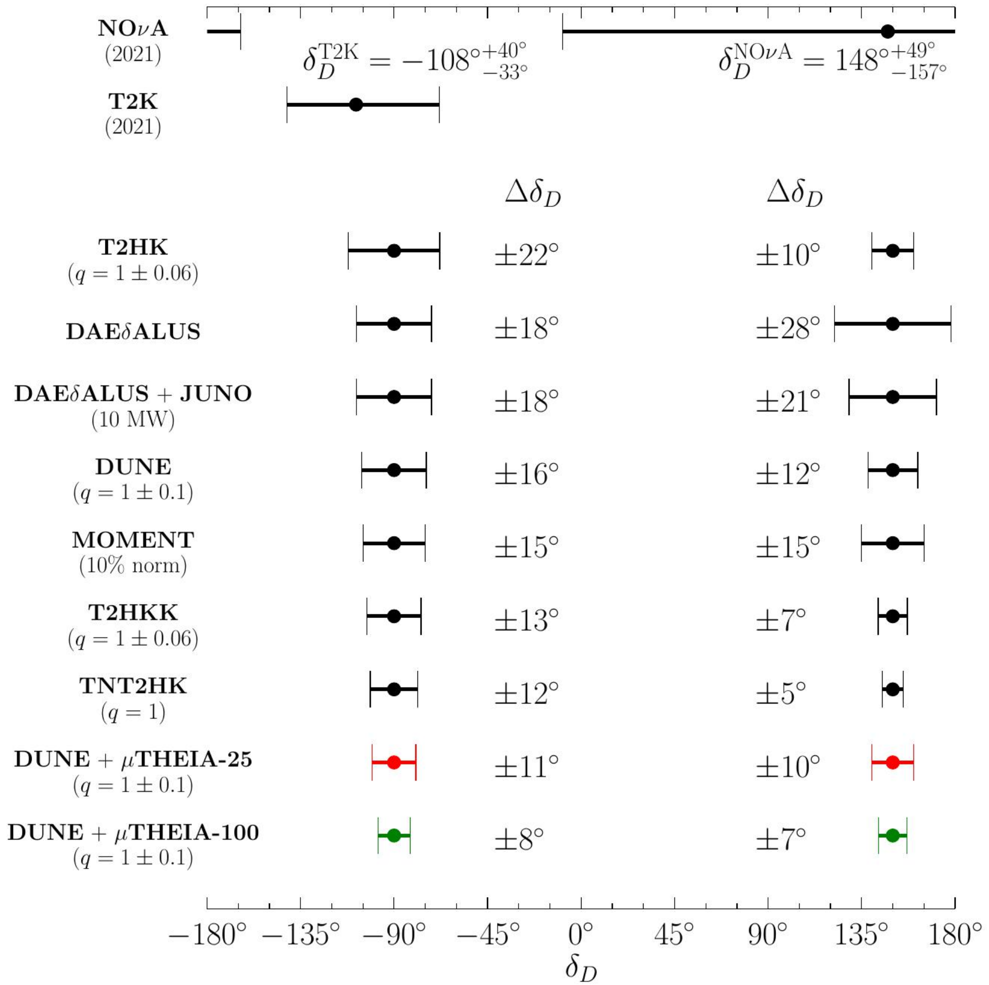


event rate

Results



CP sensitivity

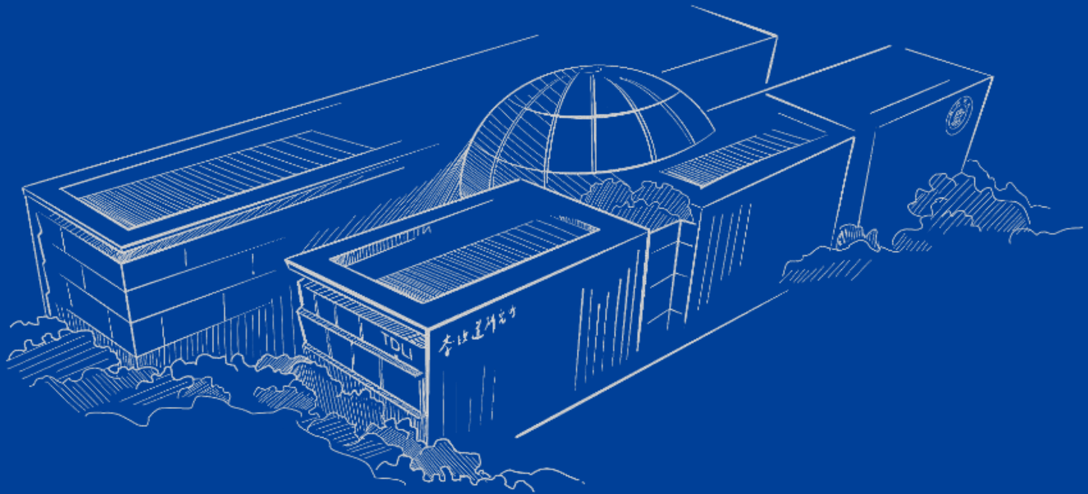


compare with other (proposed) experiments

Summary

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

Thank you for your attention!



Back-up

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

$$
P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\beta \to \nu_\alpha)
$$