T2K: Latest Results and Future Plans

Helen O'Keeffe, Lancaster University, On behalf of the T2K collaboration
NNN17, University of Warwick
27th October 2017

Neutrino Oscillations

Lancaster University

Neutrinos can change flavour during their propagation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric/accelerator

$\theta_{23} = (45\pm3)°$

$|\Delta m^2_{32}| = (2.52\pm0.04)\times10^{-3}$ eV^2

Reactor/accelerator

$\theta_{13} = (8.5\pm0.15)°$

$|\Delta m^2_{31}| = (2.52\pm0.04)\times10^{-3}$ eV^2

$\delta_{CP} \approx -90°$ (best fit)

Solar/reactor

$\theta_{13} = (33.6\pm0.8)°$

$\Delta m^2_{21} = (7.50\pm0.18)\times10^{-5}$ eV^2

Some unanswered questions:

Is θ_{23} maximal? δ = ? Mass ordering = ?

T2K neutrino oscillation probability

Lancaster University

Muon neutrino disappearance

$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}) \times \sin^2\frac{\Delta m^2_{31} L}{4E}$$

Precision measurement of θ_{23} and Δm^2_{31}

Electron neutrino appearance

$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq & \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & - \alpha \sin\delta \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & + \alpha \cos\delta \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\Delta \frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ & + \mathcal{O}(\alpha^2) \end{aligned}$$

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right|$$

$$\Delta = \frac{\Delta m^2_{31} L}{4E}$$

$$x = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

Matter effects included

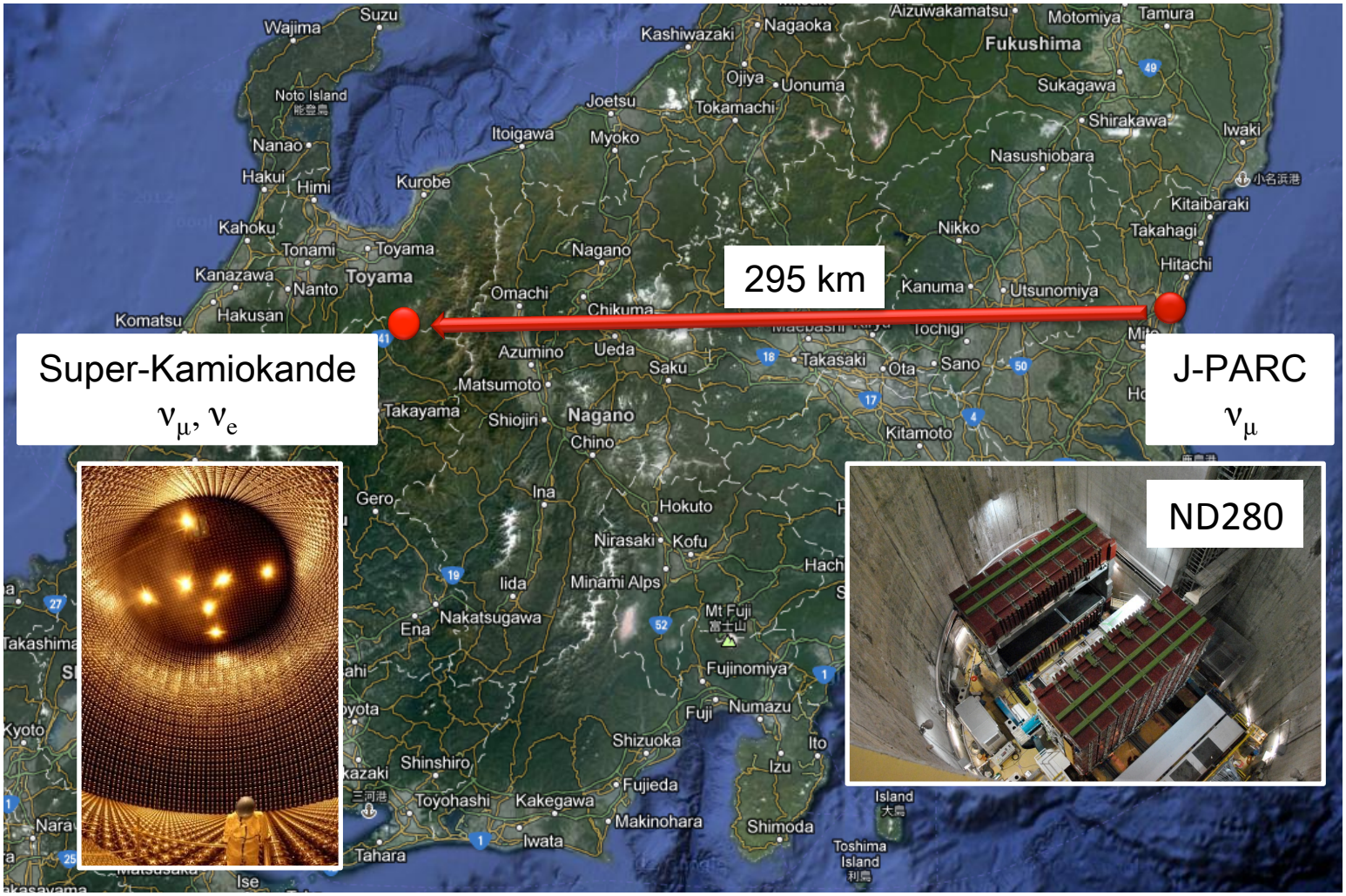
Leading term dependence on $\sin^2\theta_{13}$

If $\sin\delta \neq 0$: Asymmetry of appearance probabilities for ν and anti-ν

Tokai to Kamioka (T2K) experiment

Lancaster University

~500 members from 64 institutes across 12 countries



Neutrino oscillations and T2K

Lancaster University

Measurements made by T2K experiment

ν_μ disappearance	Phys. Rev. Lett. 112 (2014) 181801
ν_e appearance	Phys. Rev. Lett. 112 (2014) 061802
$\nu_\mu + \nu_e$ joint fit	Phys. Rev. D 91 (2015) 072010
anti-ν_μ disappearance	Phys. Rev. Lett. 116 (2016) 181801

Combined ν and anti-ν measurement Phys. Rev. Lett. 118 (2017) 151801

Other analyses e.g. cross-sections, beam properties etc

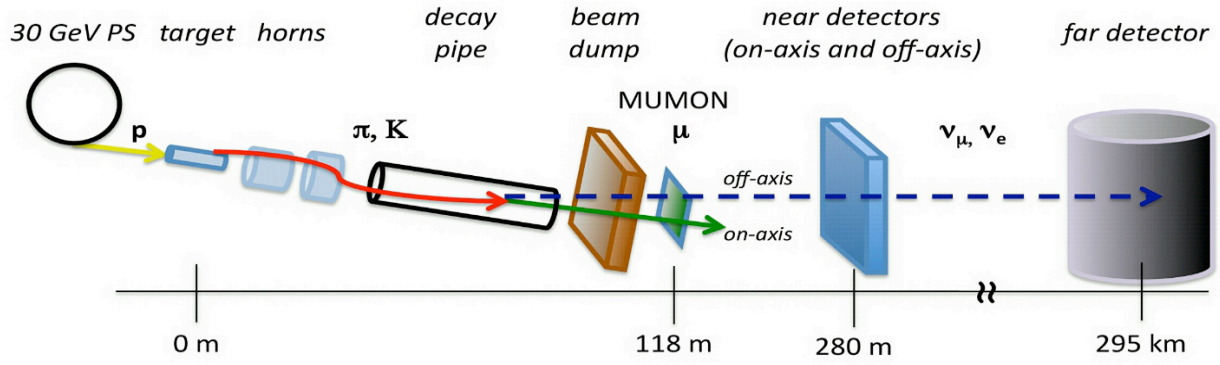
Measurements to be made by T2K

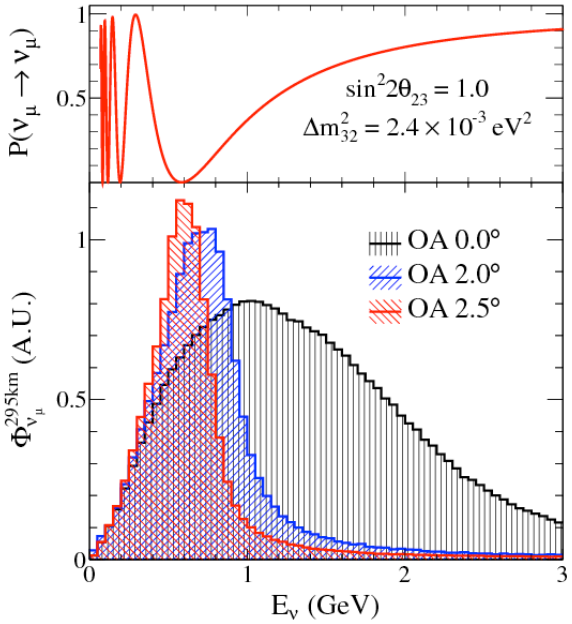
anti-ν_e appearance and probe CP violation

Improved measurements of θ_{23} and θ_{13}

Precision cross-section measurements at near detector

T2K neutrino beam



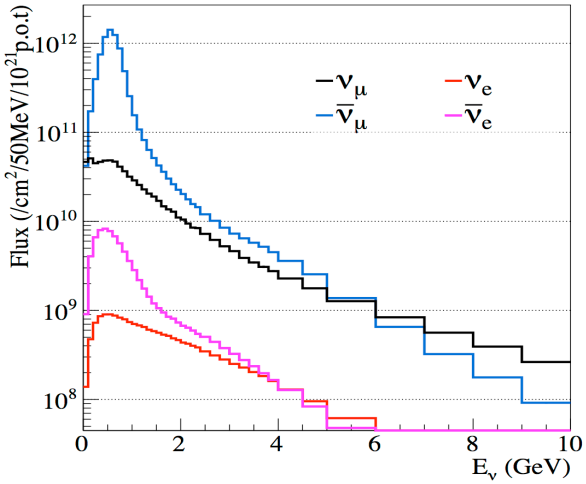


High-purity ν_μ beam

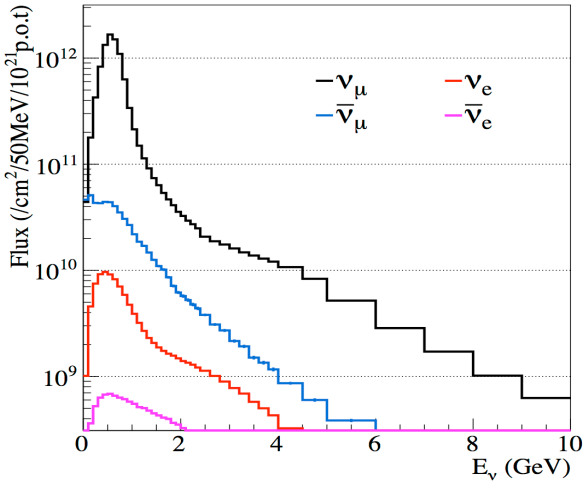
Reverse horn current to produce anti-ν_μ beam

Place detectors 2.5° off the beam axis

Antineutrino-mode flux at ND280



Neutrino-mode flux at ND280



Dedicated hadron production measurements from NA61/SHINE

(Eur. Phys. J. C76 (2016) no.2, 84)

T2K beam performance

Protons on target, Jan. 2010 – April 2017

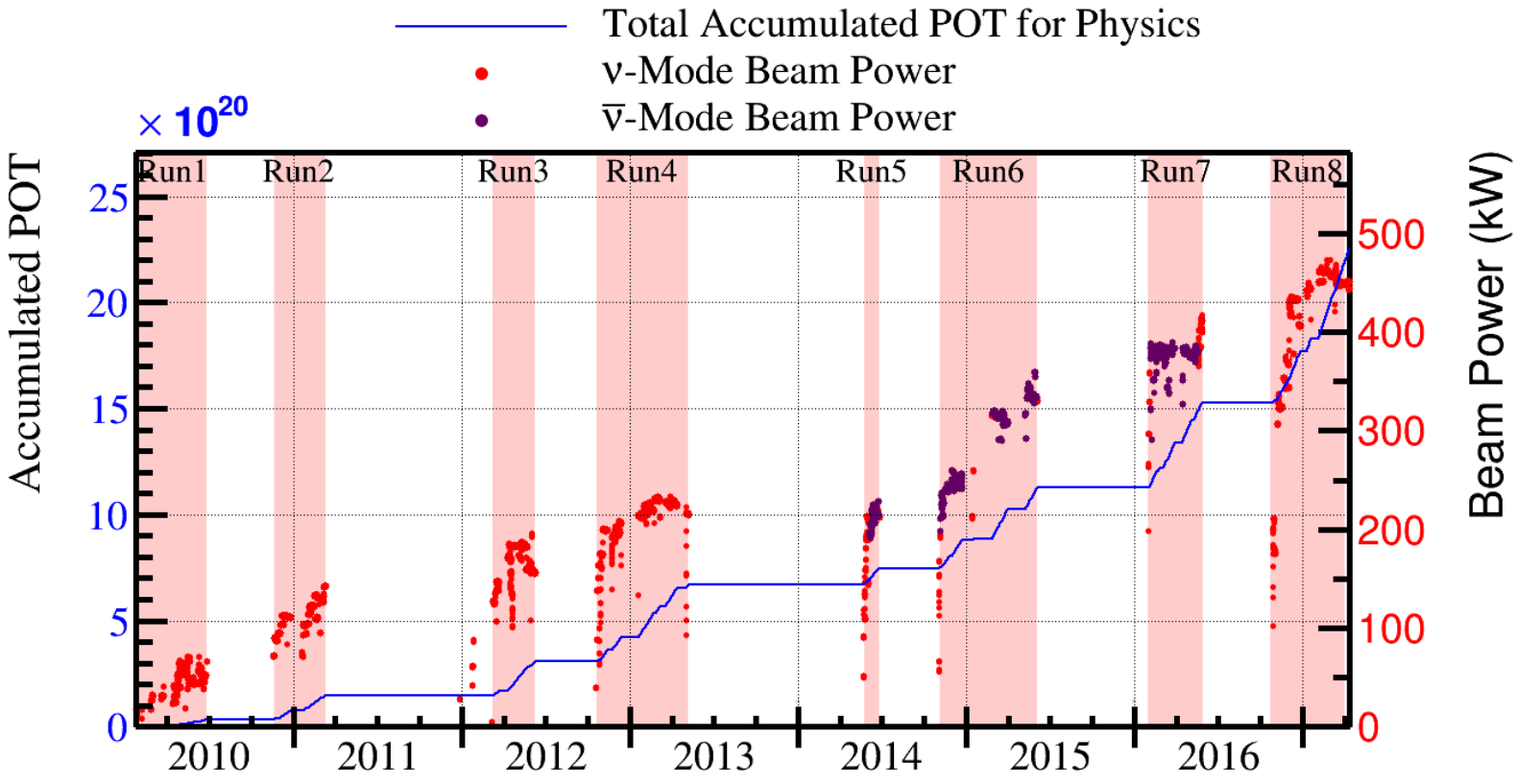
Neutrino mode = 14.93 x 10^{20}

Anti-neutrino mode = 7.62 x 10^{20}

In 2017

470 kW stable operation

Doubled ν-mode statistics in 1 year of operation!



Near detectors

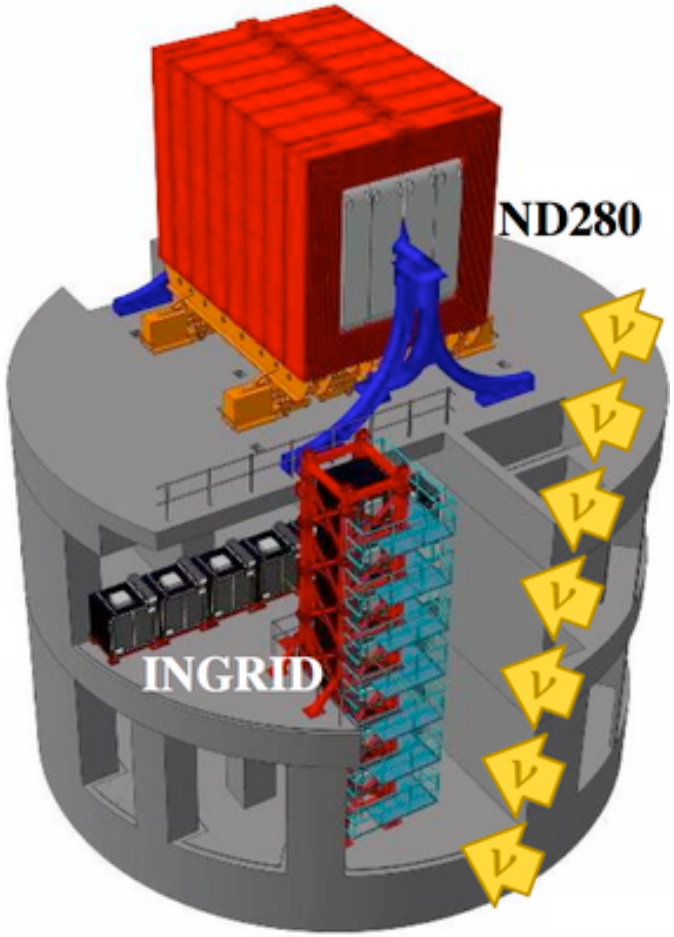
Located 280 m downstream of target

Measure ν spectrum before oscillation

$$N_{ND} = \int dE \phi(E) \times \sigma(E) \times \epsilon_{ND}(E)$$

Number of events	Neutrino flux	Interaction cross section	Detector efficiency

- Predict spectrum at far detector
- Reduce systematic uncertainty on oscillation analyses from 14% to 6%



Near detector: INGRID

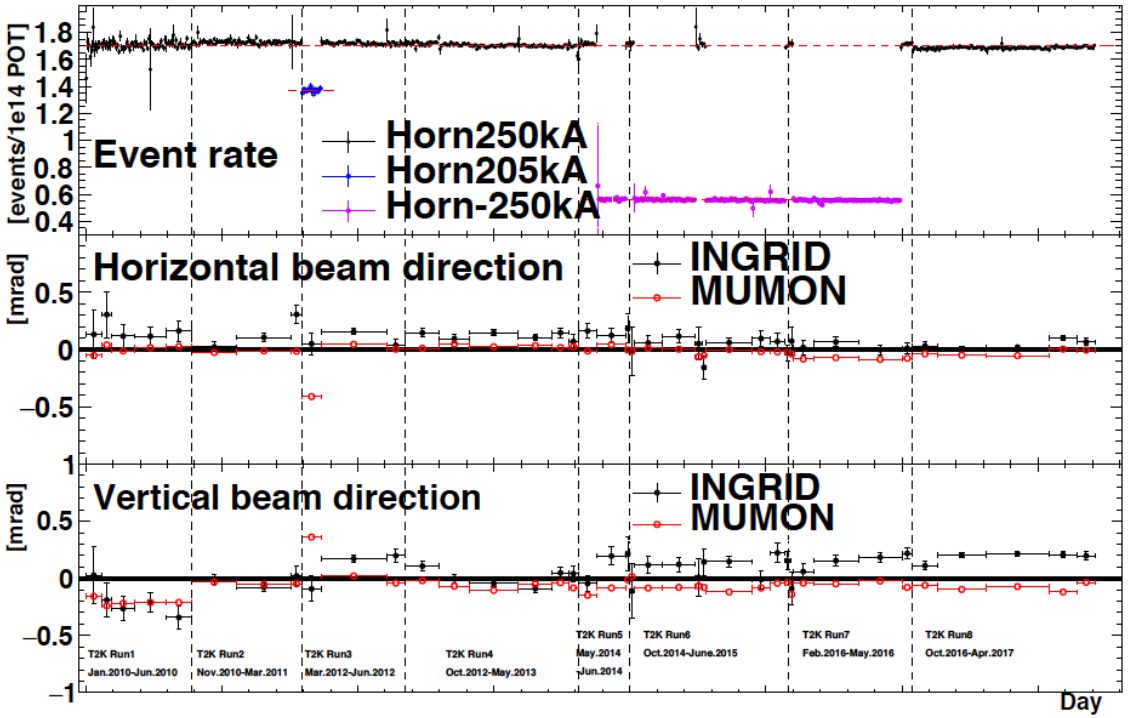
INGRID

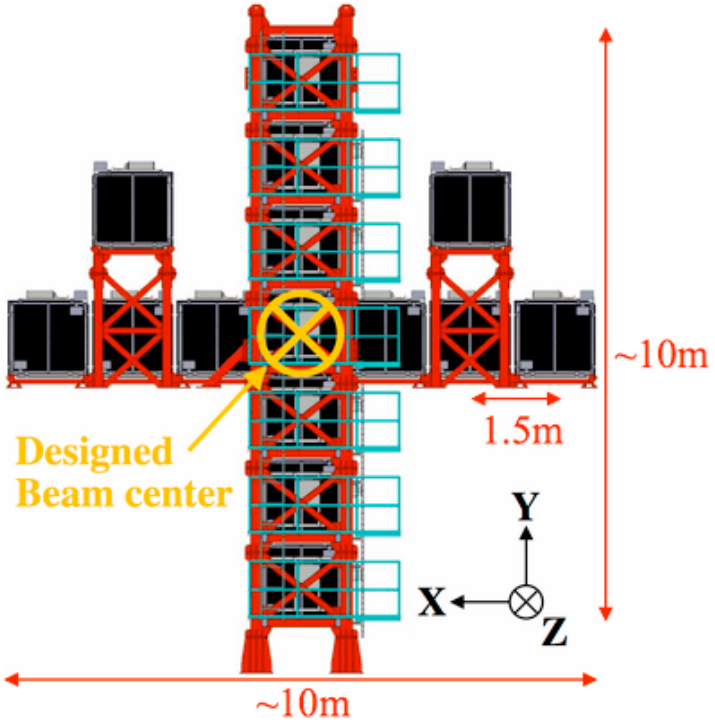
On-axis near detector

Fe/scintillator calorimeters

Monitor beam direction/stability

Constrain flux systematics and beam direction





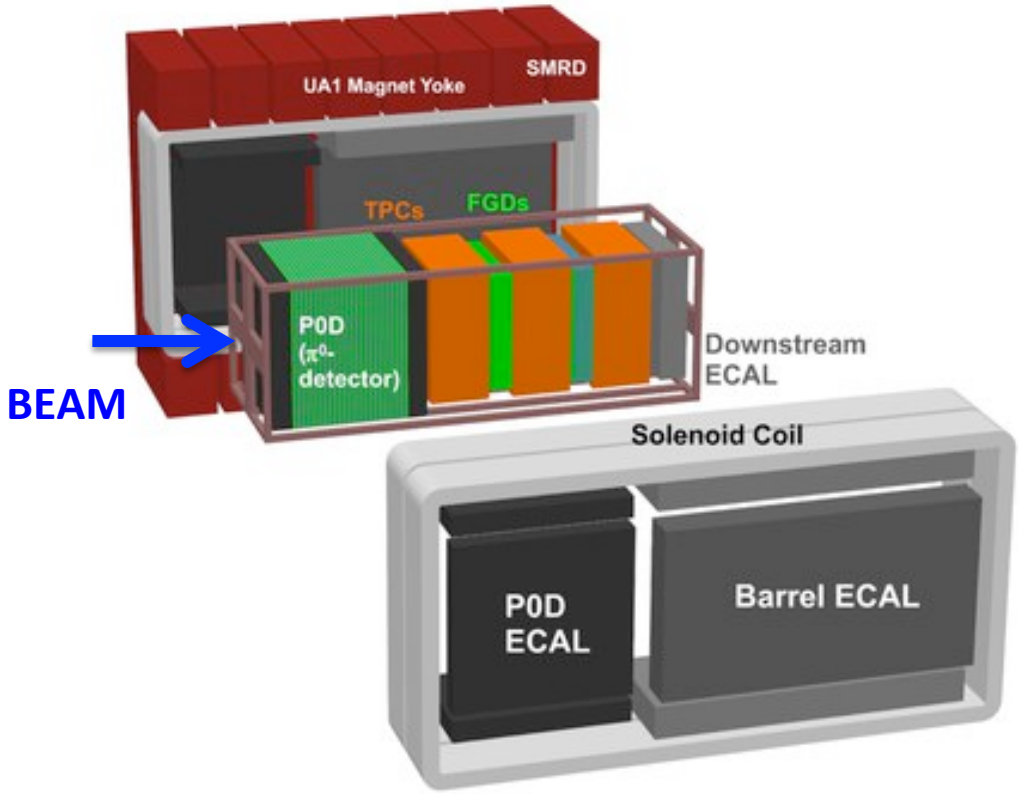
Near detector: ND280

Situated 2.5° off-axis

- Same direction as Super-K
- Comprised of five sub-detectors in a 0.2 T magnetic field
- Tracking detectors, calorimeter and muon range detector
- Carbon and water targets

Measurements of

- Charged-Current ν_μ events (normalisation and spectrum)
- Neutral-Current π^0, Charged-Current ν_e backgrounds
- Neutrino interaction properties

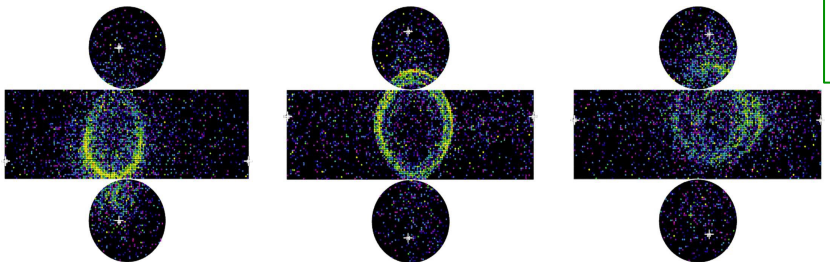


Far detector: Super-Kamiokande

Super-Kamiokande far detector

- 50 kton water-Cherenkov detector
- No magnetic field
- Excellent μ/e separation

<1% μ misidentified as e



Electron ***Muon*** ***π^0***

$$N_{FD} = \int dE \phi(E) \times \sigma(E) \times \epsilon_{FD}(E) \times P(\nu_\alpha \to \nu_\beta; E; \theta_{ij}, \Delta m^2_{ij})$$

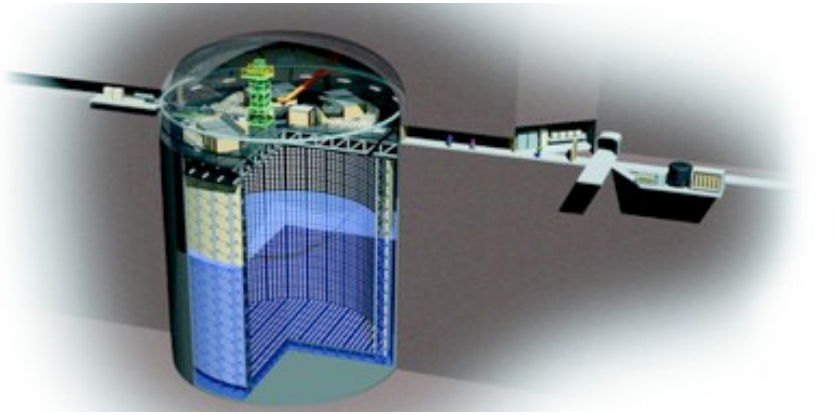
Number of events

Neutrino flux

Interaction cross section

Detector efficiency

Oscillation probability



Since 2016, 5 different CC samples used

ν mode

CCQE 1 μ-like ring, ≤ 1decay e

CCQE 1 e-like ring, 0 decay e

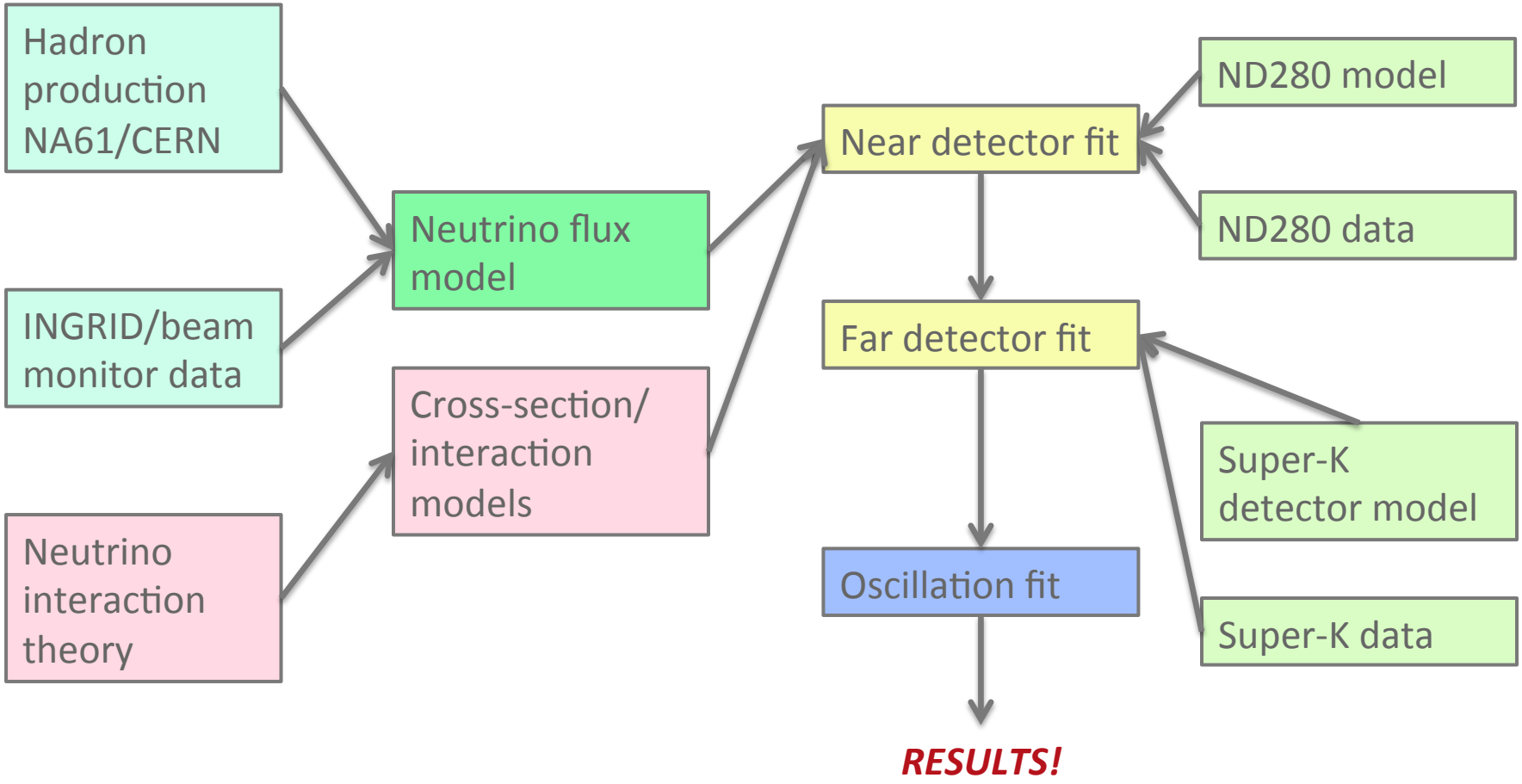
CC1π 1 e-like ring, 1 decay e

anti-ν mode

CCQE 1 μ-like ring, ≤ 1 decay e

CCQE 1 e-like ring, 0 decay e

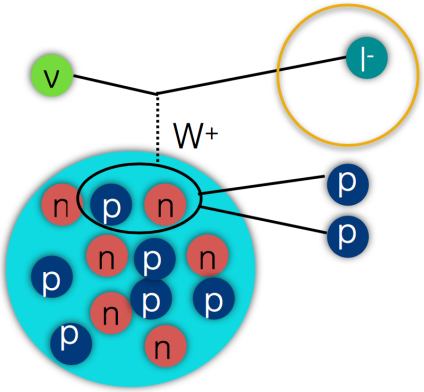
T2K analysis strategy

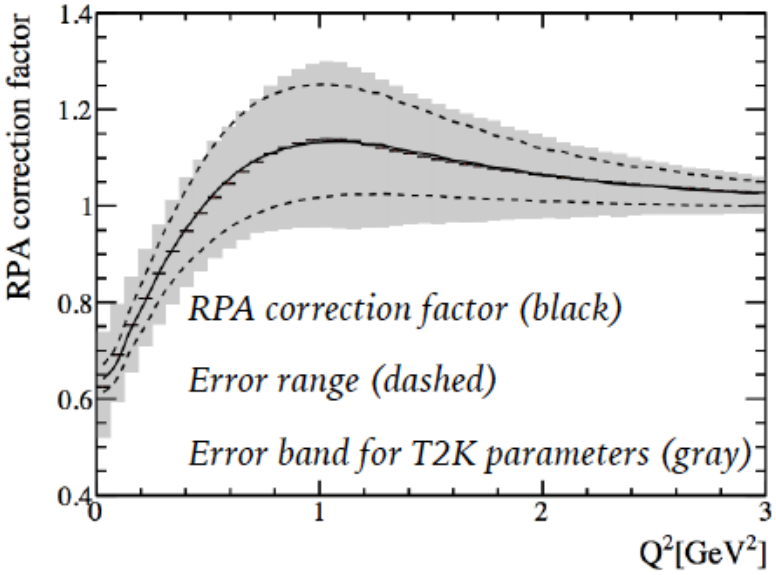


Improvements for 2017 oscillation analysis

Improvements in Monte Carlo generation, specifically NEUT

- Inclusion of muti-nucleon scattering Valencia 2p-2h model
- Improved pion production model
- New parameterizations of the uncertainties in multi-nucleon and Random Phase Approximation (long-range correlations in the nucleus) modelling





Improvements for 2017 oscillation analysis

Lancaster University

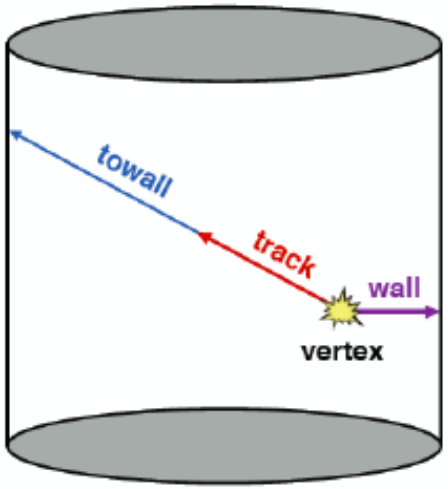
Super-Kamiokande event selection

fitQun = New maximum-likelihood event reconstruction algorithm that brings with it new selection criteria

Newly optimised fiducial volume cuts -> cut on two variables

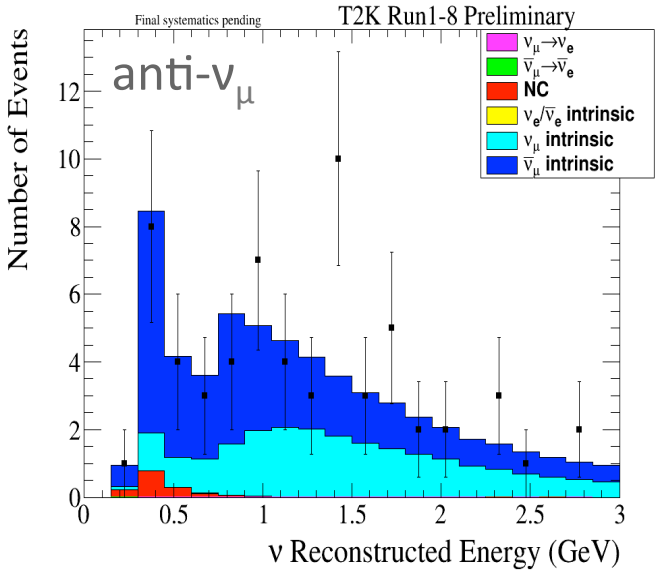
- distance of vertex from wall (Wall)
- Distance to the wall along the particle trajectory (Towall)

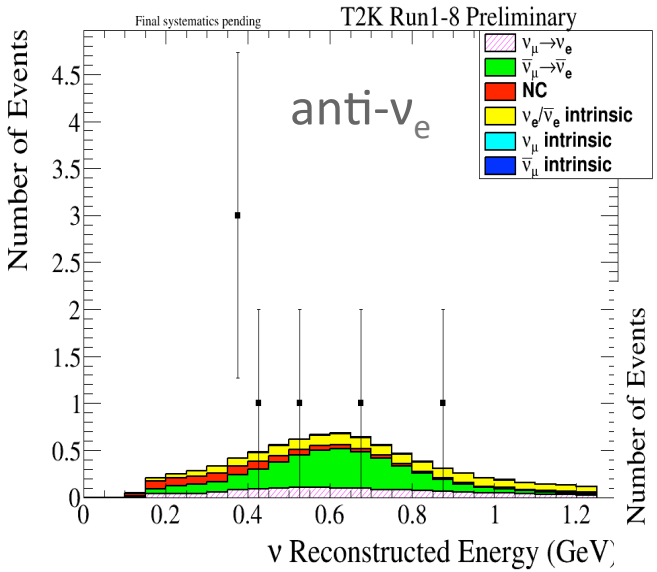
Effective statistics increase ~30%

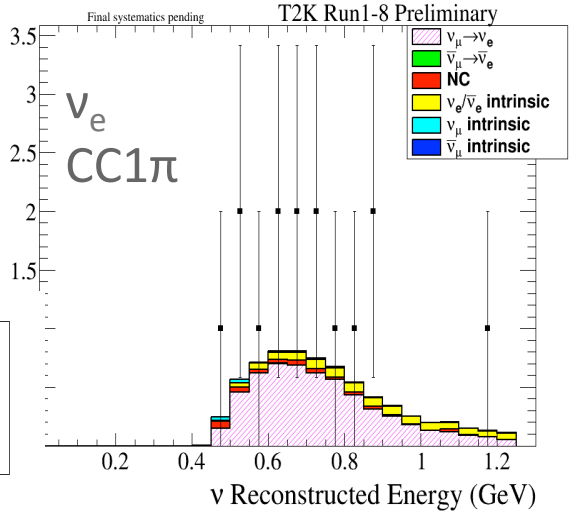


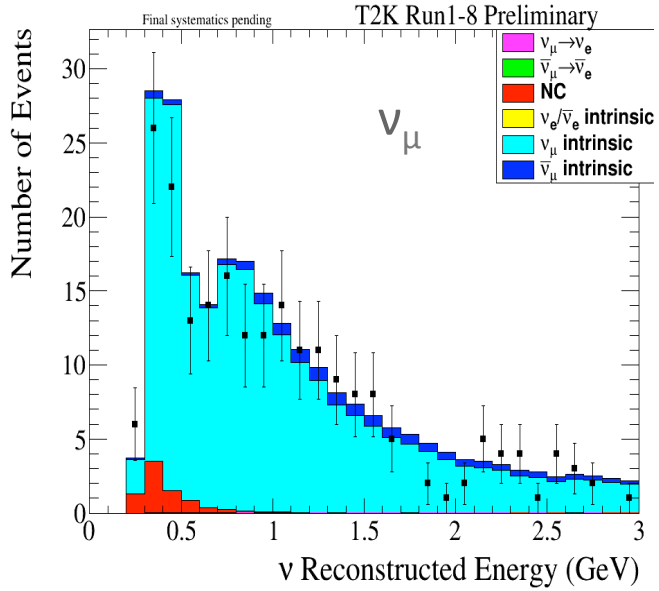
	fiTQun Selection		APFit Selection	
Sample	Candidates	Purity	Candidates	Purity
CCQE 1-Ring e-like neutrino	69.5	81.2%	56.5	81.4
CCQE 1-Ring mu-like neutrino	261.6	79.7%	268.7	68.1%
CC1pi 1-Ring e-like neutrino	6.9	78.8%	5.6	72.0%
CCQE 1-Ring e-like anti-nu	7.6	62.0%	6.1	63.7%
CCQE 1-Ring mu-like anti-nu	62.0	79.7%	65.4	70.5%

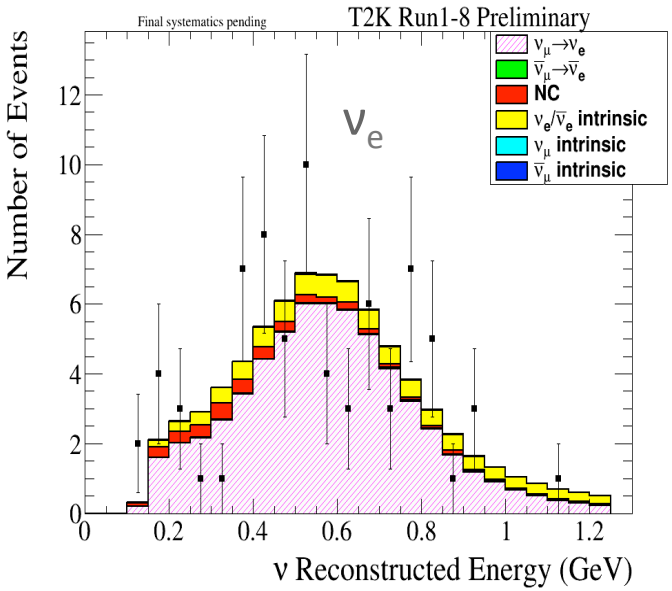
Observed spectra at Super-K











Observed and predicted event rates

	Predicted rates				Observed
Sample	**$\delta_{CP} = -\pi/2$**	**$\delta_{CP} = 0$**	**$\delta_{CP} = \pi/2$**	**$\delta_{CP} = \pi$**	**Events**
CCQE 1-Ring e-like ν	73.5	61.5	49.9	62.0	74
CCQE 1-Ring mu-like ν	267.8	267.4	267.7	268.2	240
CC1pi 1-Ring e-like ν	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like anti-ν	7.93	9.04	10.04	8.93	7
CCQE 1-Ring mu-like anti-ν	63.1	62.9	63.1	63.1	68

Results: Atmospheric parameters

2016 analysis

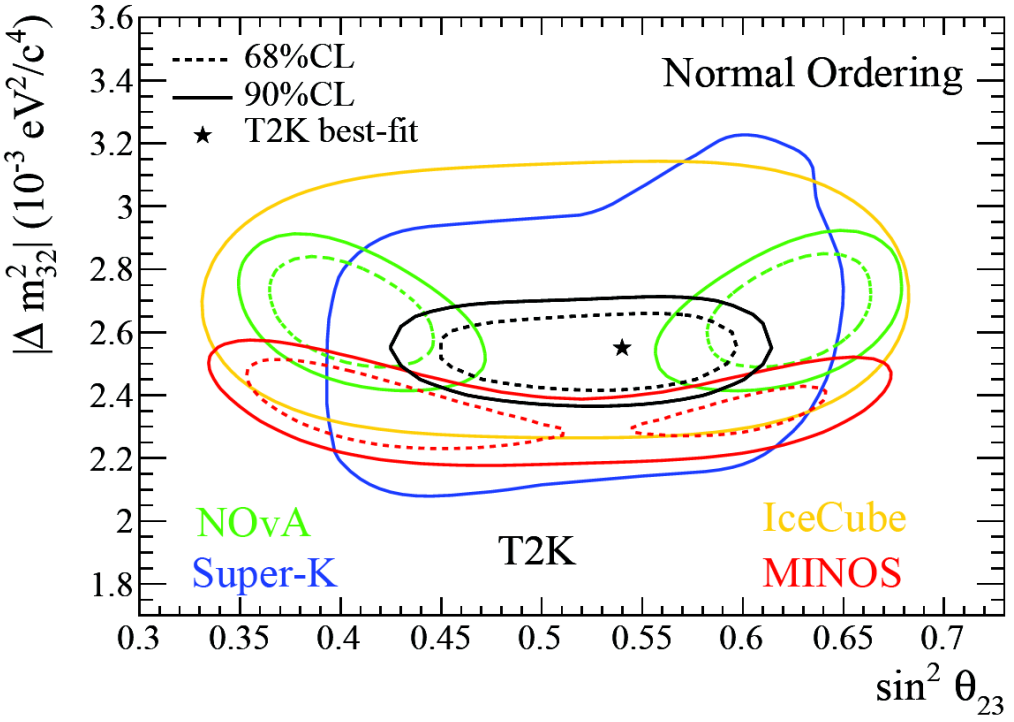
- Compatible and consistent results with other experiments
- Consistent results for ν and anti-ν data

On going studies in to the effect of systematic uncertainties from neutrino interaction models

Best fit point for normal ordering

$$\sin^2\theta_{23} = 0.55$$

$$\Delta m^2_{23} = (2.54 \pm 0.08) \times 10^{-3}\ \mathrm{eV}^2/\mathrm{c}^4$$



Results: θ_{13}

T2K-only $\sin^2\theta_{13}$ agrees well with reactor value

T2K only:

$$\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047} \text{ (NH)}$$

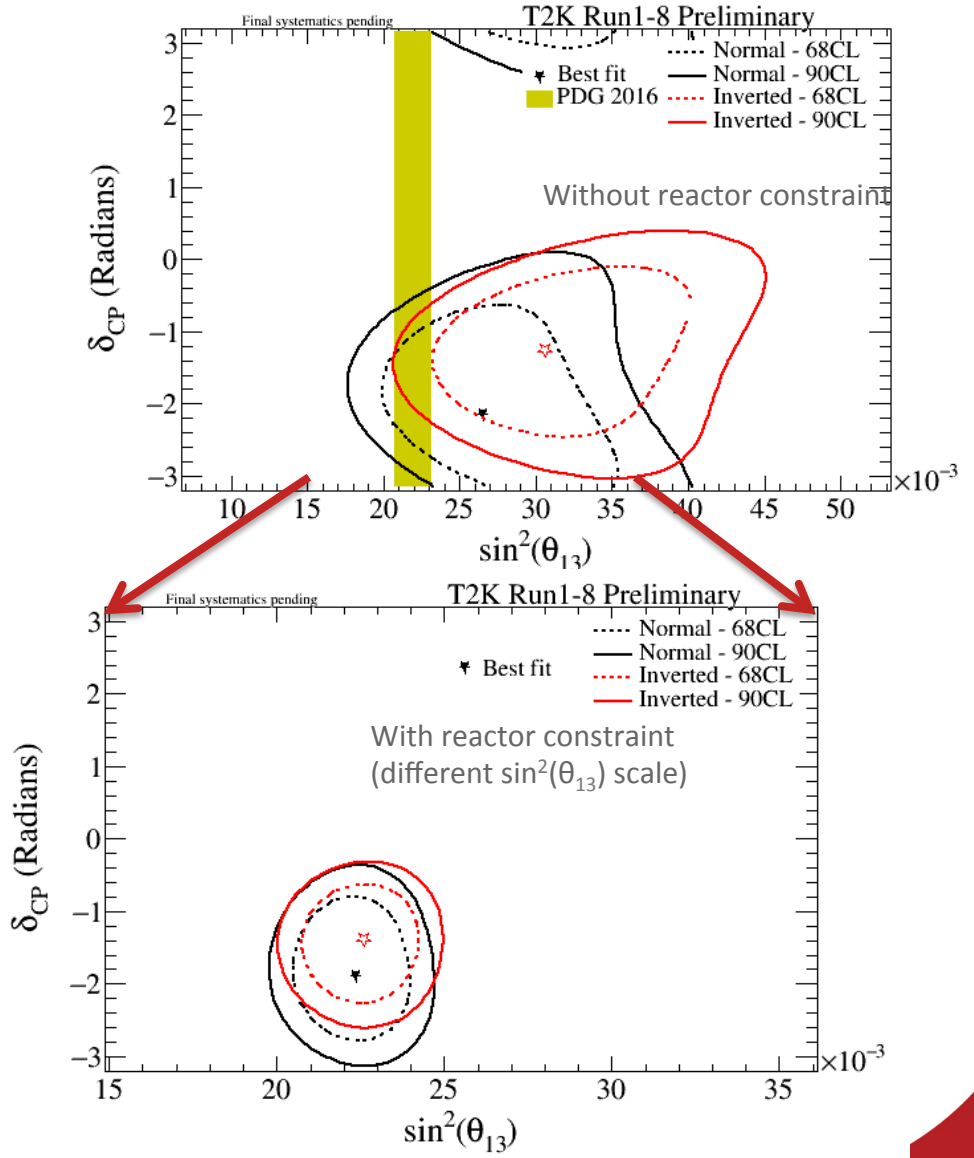
PDG2016:

$$\sin^2\theta_{13} = 0.0210 \pm 0.0011$$

T2K-only data excludes some δ_{CP} parameter space at 90% C.L.

Adding reactor measurement improves constraint

T2K data with and without reactor constraint show preference for value near -2 radians



Results: δ_{CP}

Confidence intervals for the results with reactor constraint are calculated using Feldman Cousins method

Best fit point

-1.83 radians in NH

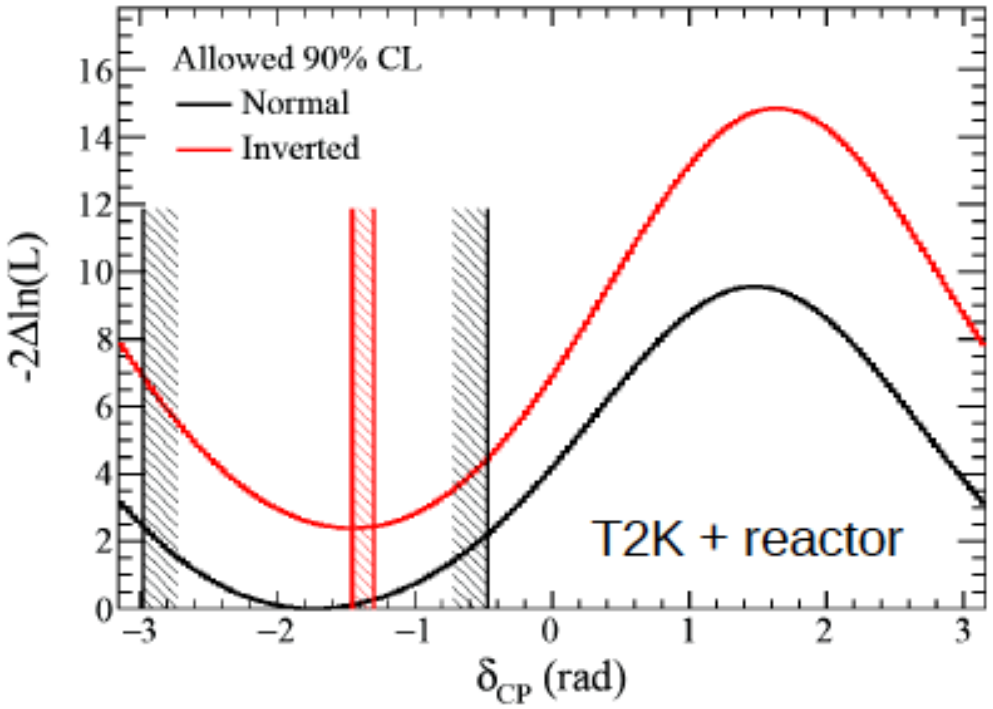
1σ confidence interval

NH [-2.49, 1.23] radians

2σ confidence interval

NH [-2.98, -0.60] radians

IH [-1.54, -1.19] radians



CP conserving values (0,π) fall outside of 2σ CL intervals

Octant and hierarchy preferences

Bayesian analysis can be used to infer preference for θ_{23} octant and mass ordering

Assume equal probability for both octant and mass ordering hypotheses

T2K prefers normal mass ordering and upper octant of θ_{23}

No conclusive statement yet

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
Normal ordering	0.193	0.674	0.868
Inverse ordering	0.026	0.106	0.132
Sum	0.219	0.781	

T2K-II

Extended T2K operation proposed to collect 20.0 x 10^{21}POT

- T2K approved for 7.8 x 10^{21} POT
- Proposal to extend operations to 2026
- Expect 20.0 x 10^{21} POT to 2026

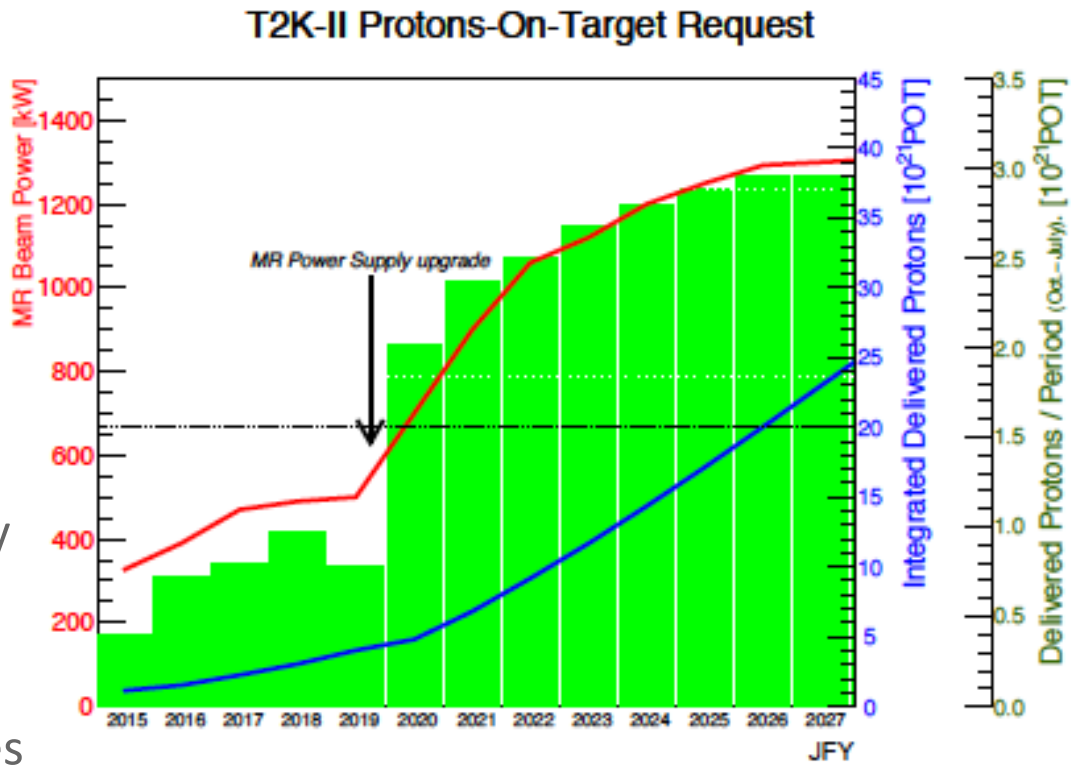
Analysis and operational improvements

Anticipate 50% increase in sensitivity

Already achieved 30% with extra samples at SK

Upgrade of Main Ring power supplies

Projected beam power of 1.3 MW



Other beam/detector upgrades

Lancaster University

Neutrino horns will run at 320 kA from next year

- Reduction in wrong sign contamination in anti-neutrino beam

Super-Kamiokande refurbishment

- Planned for summer 2018
- Preparation for addition of gadolinium (Gd) in 2019/2020
- Gd allows neutron tagging

ND280 upgrade

- Improve high-angle reconstruction
- Improved cross-section measurements

T2K-II Projected sensitivities

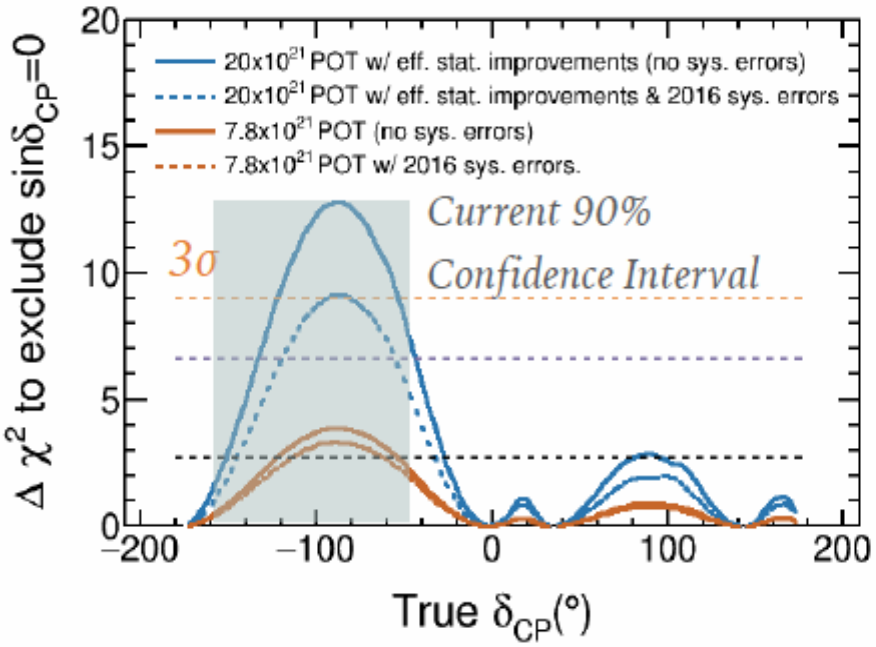
If δ_{CP} is near current best fit point

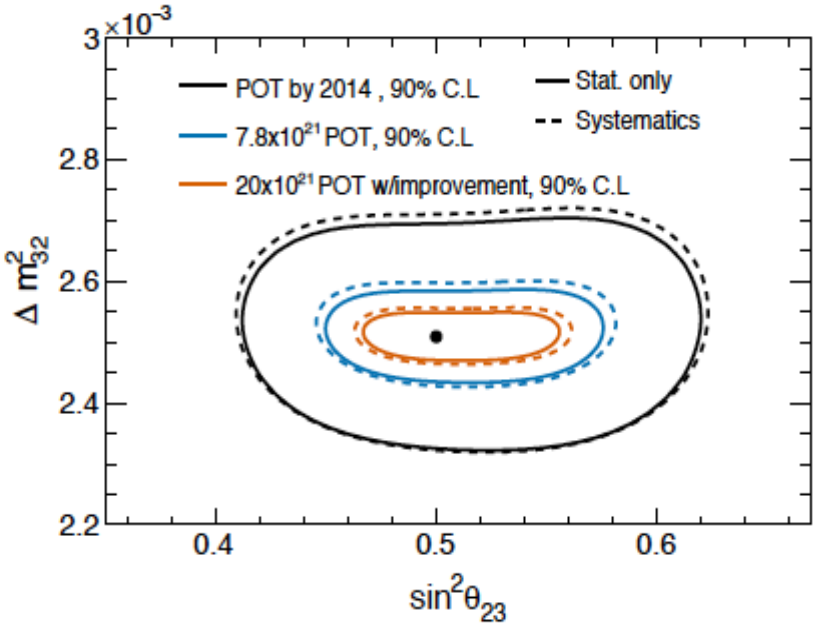
- Potential for 3σ evidence of CP violation in T2K-II

Systematic errors have a large effect on the experiment's sensitivity

- Dashed versus solid lines
- Expect systematic errors to improve

Significant reduction in atmospheric parameter space.





Summary

Updated oscillation analyses included

- Revised/improved neutrino interaction models
- New reconstruction and selection for Super-K data
- Effective increase in statistics of ~30%

Updates oscillation parameters

- δ_{CP} conserving values excluded at 2σ in both confidence and credible intervals
- Expect systematic errors to improve

Extended running of T2K proposed

- T2K-II operation to 2026 to collect 20.0 x 10^{21} POT
- Expect sensitivity to exclude δ_{CP} conserving values at 3σ

Exciting programme of neutrino oscillation physics still to come!

Back up slides

Previous ν_e selection at Super-K

Lancaster University

Fully contained event

Vertex within the fiducial volume

Single ring

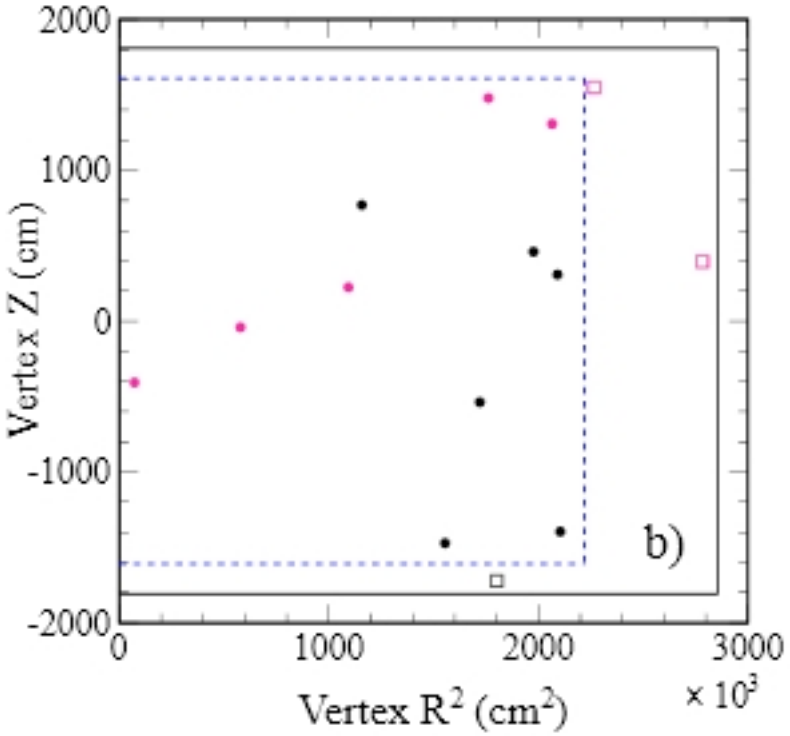
e-like only

$E_{visible} > 100$ MeV

No decay electrons

$m_{\pi} < 105$ MeV

Reconstructed ν energy < 1250 MeV



The 5 samples at Super-K

Neutrino mode

CCQE 1 μ-like ring, ≤ 1decay e

CCQE 1 e-like ring, 0 decay e

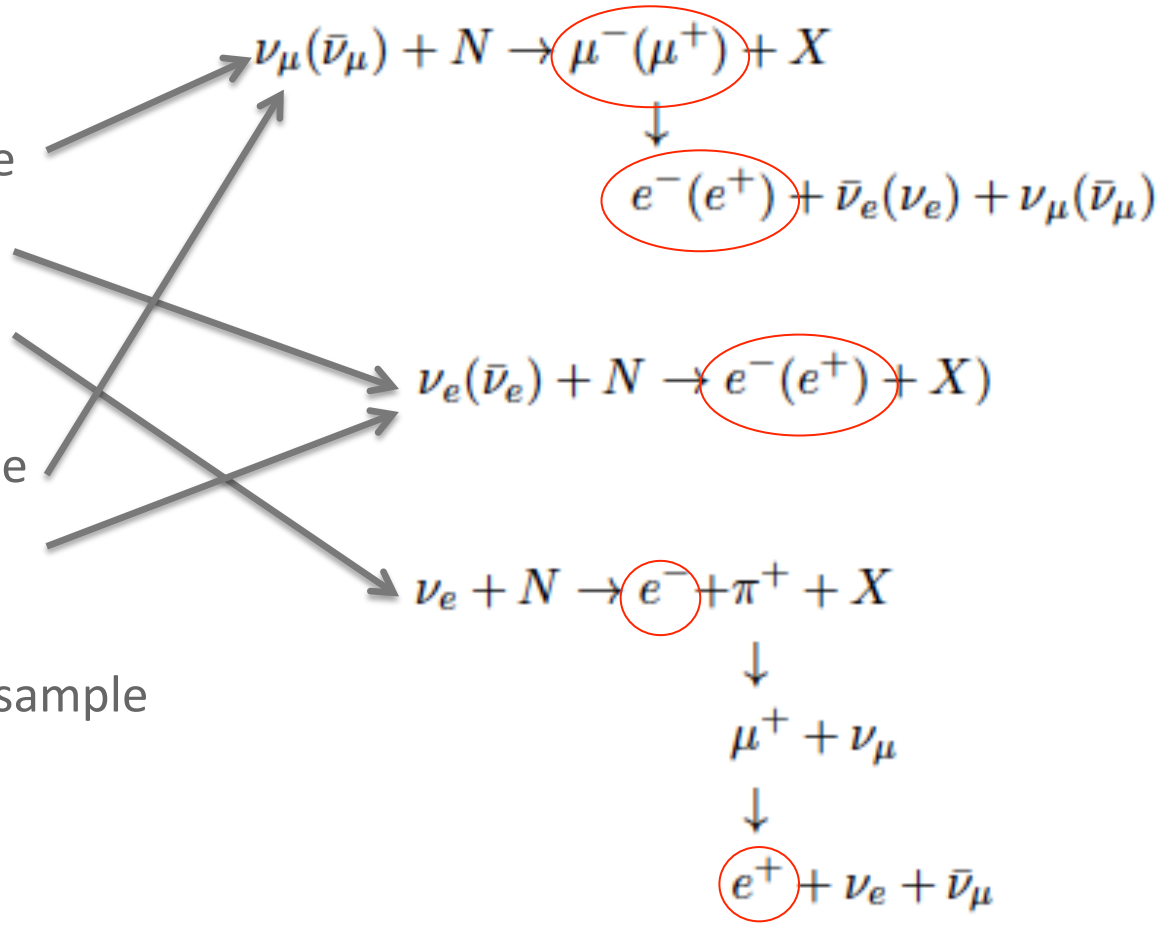
CC1π 1 e-like ring, 1 decay e

Antineutrino mode

CCQE 1 μ-like ring, ≤ 1 decay e

CCQE 1 e-like ring, 0 decay e

No antineutrino mode CC1π sample due to π^- absorption



= detected particle

The T2K collaboration

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U of Science
Yokohama National U.

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
IFIRSE
IOP, VAST

~500 members, 64 Institutes, 12 countries