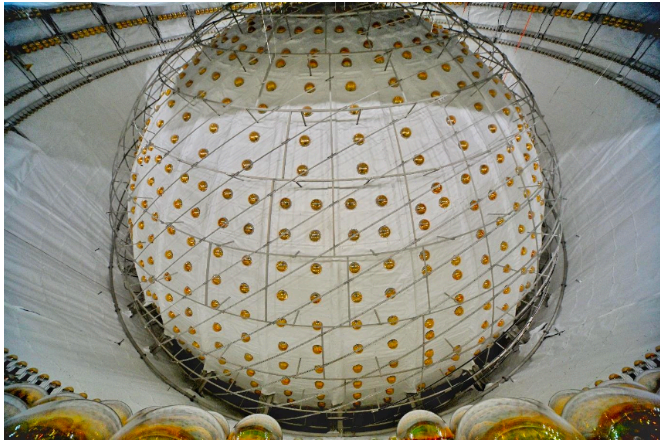
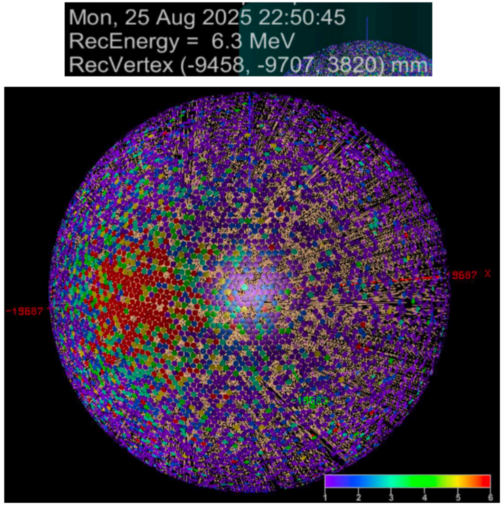
Experimental Overview of Neutrino Oscillation

Akira Konaka (TRIUMF)
October 1, 2025

The main Hyper-Kamiokande cavern after excavation completed



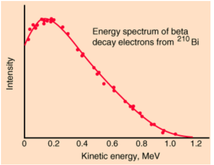


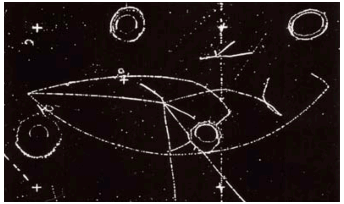
Prompt e+ signal

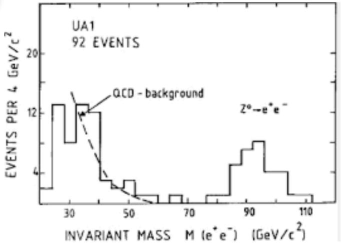
Discoveries and Precision measurement

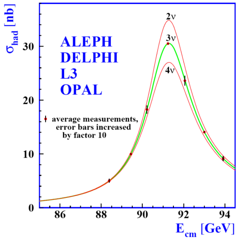
Weak interaction

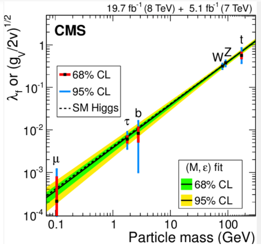
Discoveries β decays weak int., ν	**Precision measurement** Parity violation, NC → Electroweak Interaction	**Discoveries** W,Z,Higgs	**Precision measurement** Standard model test → new paradigm?





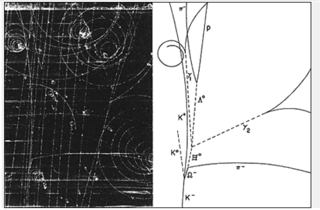






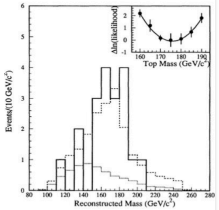
Quarks

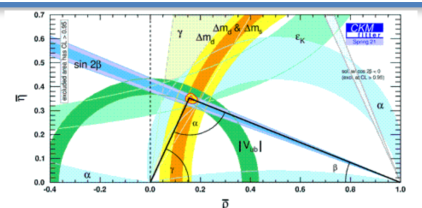
Discoveries s-quark (K,Ω)	**Precision measurement** FCNC, CP violation → CKM paradigm	**Discoveries** c,b,t	**Precision measurement** Unitarity test (K,B) → new paradigm?



$K_L \rightarrow \mu\mu$ (FCNC)
(c mass prediction)

$K_L \rightarrow \pi\pi$ (CPV)

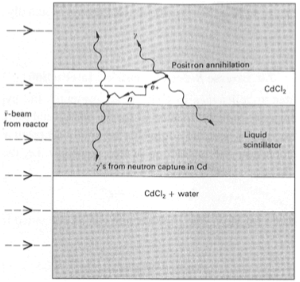




Discoveries and Precision measurement (Neutrinos)

Neutrinos

Discoveries	Precision measurement	Discoveries	Precision measurement
ν observation (inverse β decay)	ν flavours: ν_e, ν_μ, ν_τ → PMNS paradigm	ν oscillations $\theta_{23}, \theta_{12}, \theta_{13}, \delta$	Precision test of PMNS → new paradigm?



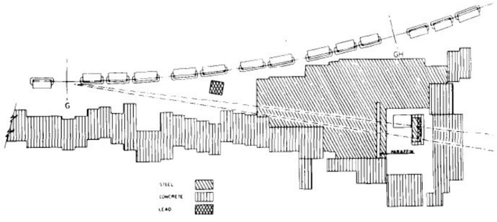
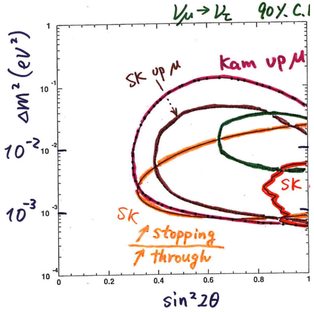
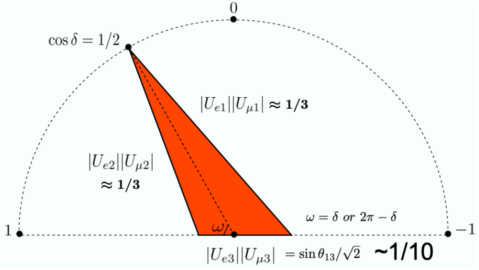
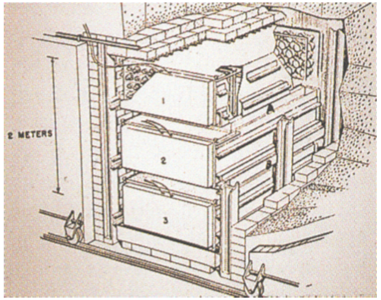
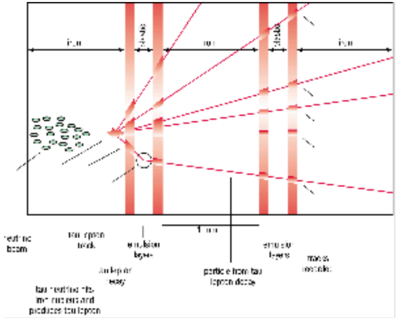


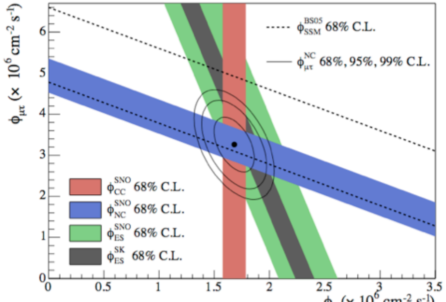
Figure 1. Plan view of the A.G.S. neutrino experiment.

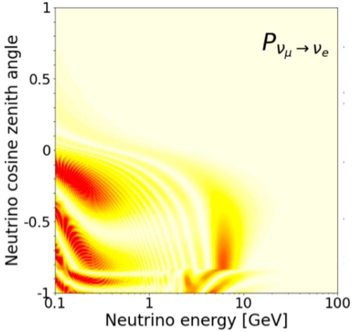








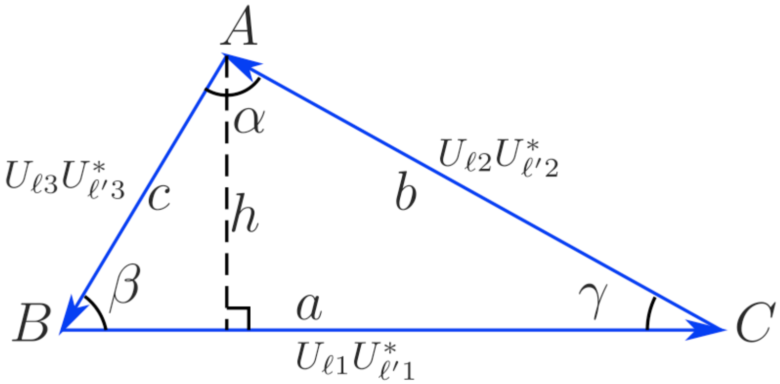




Lepton mixing (PMNS)

weak eigenstate — Pontecorvo-Maki-Nakagawa-Sakata mass mixing matrix — mass eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Unitarity condition: $U^\dagger U=1$

Normalization

$|U_{e1}|^2+|U_{e2}|^2+|U_{e3}|^2 = 1$

$|U_{\mu 1}|^2+|U_{\mu 2}|^2+|U_{\mu 3}|^2 = 1$

$|U_{\tau 1}|^2+|U_{\tau 2}|^2+|U_{\tau 3}|^2 = 1$

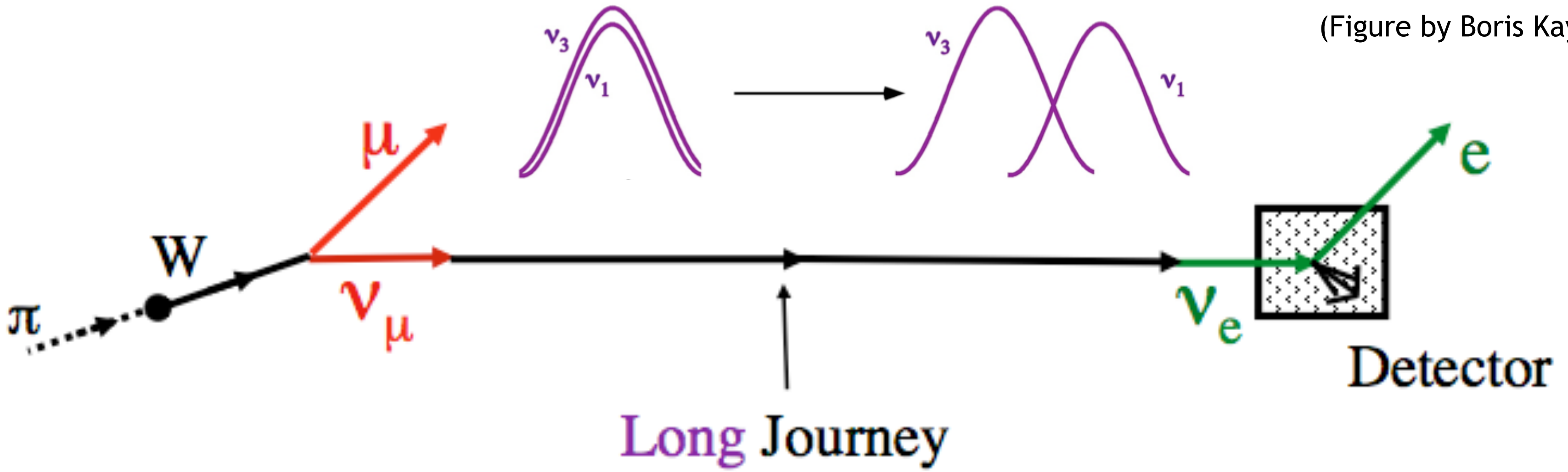
Unitarity triangle

$U_{e1}U^*_{\mu 1}+U_{e2}U^*_{\mu 2}+U_{e3}U^*_{\mu 3} = 0$

$U_{\mu 1}U^*_{\tau 1}+U_{\mu 2}U^*_{\tau 2}+U_{\mu 3}U^*_{\tau 3} = 0$

$U_{\tau 1}U^*_{e1}+U_{\tau 2}U^*_{e2}+U_{\tau 3}U^*_{e3} = 0$

(Figure by Boris Kayser)



$$
\begin{aligned}
P_{l\to l'} &= |<\nu_{l'}(t)|\nu_l(t)>|^2 \\
&= |\sum_i <\nu_{l'}|\nu_i> e^{-iE_it} <\nu_i|\nu_l>|^2 \\
&= |\sum_i U^*_{li}U_{l'i}e^{-im_i^2L/2E}|^2 = \sum_{i,j} U^*_{li}U_{l'i}(U^*_{lj}U_{l'j})^* e^{-i(m_i^2-m_j^2)L/2E}
\end{aligned}
$$

Neutrino disappearance

$$P_{disapp} = 1 - P_{\ell\to\ell}$$
$$= 4|U_{\ell 2}|^2 |U_{\ell 1}|^2 \sin^2\Delta_{21}$$
$$+ 4|U_{\ell 3}|^2 |U_{\ell 2}|^2 \sin^2\Delta_{32}$$
$$+ 4|U_{\ell 3}|^2 |U_{\ell 1}|^2 \sin^2\Delta_{31}$$

$\Delta_{21} = (m^2_2 - m^2_1)/4E = \Delta m^2_{12}/4E$

$\Delta_{32} = (m^2_3 - m^2_2)/4E = \Delta m^2_{32}/4E$

$\Delta_{31} = (m^2_3 - m^2_1)/4E = \Delta m^2_{31}/4E$

$\Delta_{31} = \Delta_{32} + \Delta_{21}$

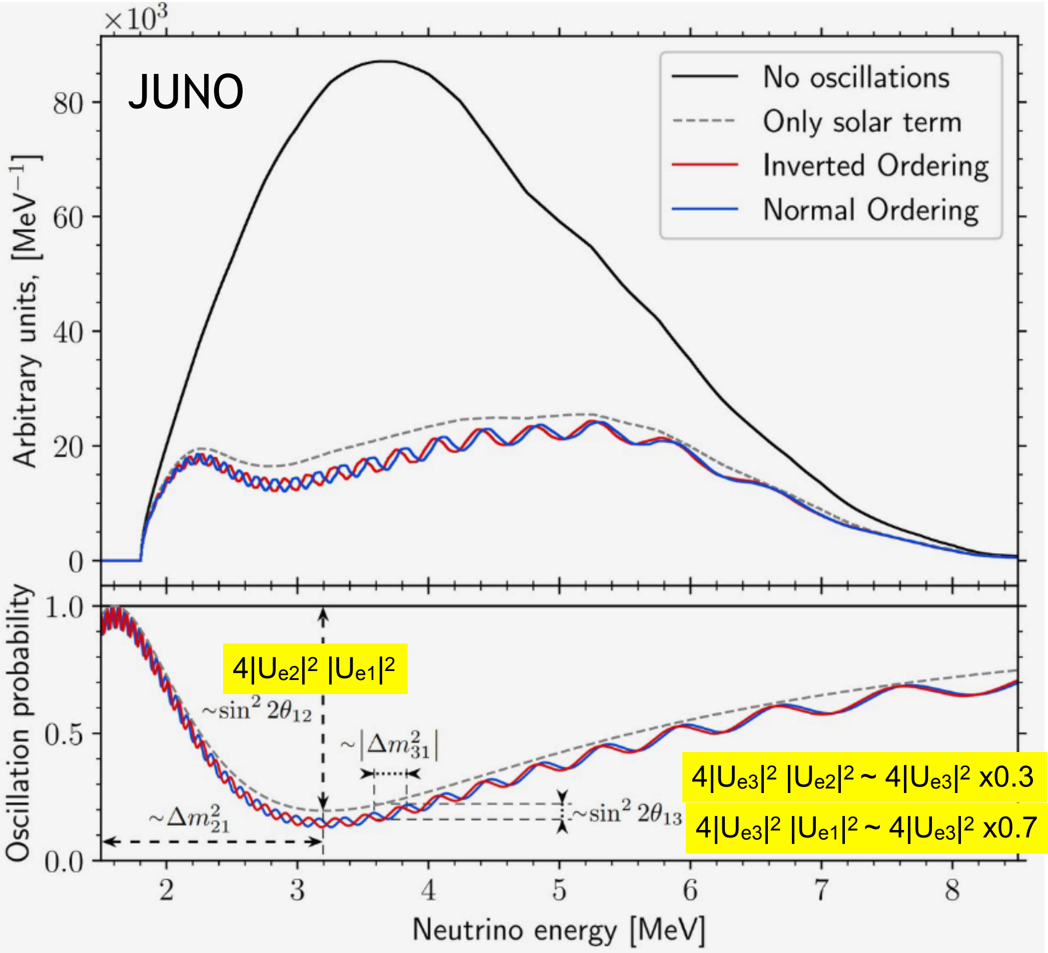
$|\Delta m^2_{21}|^2 \sim 7.4\text{x}10^{-5}\ eV^2$

$|\Delta m^2_{32}|^2 \sim |\Delta m^2_{31}|^2 \sim 2.5\text{x}10^{-3}\ eV^2$

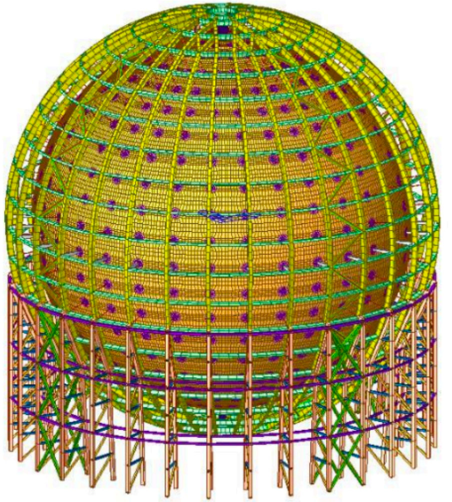
$||\Delta m^2_{32}|^2 \sim |\Delta m^2_{31}|^2| \ / \ |\Delta m^2_{32}|^2 \sim 3\%$

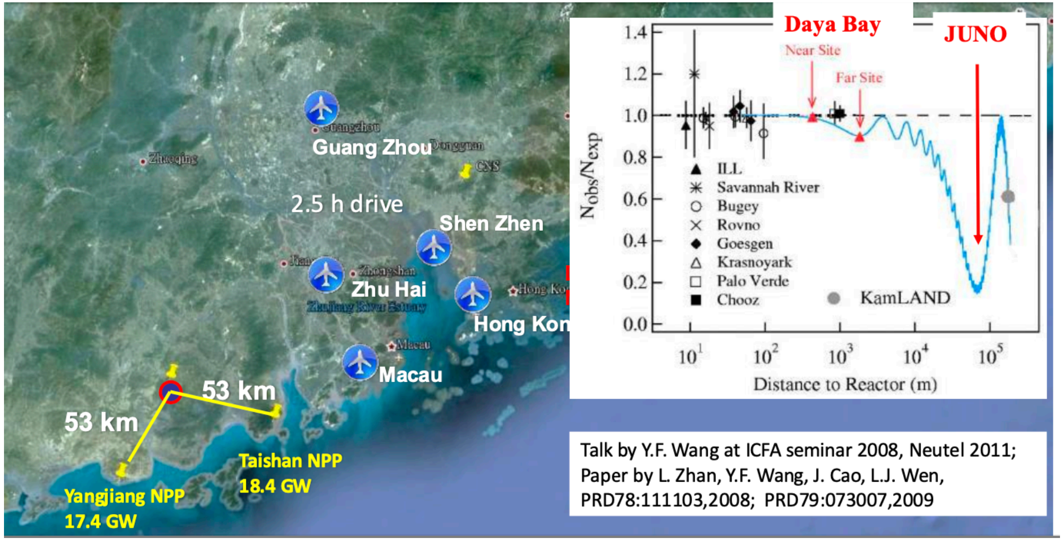
$|\Delta m^2_{31}|^2 > |\Delta m^2_{32}|^2$ ~ normal ordering

$|\Delta m^2_{31}|^2 < |\Delta m^2_{32}|^2$ ~ inverted ordering



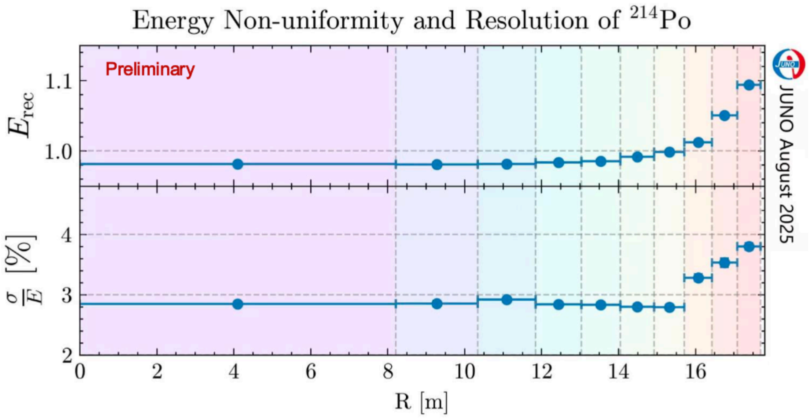
- JUNO data taking started in Aug. 2025 !
  - reactor neutrino oscillation: Δm^2_{31} and Δm^2_{21}
  - excellent energy resolution: ~3% @0.92MeV ^{214}Po





Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen,
PRD78:111103,2008; PRD79:073007,2009

Yifang Wang Lepton-Photon 2025



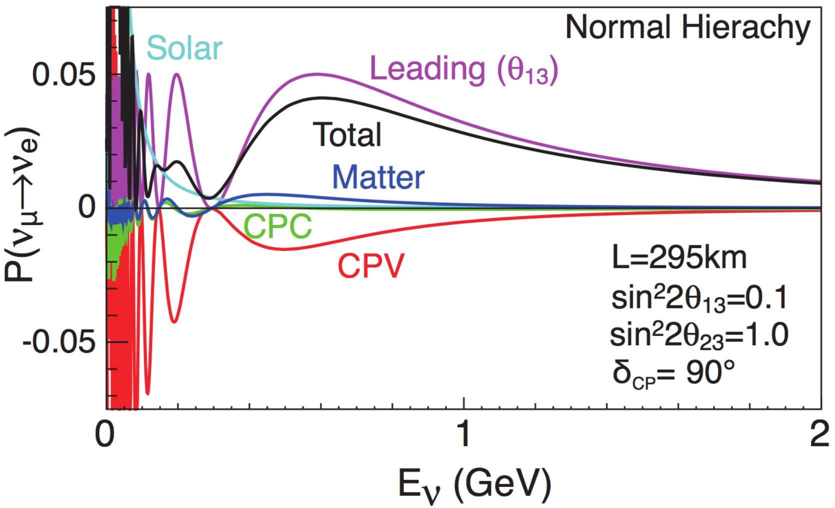
Neutrino appearance

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U^*_{\alpha j}\, U_{\beta j} e^{-i\frac{m_j^2}{2E}L} \right|^2$$

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

change sign for anti-neutrino →

$$+2\sum_{i>j} \Im(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij}}{2E}L\right)$$



Large lepton mixing leads to potentially large CP violation

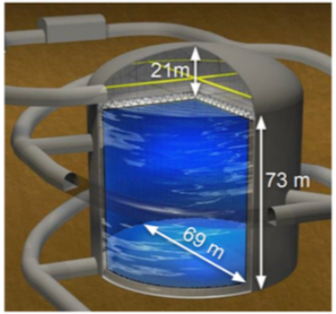
T2K/HyperKamiokande case:

At the peak of E_ν=0.6GeV

$$\frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq -0.28 \sin\delta_{CP} + 0.07$$

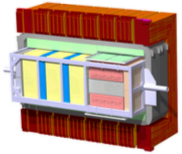
matter effect

Hyper-Kamiokande

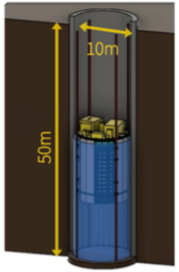


8x larger fiducial mass than SK
20,000 50-cm diameter PMTs with improved photon detection

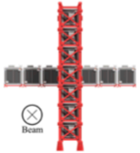
Upgraded ND280 detector with new Super-FGD, High Angle TPCs and TOF detectors



Neutrino beam from 30 GeV J-PARC Main Ring with power upgraded to **1.3 MW**

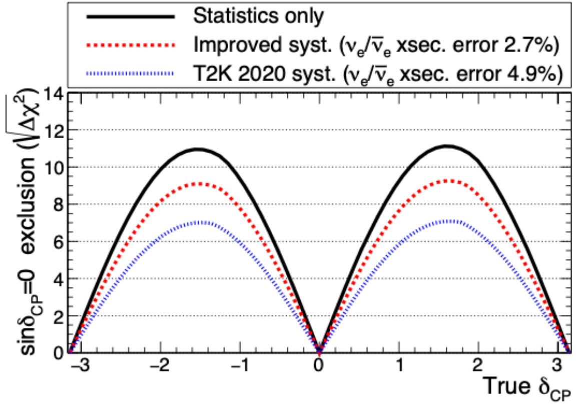


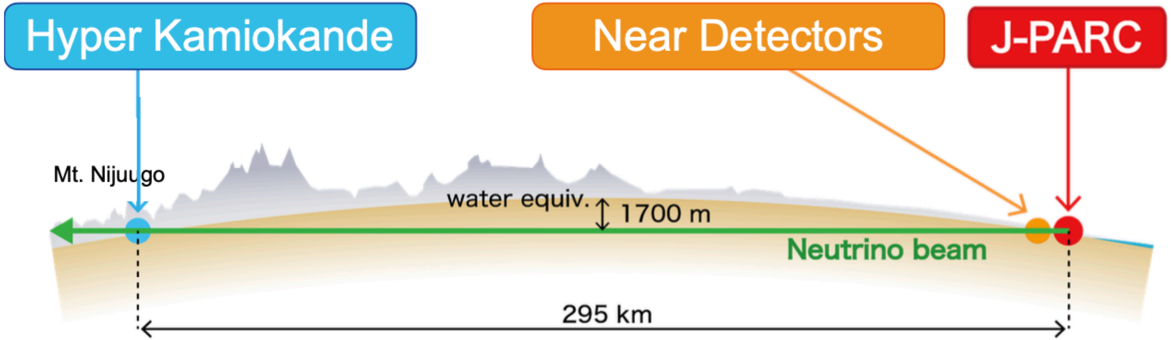
INGRID detector measures beam direction



IWCD water Cherenkov detector at 850 m baseline
PRISM capability to move vertically in beam

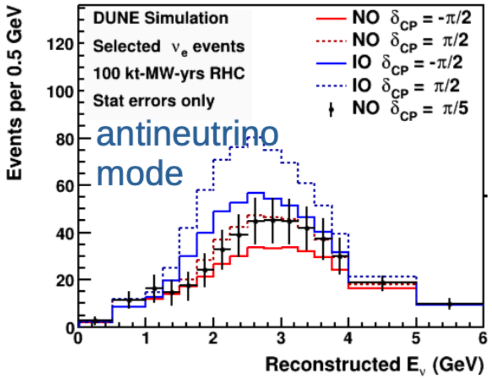
off-axis narrow-band beam
and 187kton fiducial water Cherenkov

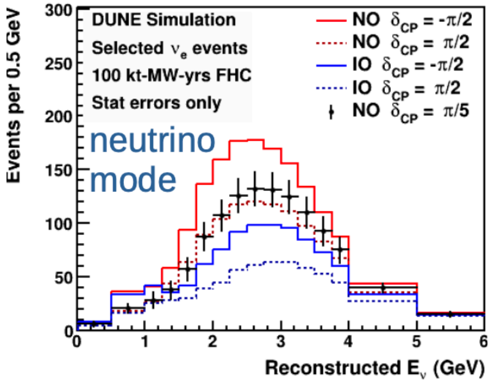


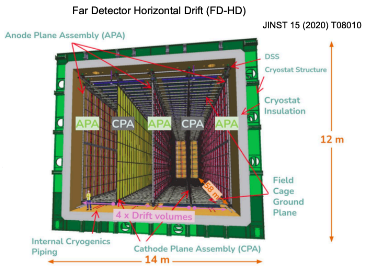


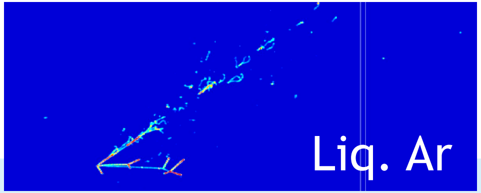
M.Hartz Lepton-Photon

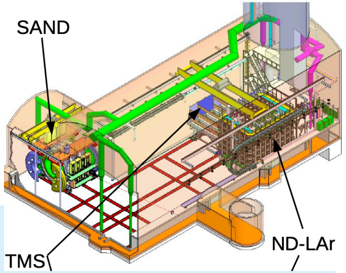
on-axis wide-band beam
→ precise oscillation shape study

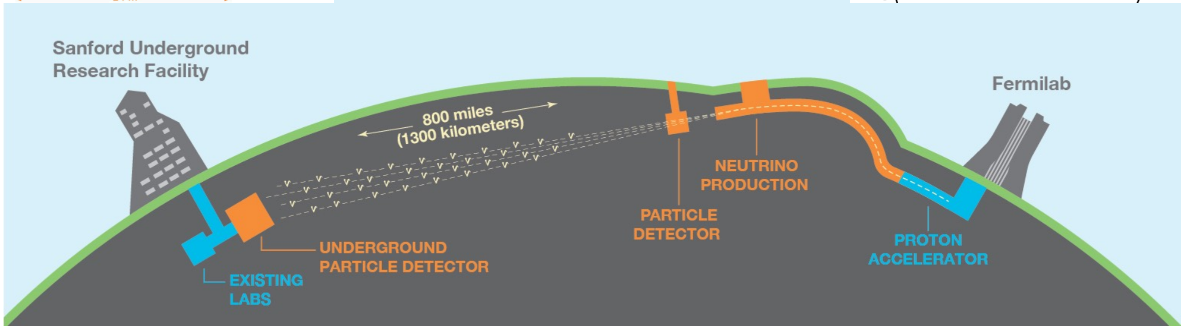


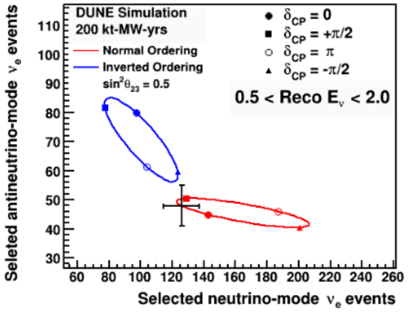


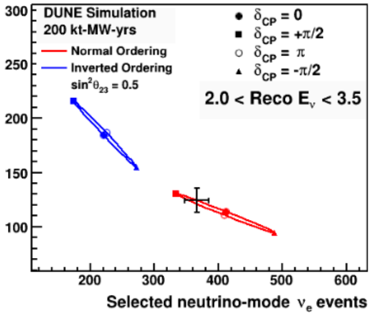


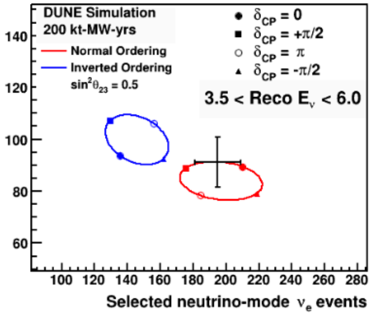






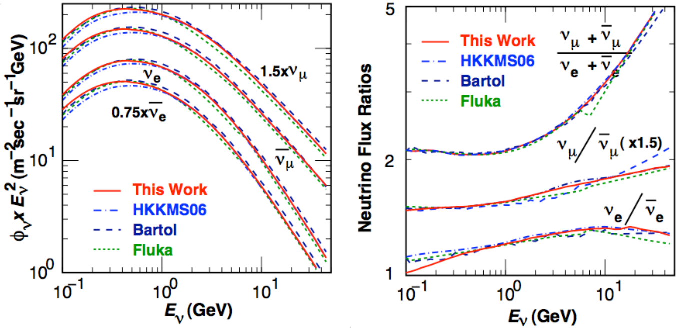




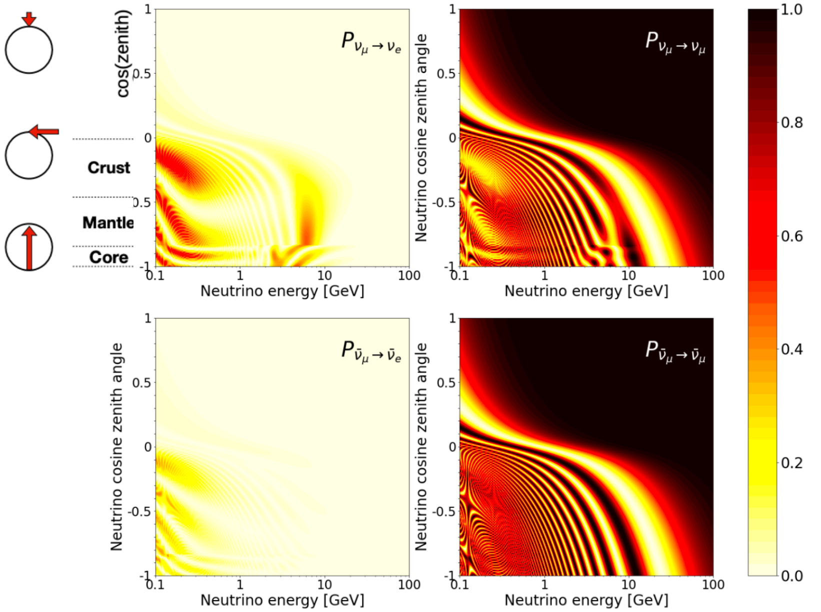


Atmospheric neutrino oscillations

- Atmospheric neutrino flux
  - $\Phi_\nu \sim E_\nu^{-2}$ (sub to multi GeV)
  - $\nu_\mu/\nu_e \sim 2$ up to ~2GeV
    - $\pi^+ \rightarrow \mu^+\nu_\mu : \mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e$
      $\pi^- \rightarrow \mu^-\bar{\nu}_\mu : \mu^- \rightarrow e^-\nu_\mu\bar{\nu}_e$
    - μ reaches the earth before decay at higher energy

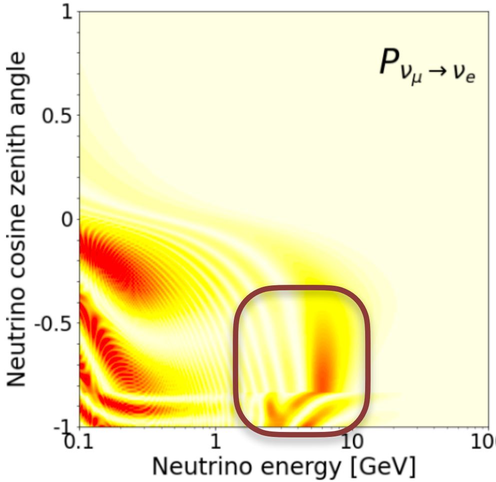


- Atmospheric neutrino oscillation
  - zenith angle → baseline length
    - Δm^2_{21}: sub-GeV, Δm^2_{31}: multi-GeV
  - matter resonance in $\nu_\mu \rightarrow \nu_e$ oscillation
    - Neutrinos only for normal mass ordering → identification of the mass ordering

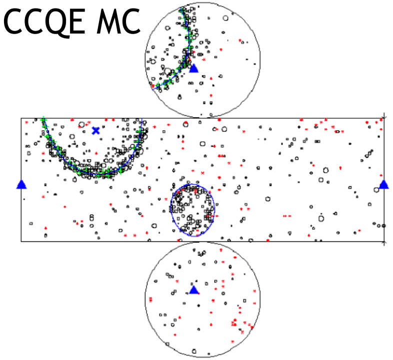


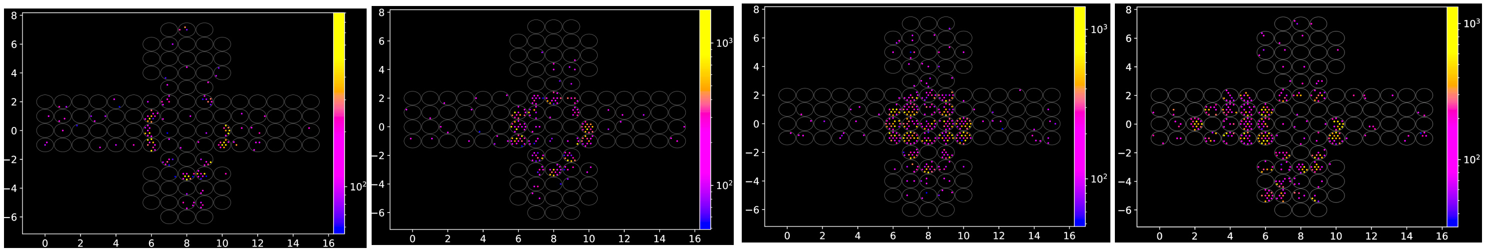
multi-GeV atmospheric neutrino oscillation

- Charged lepton in the neutrino direction
  - mass ordering sensitivity for SuperK, IceCube, HyperK, ORCA
  - uncertainties from the hadronic shower
    - hadron detection: DUNE, THEIA
- Full multi-GeV CCQE reconst.(SuperK: arXiv:0901.1645)
  - proton momentum from the Cherenkov angle
    - threshold 1.07GeV/c: works well for P_p=1.2-1.7GeV/c
    - proton tagging → neutrino event (not anti-neutrinos)
    - WCTE control samples taken for protons in water Cherenkov
  - over-constrained → positive CCQE identification



CCQE MC

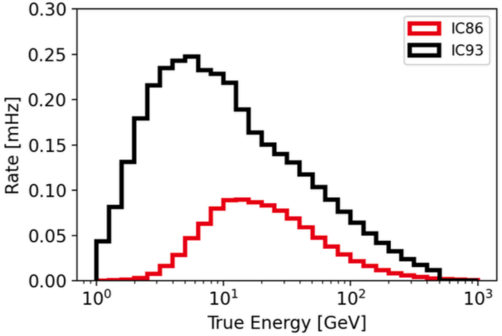


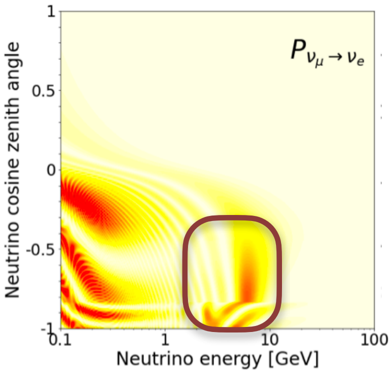


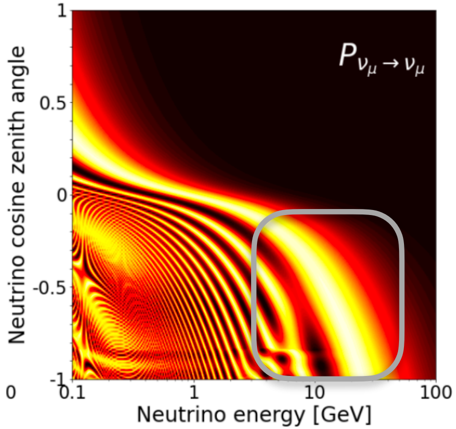
1.5GeV/c proton event display from the Water Cherenkov Test Experiment (WCTE)

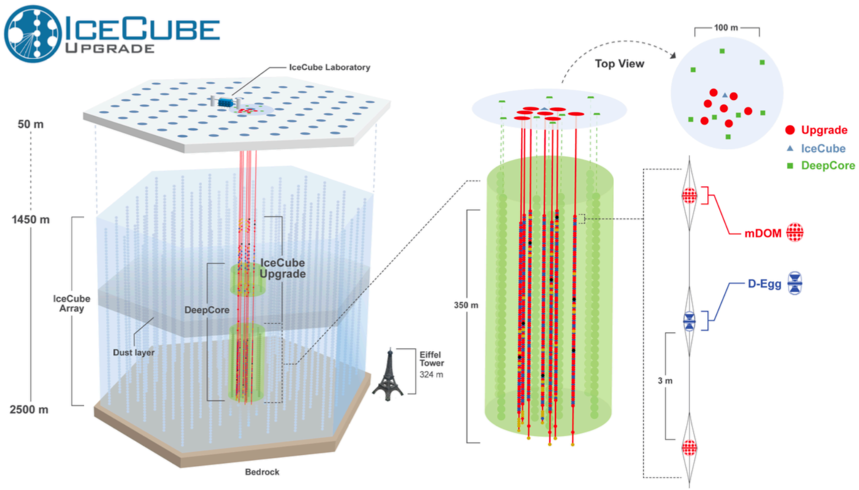
IceCube upgrade for the multi-GeV oscillation

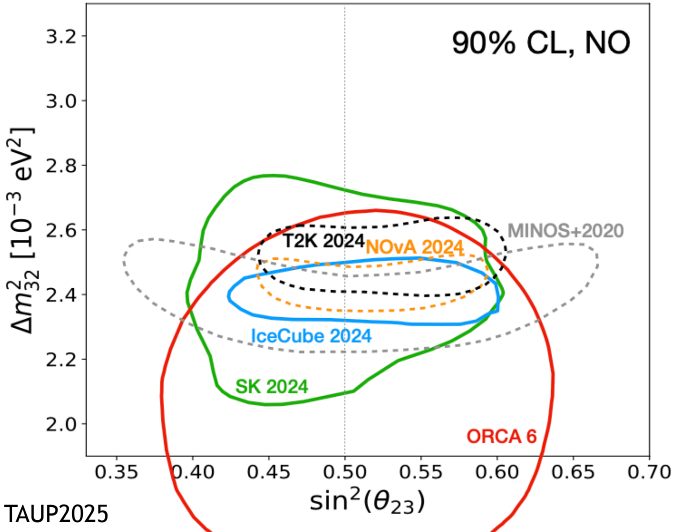
arXiv:2509.13066







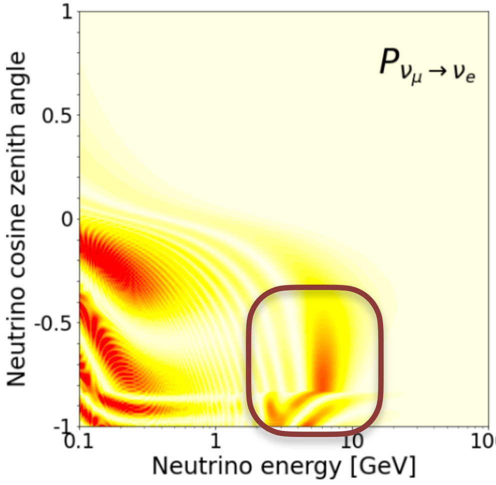


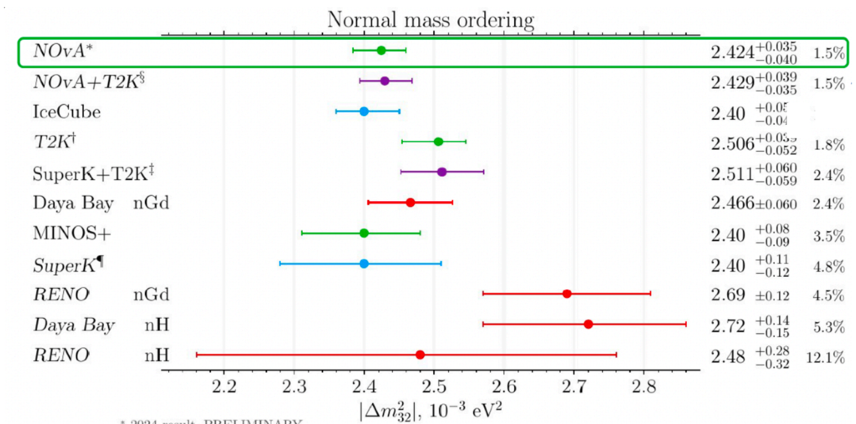


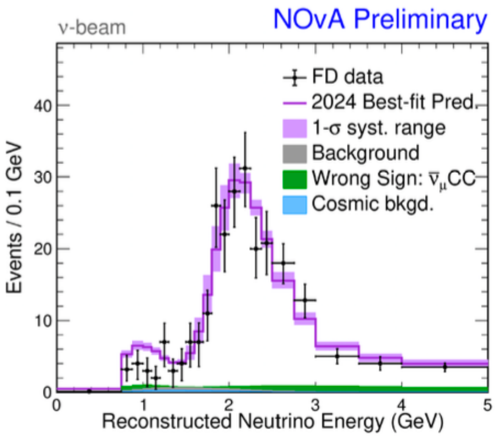
Neutrino mass ordering

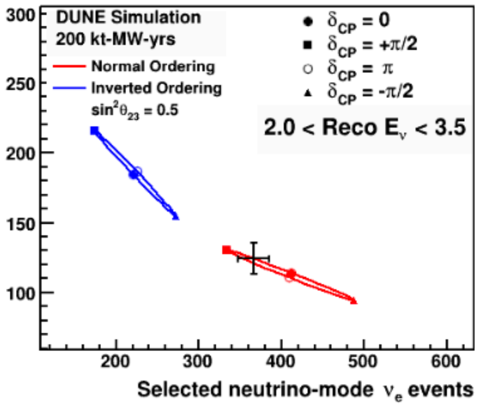
- Matter resonance in atmospheric $\nu_\mu \rightarrow \nu_e$
- JUNO:
  - separation of Δ_{31} and Δ_{32}
  - reactor Δm^2_{31} vs. Long baseline Δm^2_{32}
    - JUNO: 0.2% in Δm^2_{31}, NOvA latest: 1.5% in Δm^2_{32}
- DUNE matter effect in $\nu_\mu \rightarrow \nu_e$

$||\Delta m^2_{32}|^2 \sim |\Delta m^2_{31}|^2| \,/\, |\Delta m^2_{32}|^2 \sim 3\%$
$|\Delta m^2_{31}|^2 > |\Delta m^2_{32}|^2$ ~ normal ordering
$|\Delta m^2_{31}|^2 < |\Delta m^2_{32}|^2$ ~ inverted ordering



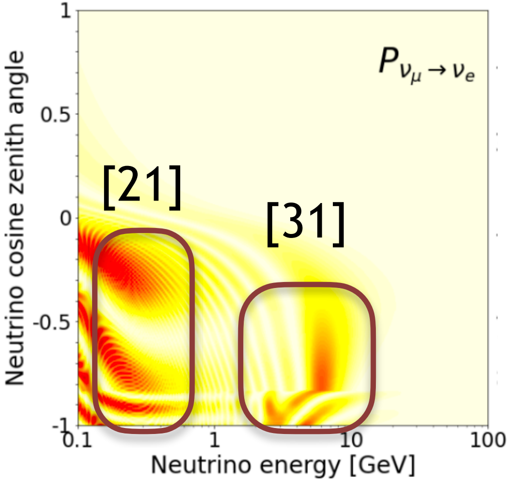


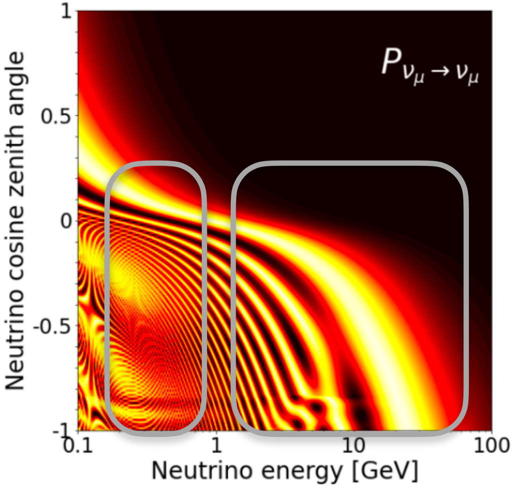




PMNS Normalization

- $|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$
  - Solar neutrino: $|U_{e2}|^2$ (MSW $\nu_e \rightarrow \nu_2$)
  - JUNO
    - Δ_{21}: $|U_{e1}|^2|U_{e2}|^2$ (KamLand)
    - $\Delta_{31}+\Delta_{32}$: $|U_{e3}|^2 (|U_{e1}|^2 + |U_{e2}|^2)$ (Daya Bay)
- $|U_{\mu1}|^2 + |U_{\mu2}|^2 + |U_{\mu3}|^2 = 1$
  - [32] ν_μ disappearance: $|U_{\mu3}|^2 (|U_{\mu1}|^2 + |U_{\mu2}|^2)$
    - T2K, SuperK, NOvA, IceCube, HyperK, DUNE
  - [31] Atm. $\nu_\mu \rightarrow \nu_e$ appearance (3-8GeV): $\Phi_{\nu\mu}/\Phi_{\nu e}$ $|U_{\mu3}|^2$ -1
    - SuperK, IceCube, ORCA, HyperK, DUNE
  - [21] Atm. ν_μ disappearance (0.2-1GeV): $|U_{\mu2}|^2$ $|U_{e2}|^2$
    - DUNE, JUNO, THEIA

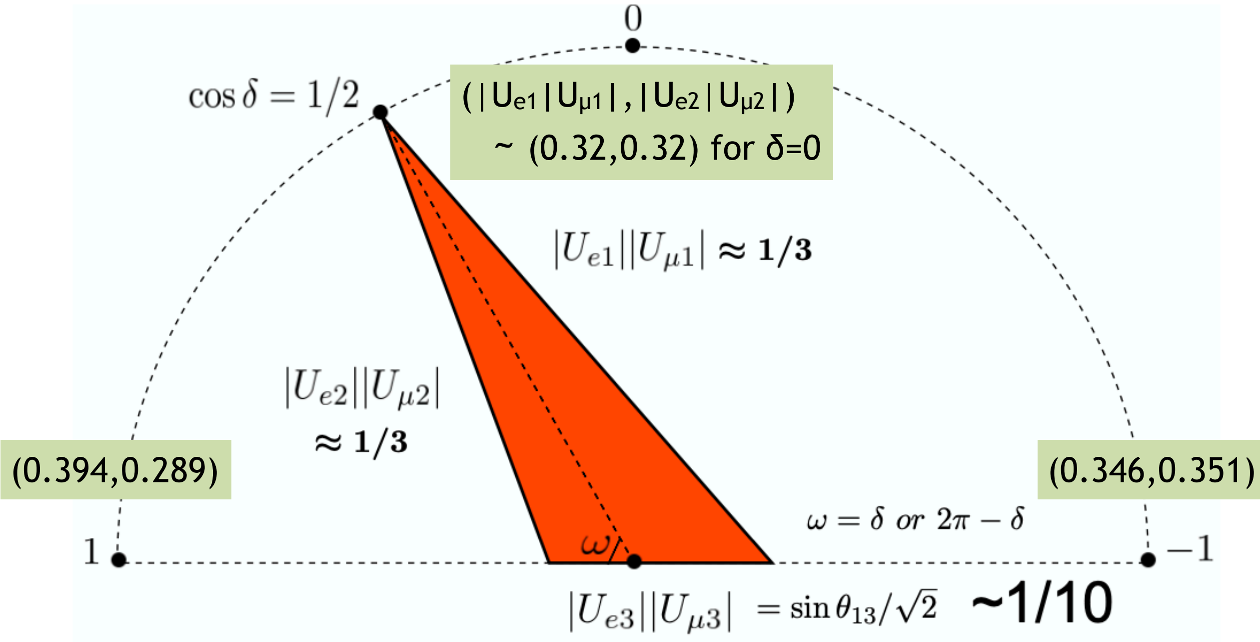




Unitarity triangle

$U_{e1}U^*_{\mu 1}+U_{e2}U^*_{\mu 2}+U_{e3}U^*_{\mu 3} = 0$

- $|U_{e1}|,|U_{\mu 1}|,|U_{e2}|,|U_{\mu 2}|$ can be measured from disappearance experiments
  → unitarity test
  → helps for small CPV
- Precision of a few % would be required
  - side of the triangle
  - CP asymmetry



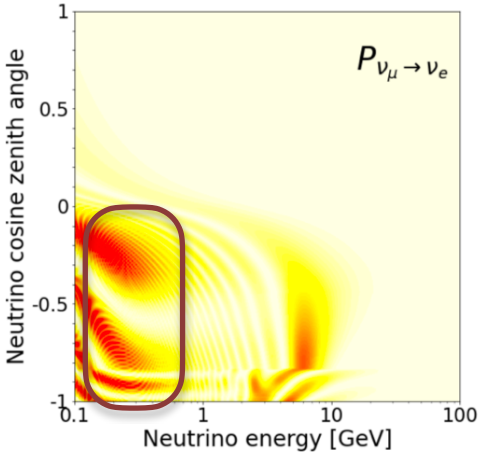
Progress in Particle and Nuclear Physics
Volume 60, Issue 2, April 2008, Pages 338-402

Stephen Parke 2013 Phys. Scr. 2013 014013

- sub-GeV atmospheric ν_e appearance
  - $\Phi_{\nu e}$ (app.) = $\Phi_{\nu\mu}P_{\mu\rightarrow e}$ - $\Phi_{\nu e}(P_{e\rightarrow\mu} + P_{e\rightarrow\tau})$
    ~ $\Phi_{\nu\mu}P_{\mu\rightarrow e}$ - $2\Phi_{\nu e}P_{e\rightarrow\mu}$
    = $\Phi_{\nu e}$ $[(\Phi_{\nu\mu}/\Phi_{\nu e})P_{\mu\rightarrow e}$ - $2P_{e\rightarrow\mu}]$
    ~ $2\Phi_{\nu e}$ $[P_{\mu\rightarrow e}$ - $P_{e\rightarrow\mu}]$

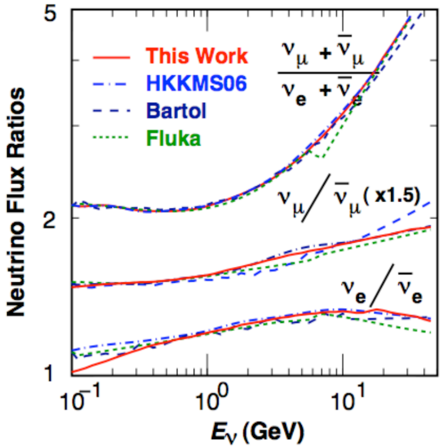
$\sin^2 2\theta_{23}$~1

$\Phi_{\nu\mu}/\Phi_{\nu e}$~2



- (2,1) matter oscillation enhancement on $P_{\mu\rightarrow e}$
  - $P_{\mu\rightarrow e}$ matter effect is observed when
    - **$P_{\mu\rightarrow e} \neq P_{e\rightarrow\mu}$: T (CP) violation**
    - $\Phi_{\nu\mu}/\Phi_{\nu e} \neq 2$
    - $\sin^2 2\theta_{23} < 1$: non-maximal mixing

main effect

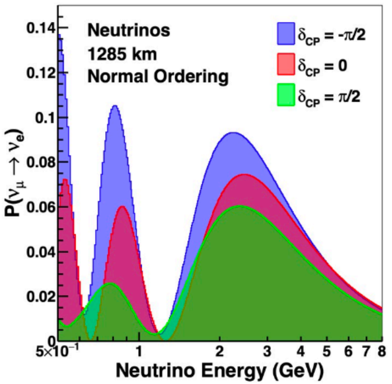


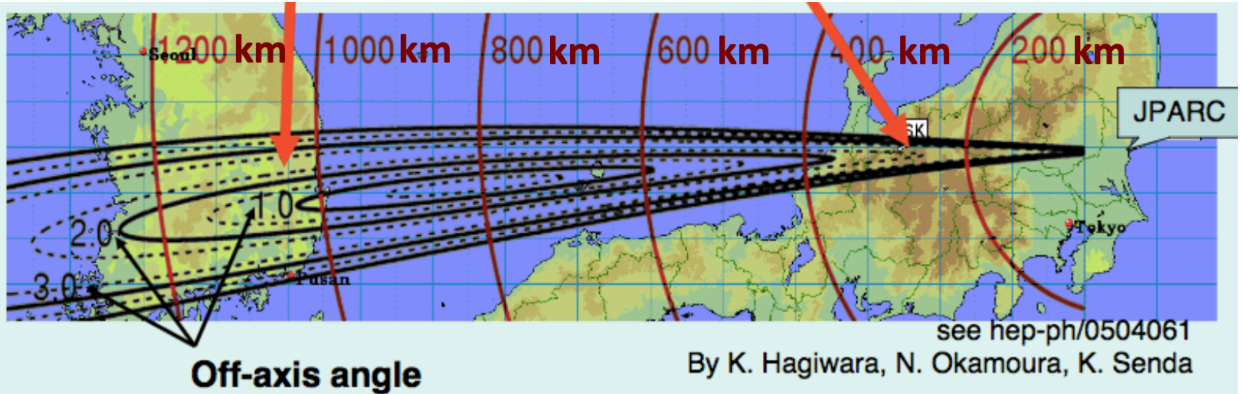
- Enhancement of the CP signal at the 2nd oscillation max.

$$\mathcal{A}_{\mathrm{CP}}^{\mu\to e} = P_{\nu_\mu\to\nu_e} - P_{\bar{\nu}_\mu\to\bar{\nu}_e} = -16J \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} .$$

$$\frac{\mathcal{A}_{\mathrm{CP}}^{\mu\to e}\left(x_{\mathrm{max}}^{(2)}\right)}{\mathcal{A}_{\mathrm{CP}}^{\mu\to e}\left(x_{\mathrm{max}}^{(1)}\right)} \approx 2.7$$

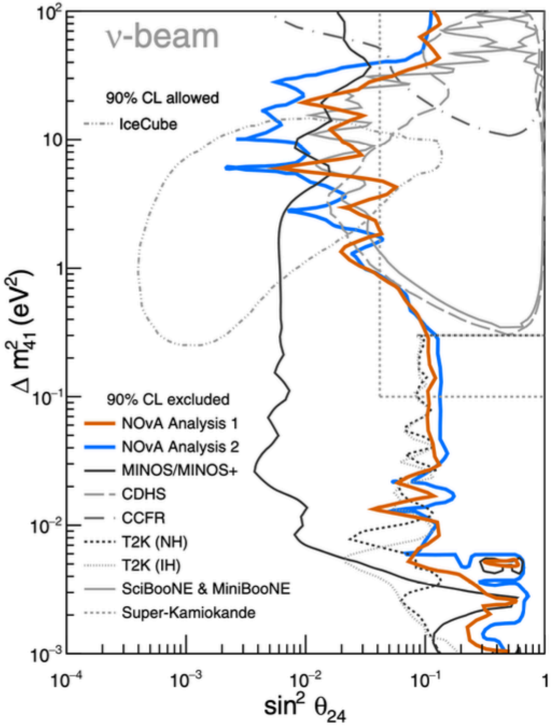
- DUNE: sub-GeV oscillation
- T2HKK: 2nd oscillation maximum in Korea
- ESSnuSB: dedicated lower energy oscillation





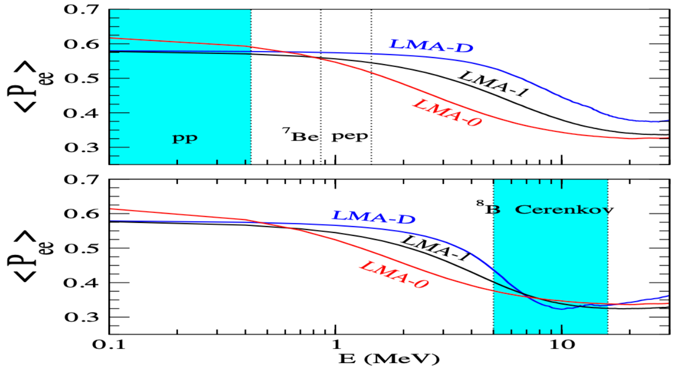
BSM neutrino oscillations

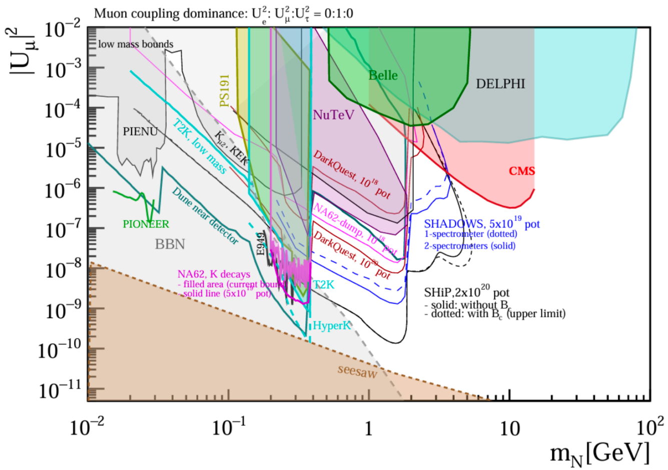
NOvA, Phys. Rev. Lett. **134**, 081804



- Systematically scan the parameter space:
- Sterile neutrinos
  - scan Δm^2 space
  - beam dump exp.
- Non-standard interactions
  - Matter oscillations
    - solar upturn

JHEP 10, 008 (2006)

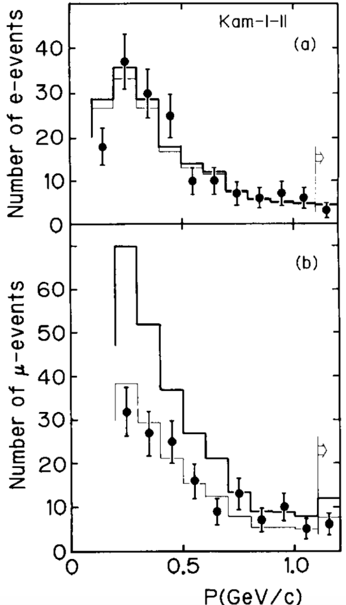




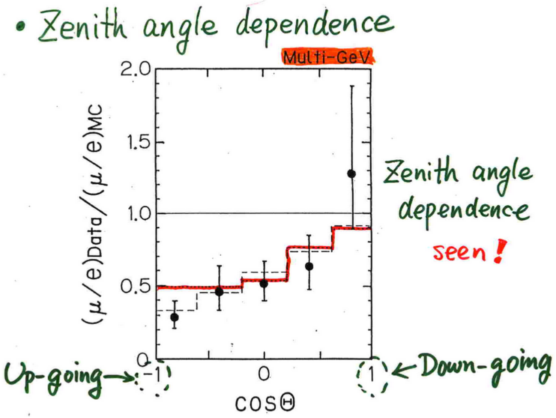
History of neutrino oscillation discovery

- Kamiokande observed 5σ deviation on both atmospheric and solar neutrinos
  - Control of systematic uncertainty (atmospheric and solar neutrino flux) essential
- We face the challenge of systematics again while a % level sensitivity required

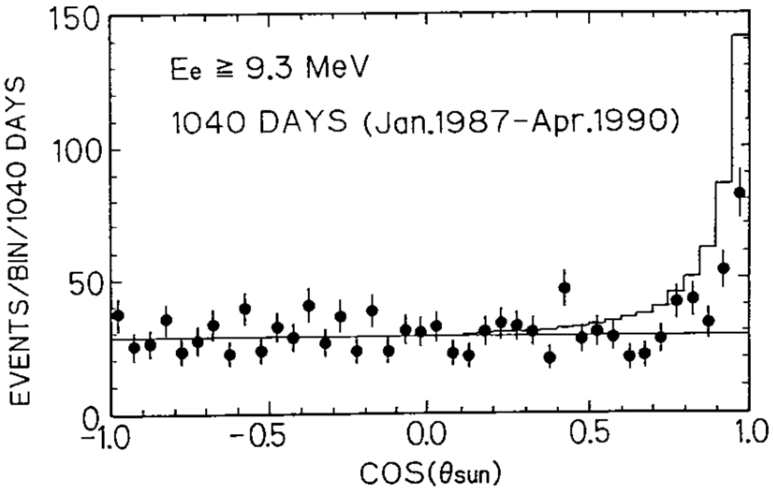
Kamiokande-II collab.
Phys.Lett. B280 (1992) 146



Kamiokande-II collab.
Phys.Lett. B335 (1994) 237



Kamiokande
Phys.Rev.Lett. 65 (1990) 1297

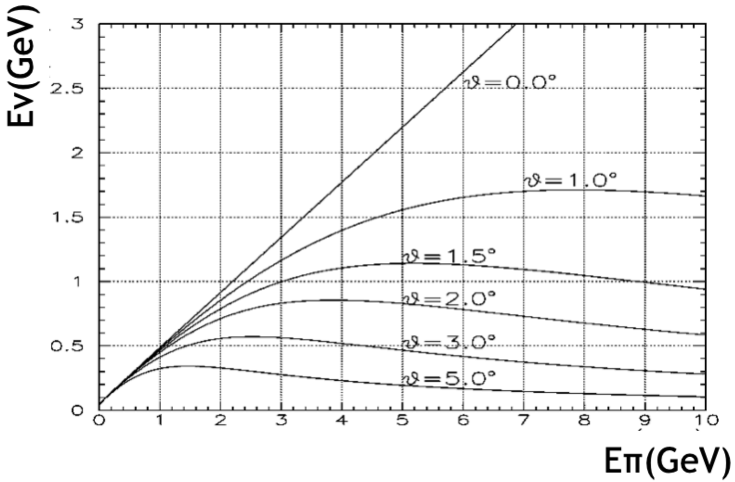


$$\text{data/SSM} = 0.46 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$$

IWCD and DUNE-PRISM

$$R(\vec{\mathbf{x}}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \rightarrow \nu_B)$$

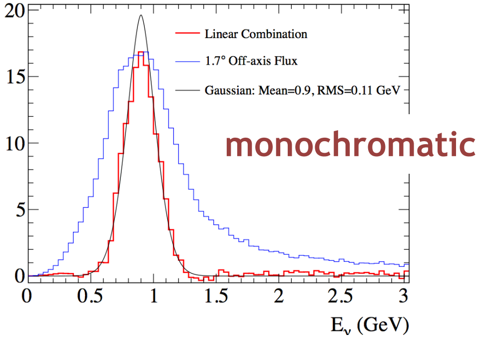
Neutrino rate at far detector | Neutrino flux | Neutrino Cross section | Detector efficiency | Oscillation probability

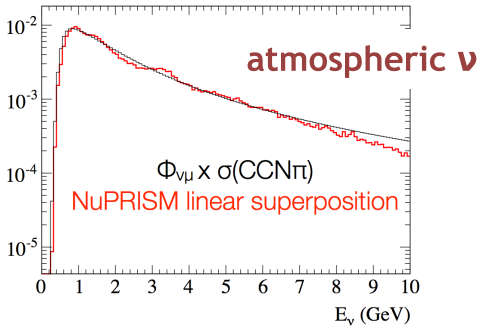


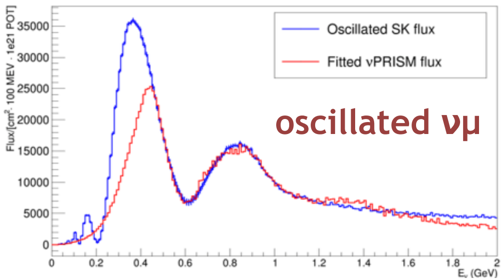
- Neutrino flux is fully correlated at different off-axis points
  - movable detector resolve [flux x cross-section] systematics
  - control sample data to constrain the uncertainty
    - Machine Learning approach would be suitable for this

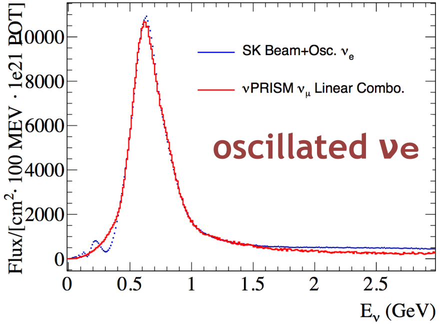
IWCD (NuPRISM) linear combination

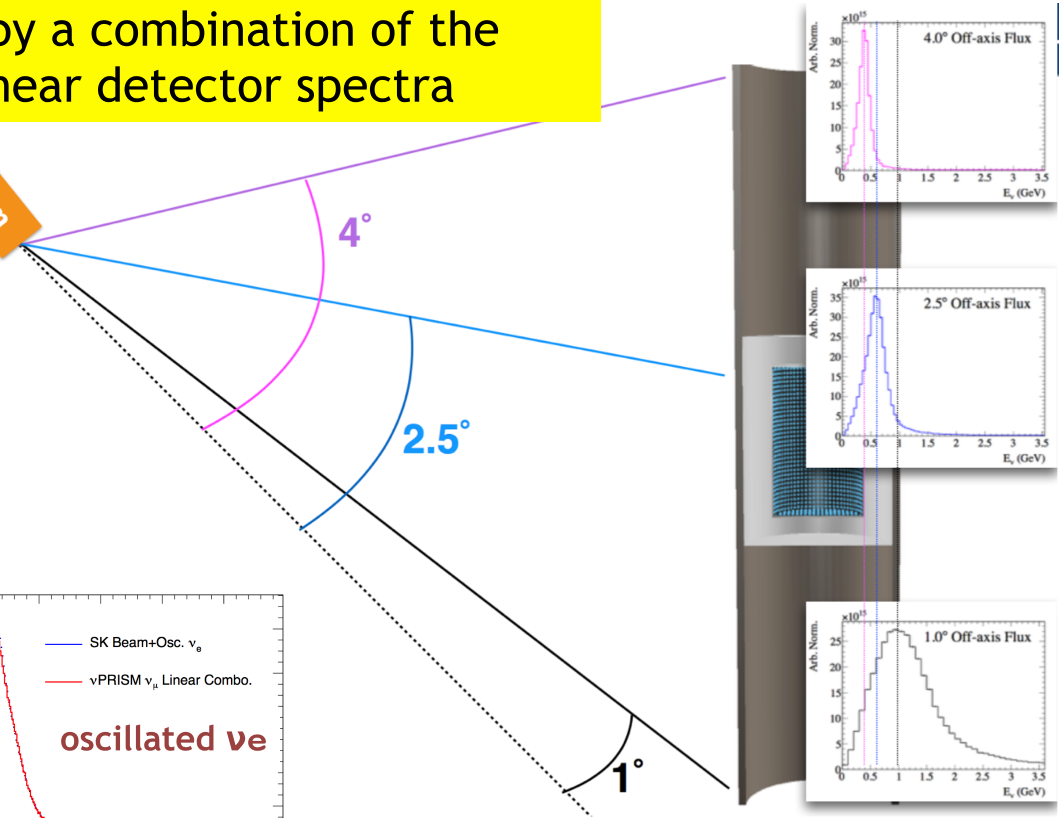
can match the far spectrum by a combination of the near detector spectra



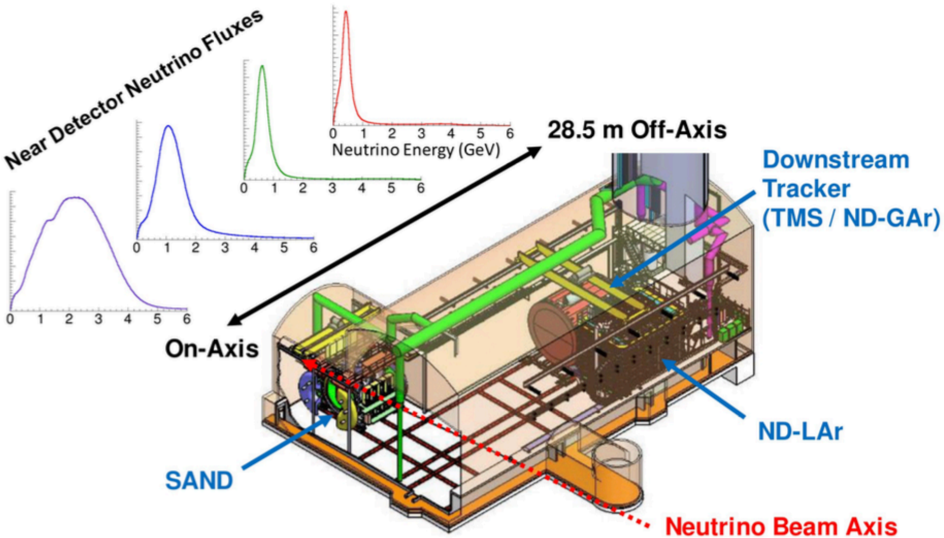


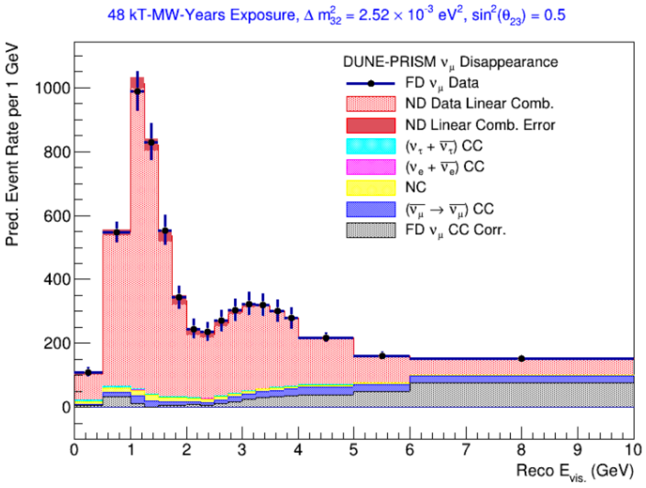


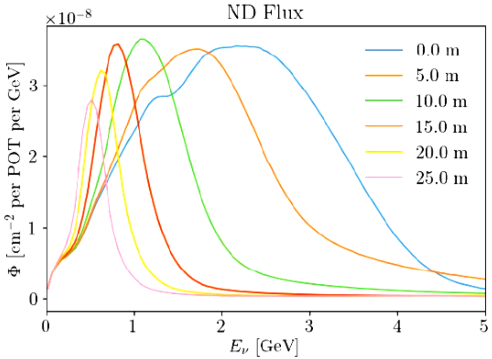




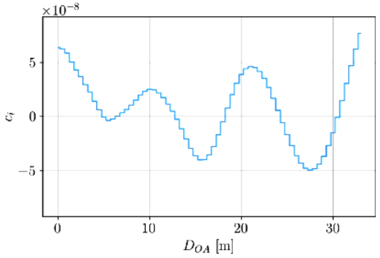
νe cross section will also be studied


Near Detector Neutrino Fluxes
Neutrino Energy (GeV)
28.5 m Off-Axis
On-Axis
Downstream Tracker (TMS / ND-GAr)
ND-LAr
SAND
Neutrino Beam Axis

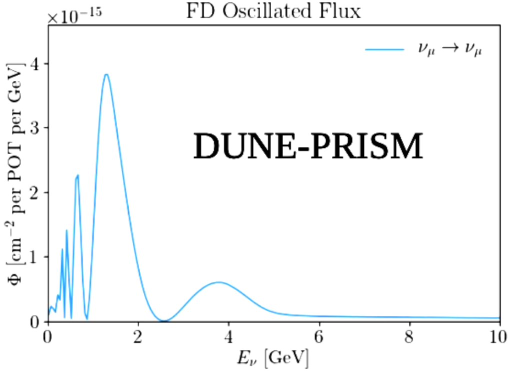

48 kT-MW-Years Exposure, $\Delta m^2_{32} = 2.52 \times 10^{-3}$ eV^2, $\sin^2(\theta_{23}) = 0.5$
DUNE-PRISM ν_μ Disappearance
FD ν_μ Data
ND Data Linear Comb.
ND Linear Comb. Error
$(\nu_\tau + \bar{\nu}_\tau)$ CC
$(\nu_e + \bar{\nu}_e)$ CC
NC
$(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ CC
FD ν_μ CC Corr.
Pred. Event Rate per 1 GeV
Reco $E_{vis.}$ (GeV)


ND Flux
$\times 10^{-8}$
0.0 m
5.0 m
10.0 m
15.0 m
20.0 m
25.0 m
Φ [cm^{-2} per POT per GeV]
E_ν [GeV]

x


$\times 10^{-8}$
c_i
D_{OA} [m]

→


FD Oscillated Flux
$\times 10^{-15}$
$\nu_\mu \to \nu_\mu$
DUNE-PRISM
Φ [cm^{-2} per POT per GeV]
E_ν [GeV]

WCTE and Proto-DUNE

$$R(\vec{\mathbf{x}}) = \Phi(E_\nu) \times \sigma(E_\nu, \vec{\mathbf{x}}) \times \epsilon(\vec{\mathbf{x}}) \times P(\nu_A \to \nu_B)$$

Neutrino rate at far detector

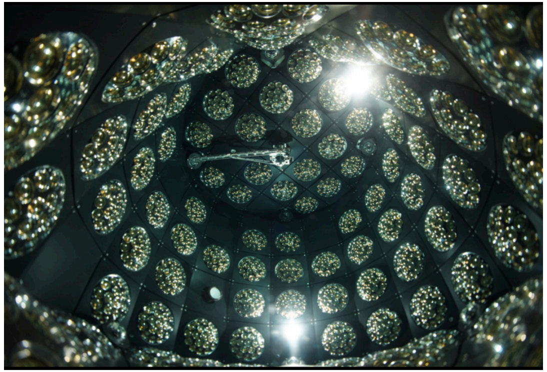
Neutrino flux

Neutrino Cross section

Detector efficiency

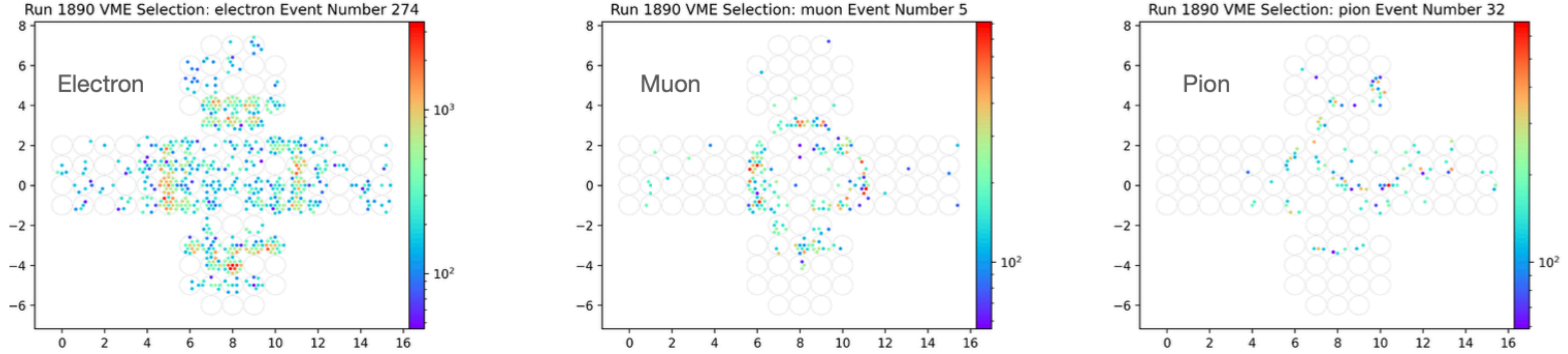
Oscillation probability

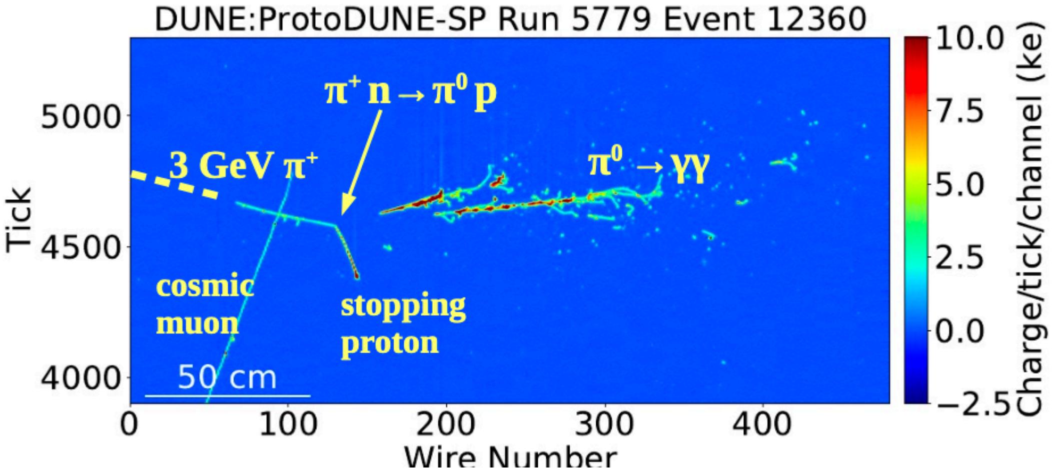
Courtesy L. Pérez Molina, EPS-HEP 2025



- Control samples for the detector response: particularly for responses on hadrons
  - WCTE: water Cherenkov
  - ProtoDune: Liquid Ar

WCTE and ProtoDUNE





- Tagged ν_μ and ν_e beam: NuSCOPE

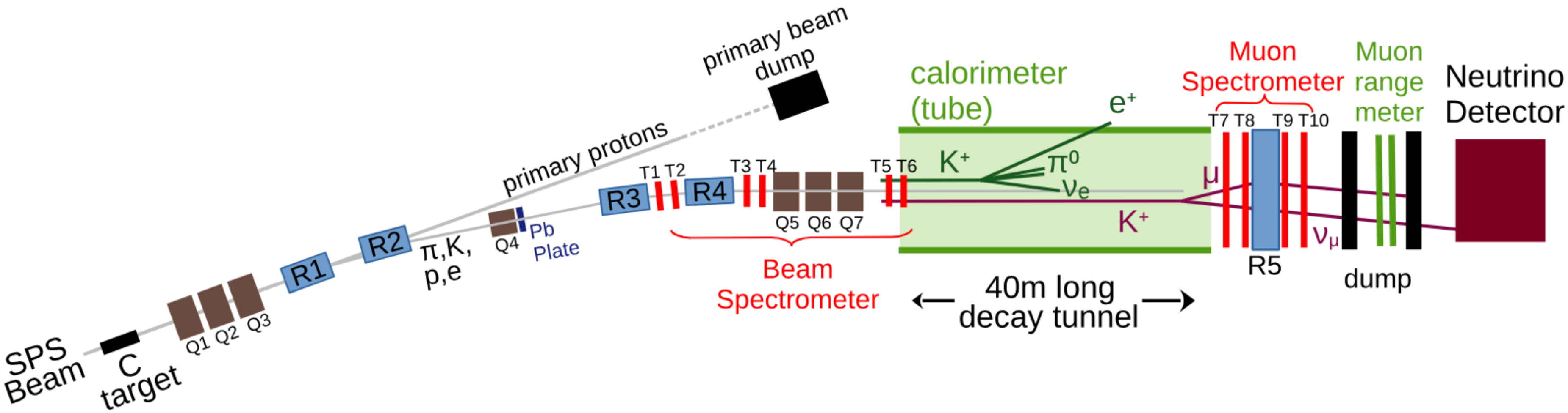


Figure 1: Layout of the experimental setup of the nuSCOPE beamline. The beamline (not to scale) combines both the ENUBET (in green) and the NuTag (in red) beam instrumentation. The first part of the beamline contains the beamline magnets (blue: rectangular bending magnets; brown: quadrupole magnets).

Summary

- The next generation of neutrino oscillation experiments is under construction or has just started operation
  - CP violation and neutrino mass ordering are the big targets
- NNN is a great opportunity to discuss what comes beyond:
  - Precise tests of the PMNS may lead us to a new paradigm