T2K & E61

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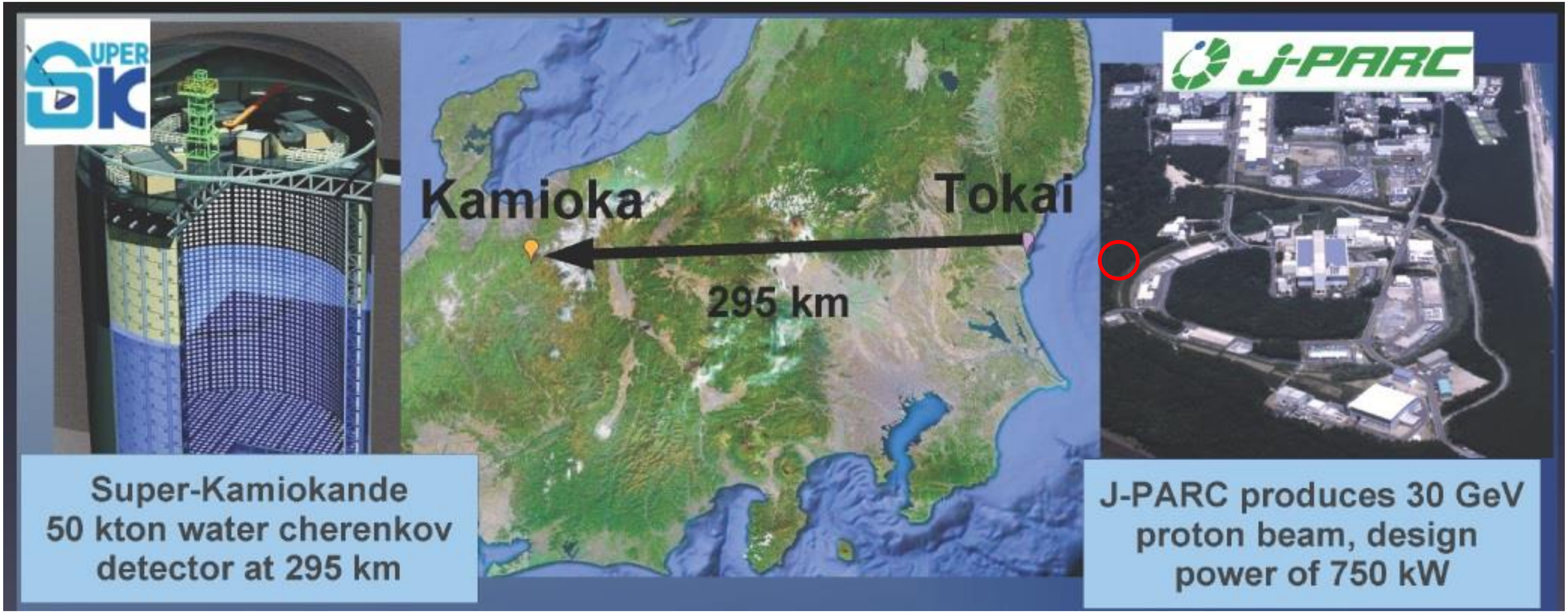
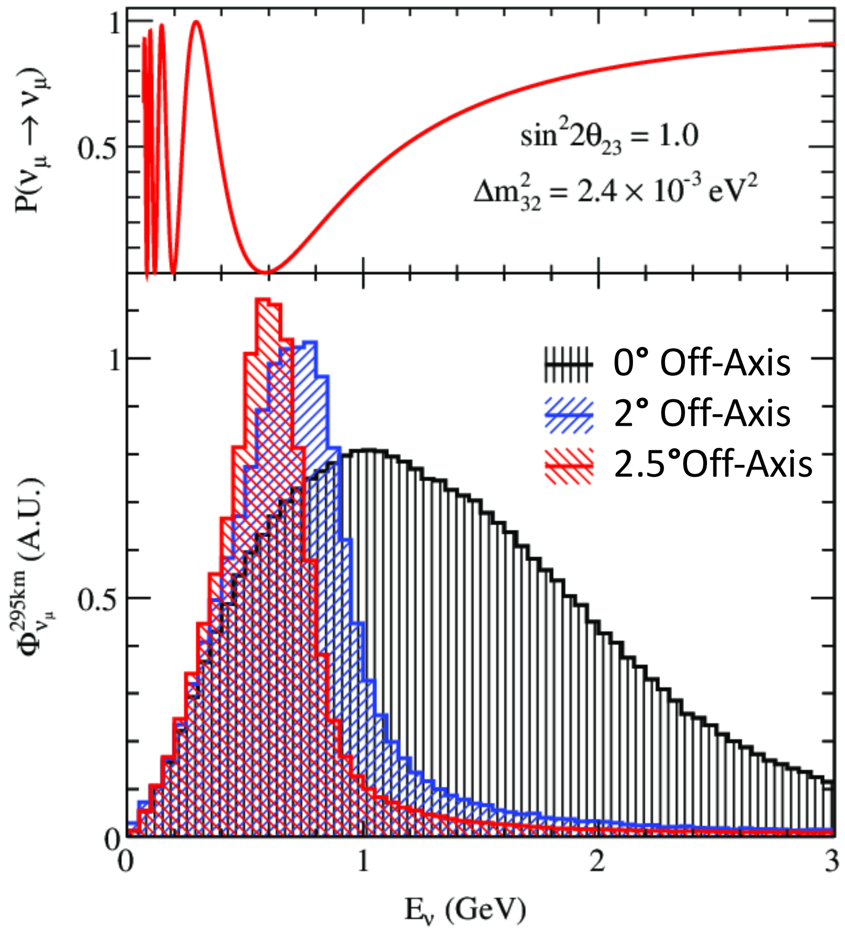

T2K
SUPER K
J-PARC
Kamioka
Tokai
295 km
Super-Kamiokande
50 kton water cherenkov
detector at 295 km
J-PARC produces 30 GeV
proton beam, design
power of 750 kW

Neutrino Production

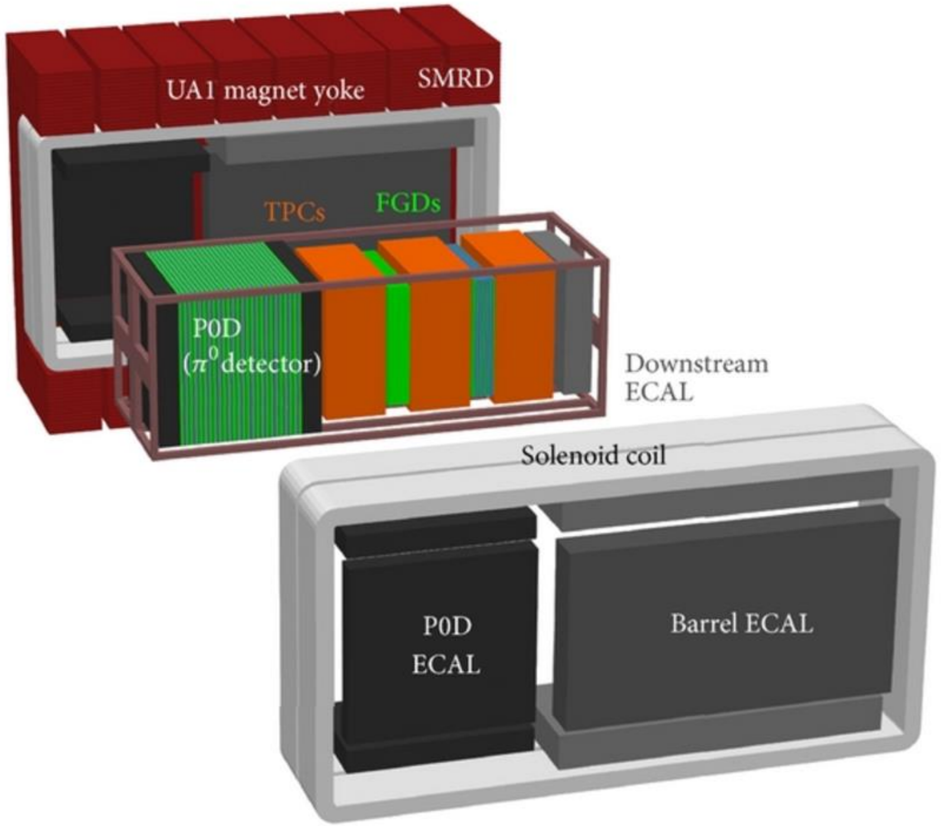
- Proton beam fired at graphite target to produce pions
- Pions charge-selected and focused using magnetic horns then allowed to decay to $\overset{(-)}{\nu}_\mu + \mu^{+(-)}$
- Strong angular dependence of neutrino energy
- Select angle from central axis to maximise oscillation probability



K. Abe et al. [T2K Collaboration], Phys. Rev. D87, 012001 (2013)

ND280

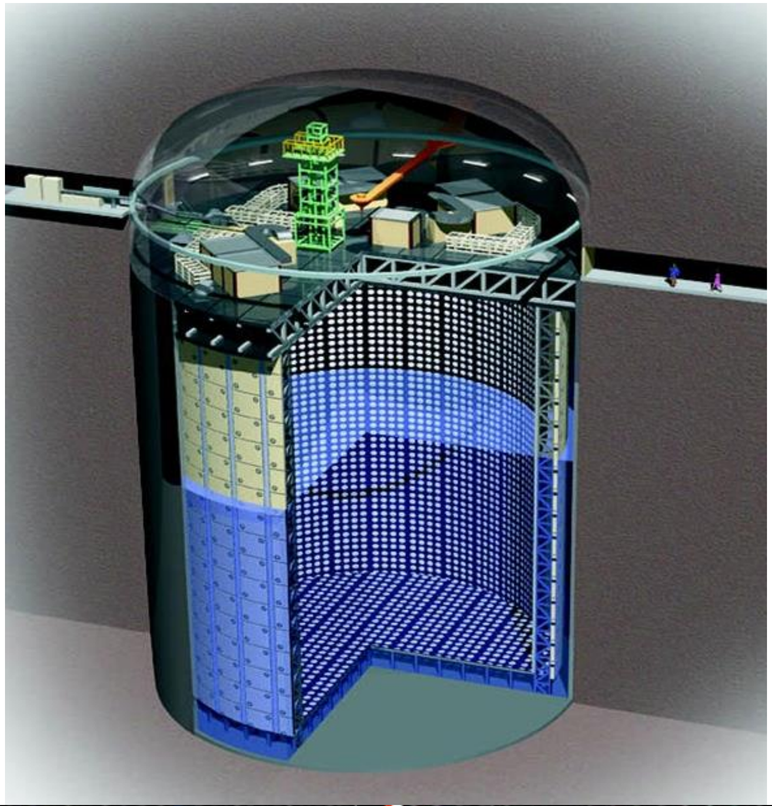
- Near detector 280m from pion production target
- Placed 2.5° from the centre of the neutrino beam
- Polystyrene scintillator Fine Grained Detector (FGD) is target mass
- Additional layers of water are present as target
- TPCs used for high precision particle tracking
- Contained in a 0.2T magnetic field to aid interaction reconstruction

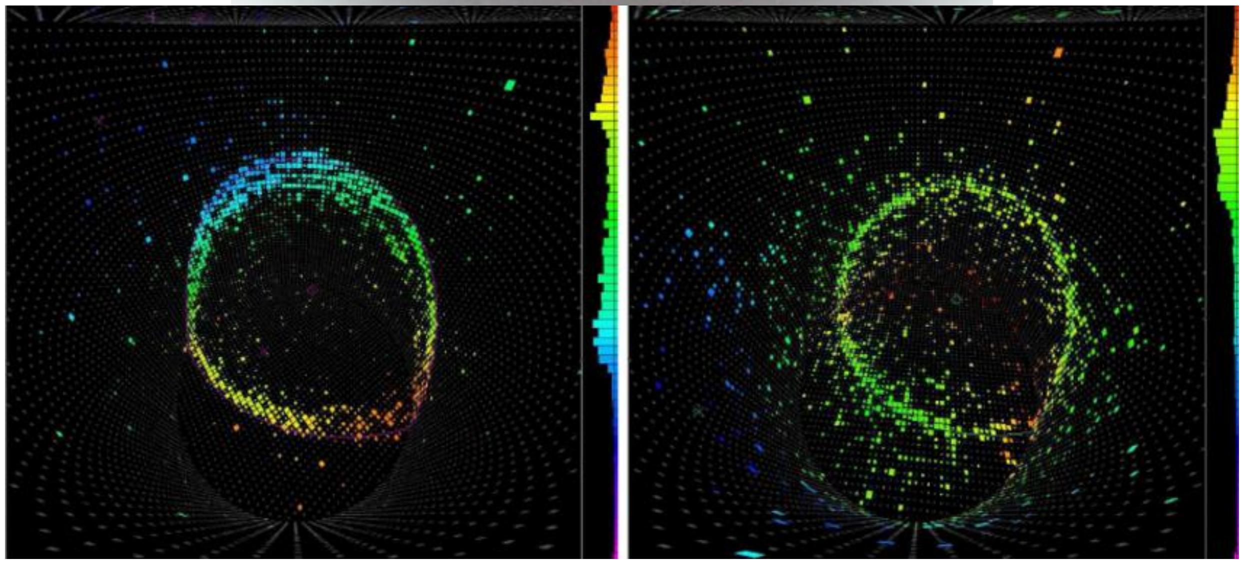


The T2K experiment (2011). K. Abe et al. (T2K collaboration). arXiv:1106.1238v2 [physics.ins-det]

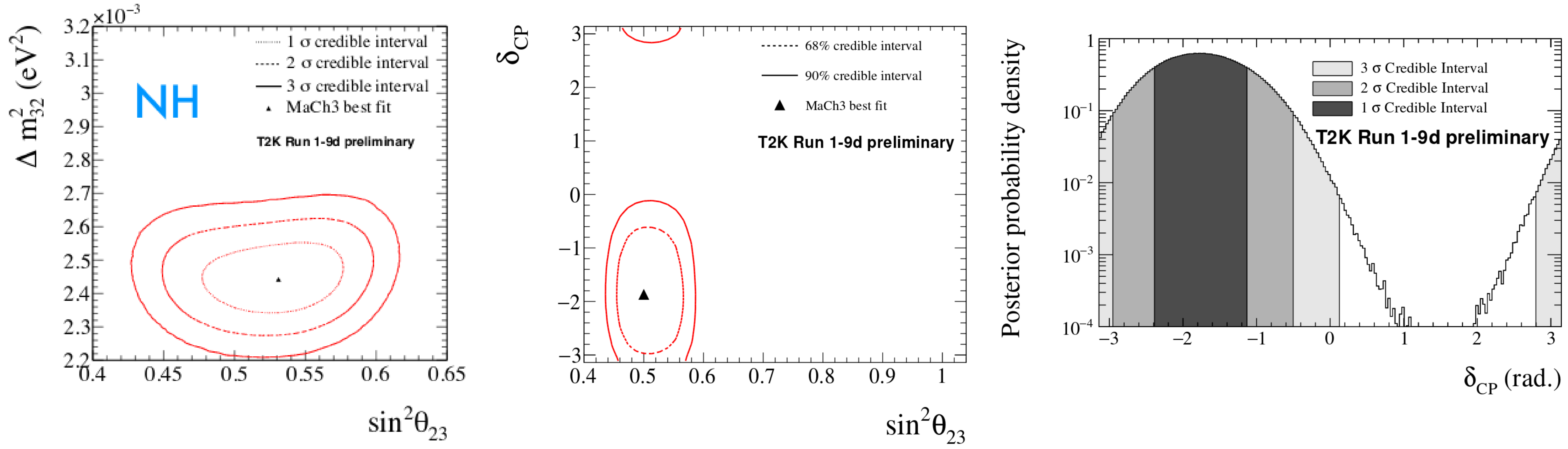
Super-K

- 50 kton water Cherenkov detector
- Instrumented with 11,129 PMTs
- In charged-current neutrino interactions muon or electron produced
- High-energy leptons radiate Cherenkov light
- Structure of Cherenkov ring gives particle ID muon (left) electron (right)





Results



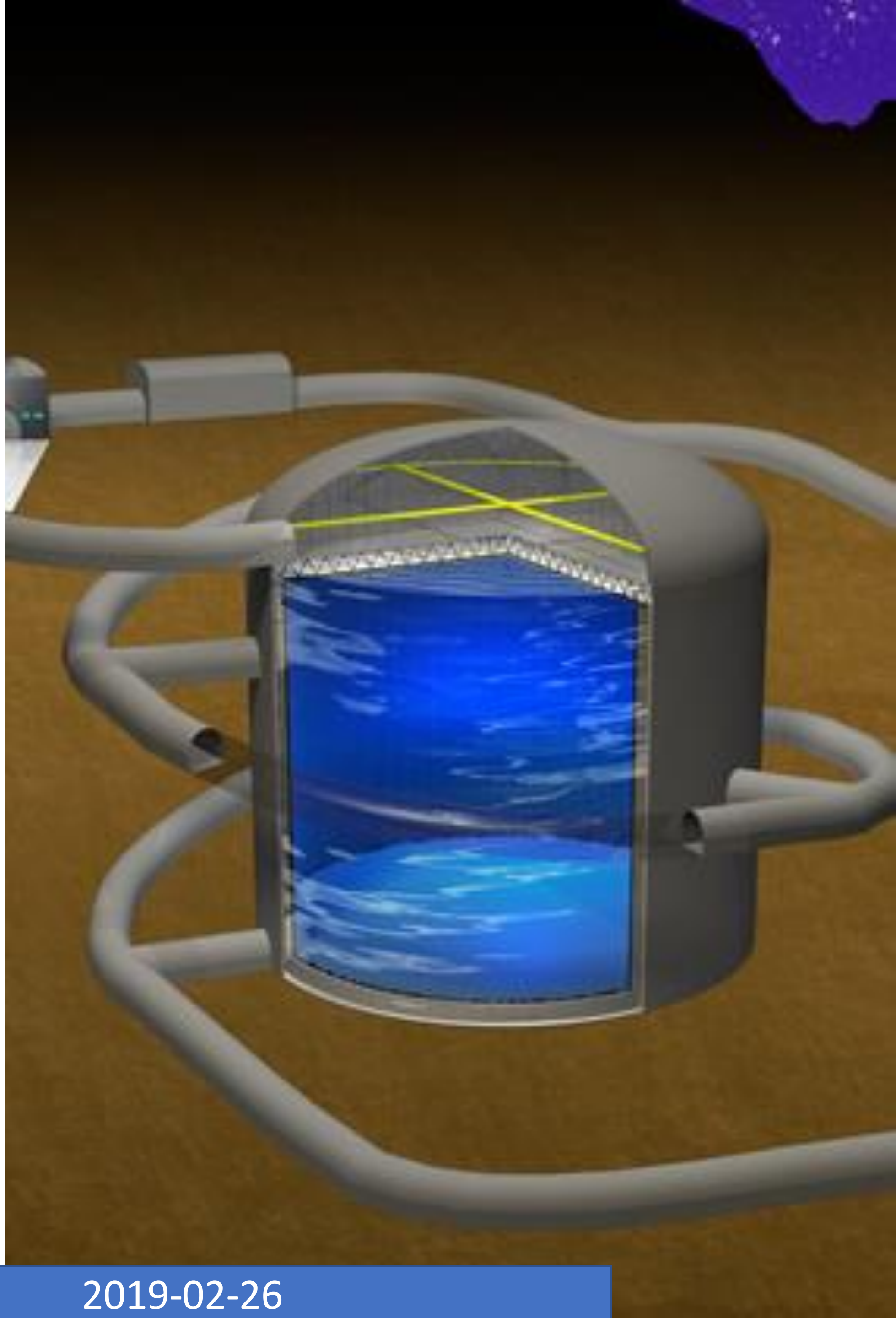
Asher Kaboth [T2K Collaboration] https://indico.ph.qmul.ac.uk/indico/contributionDisplay.py?contribId=22&confId=289

Hyper-Kamiokande

- Add a new, larger water Cherenkov detector
  - Super-K 50 kton (22.5 kton fiducial)
  - Hyper-K 230 kton (187 kton fiducial)

- Increase proton beam power from 750 kW to 1.3MW

- Overall about a 15 times increase in event rate



E61 - Motivation

- T2K currently has a 10% statistical error, 5-6% systematic error
- Goal for Hyper-K is a 3% statistical error
- Need to reduce systematic errors to below 3%

Source (%)	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
Super-Kamiokande detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2

'Combined Analysis of Neutrino and Antineutrino Oscillations at T2K' K.Abe et al. [T2K Collaboration] Phys. Rev. Lett. 118, 151801

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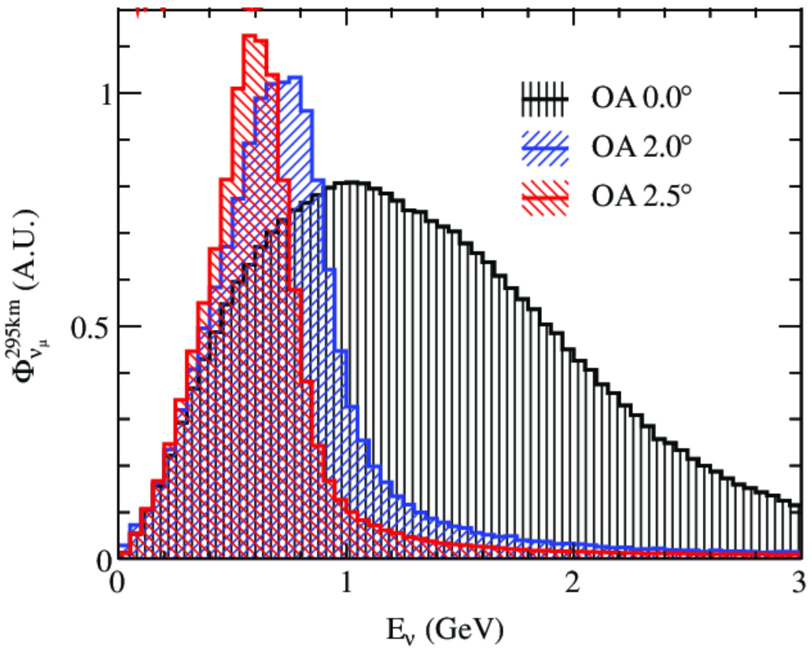
E61

- Use a 3 kton water Cherenkov near detector for Hyper-K
- Scan detector over off-axis angle to record several different energy distributions
- Combining readings together, new energy spectra can be synthesised



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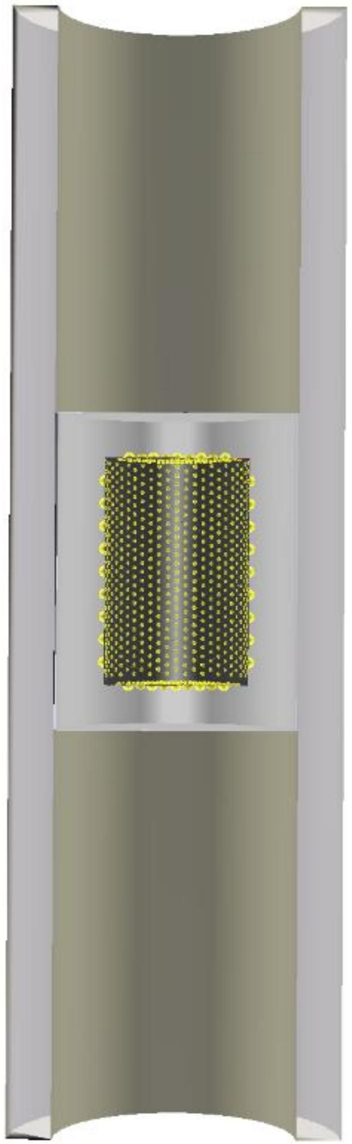
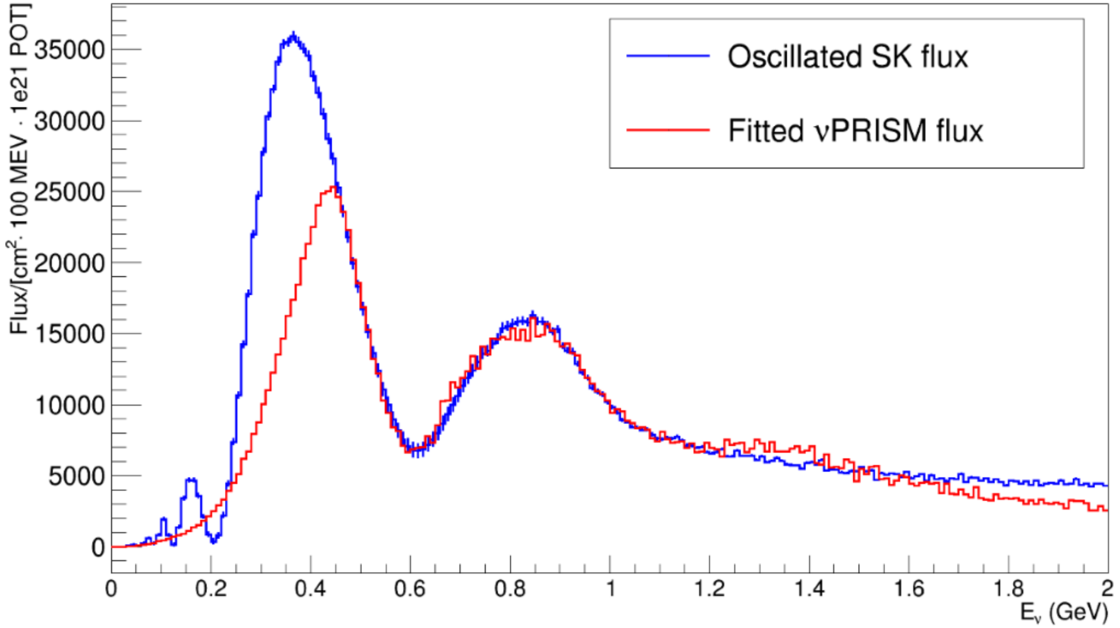


'Letter of intent to construct a nuPRISM detector in the J-Parc Neutrino beamline' (2014), S. Bhadra et al. arXiv:1412.3086v2

E61

- For given oscillation parameters, an oscillated flux can be synthesised
- A fit can be performed between the predicted flux and that observed at Hyper-K to extract oscillation parameters
- Flux matching: Same neutrino flux onto the same material in both near and far detectors



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Conclusion

- Neutrino Physics is heading into the precision era
- E61 has great potential to reduce systematic errors
- Moveable detector allows for synthesis of energy spectra

Backups

Phenomenology

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$
$$+ 2\sum_{i>j} \mathrm{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right),$$

Probability of neutrino initially of flavour α oscillating to flavour β

- Frequency of oscillation dependent on Δm^2, L/E
- Magnitude of oscillation dependent on PMNS matrix
- In experiments L is fixed, measure P_{osc} as a function of E
- Only relative square mass differences can be inferred from oscillation experiments
- The complex phase, δ_{CP} of the PMNS matrix is of particular interest

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

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