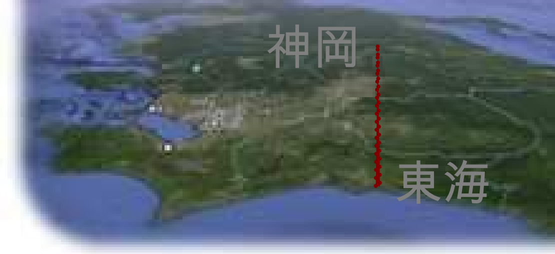
T2K: A long-baseline neutrino oscillation experiment

-Phill Litchfield,
for the T2K collaboration

2010/8/6

Outline



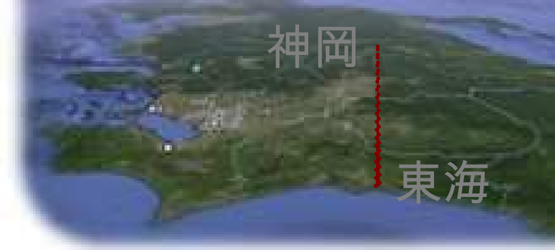
- Neutrino oscillation physics with T2K

Experimental challenges and how T2K approaches them:

- Getting enough data
- Making a suitable beam
- Flux prediction
- Cross sections
- Detector technology

- Sensitivities for planned run
- Will also show performance data from Near Detectors

Neutrino oscillation physics



(Weak) flavour basis ≠ Mass/propagation basis:

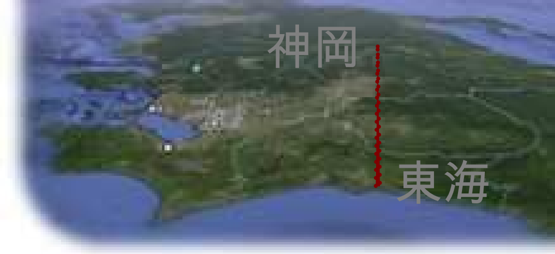
$$\left|\nu_\alpha\right\rangle = \sum_i U_{\alpha i}\left|\nu_i\right\rangle; \qquad U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\omega_1} & 0 \\ 0 & 0 & e^{-i\omega 2} \end{pmatrix}}_{\text{Majorana phases}}$$

- Phase of each propagation state advances at different rate.
- Leads to transitions between flavour states when detected at a distance from production point.

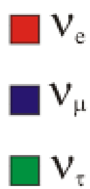
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} \Im\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

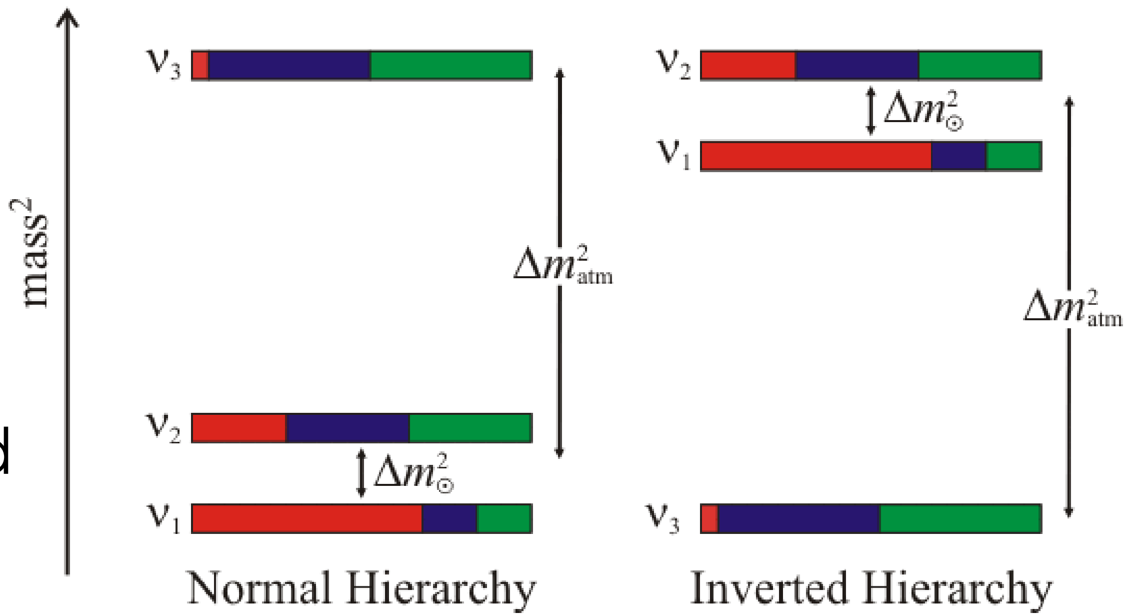
[Oscillations conserve lepton nº, so Majorana phases unobservable]

Neutrino oscillation physics



(Weak) flavour basis ≠ Mass/propagation basis:



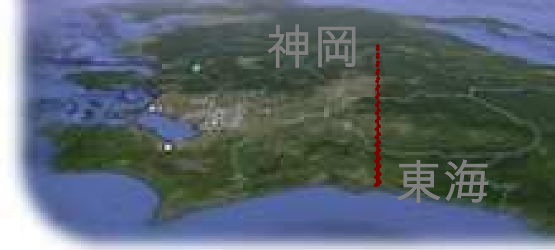


Only oscillations driven by the larger atmospheric Δm^2 have developed over T2K baseline.

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

Oscillations visible when $\Delta m^2 L/E \sim O(1)$: need E low and L large!

Oscillation parameters



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

T2K uses a beam of initially ν_μ and can identify events as originating from ν_μ or ν_e interactions. It can therefore probe the magnitude of elements $U_{\mu 3}$ (ν_μ disappearance) and U_{e3} (ν_e appearance)

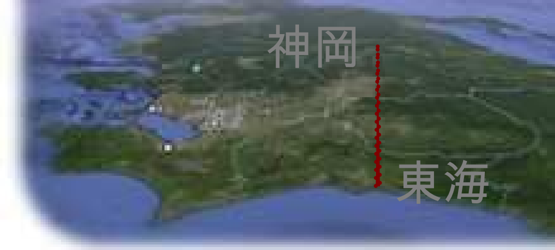
A common parameterisation is:

$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Which gives $U_{\mu 3} = s_{23}c_{13} \approx s_{23}$, and $U_{e3} = s_{13}e^{-i\delta}$

ν_μ disappearance channel

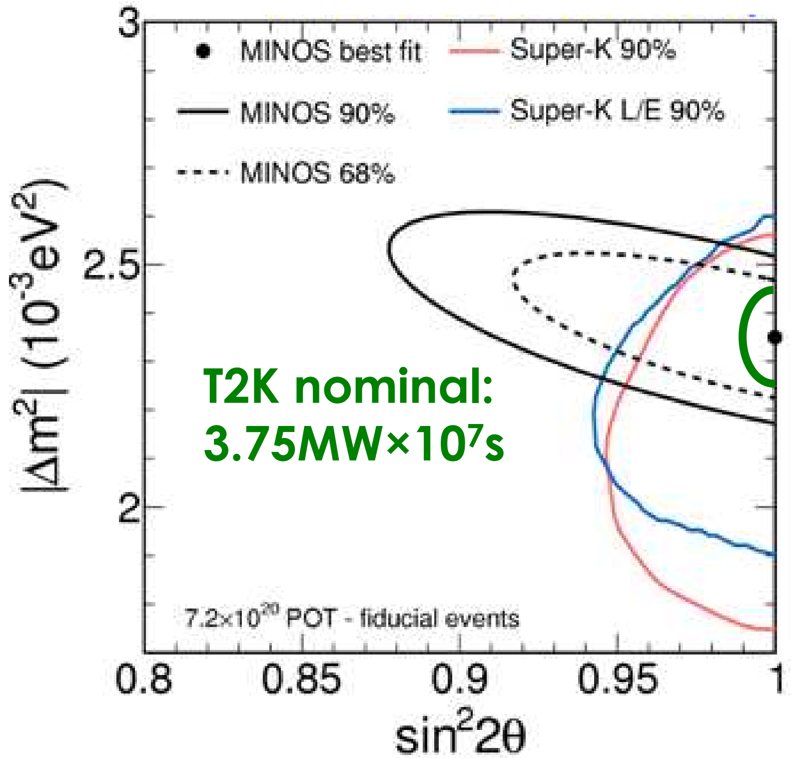


$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right)$$

The ν_μ disappearance channel is also sensitive to the mass^2 splitting.

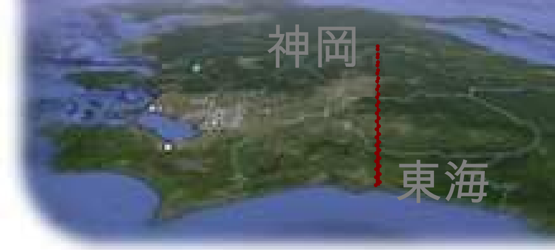
Has been measured by previous experiments, but T2K should achieve significantly better precision over its nominal run:

MINOS & Super-K preliminary @ Nu'10



- 0.75MW primary beam, 5 nominal years (10^7s/year)
- [~5×10^{21} POT, proton momentum 30 GeV/c]

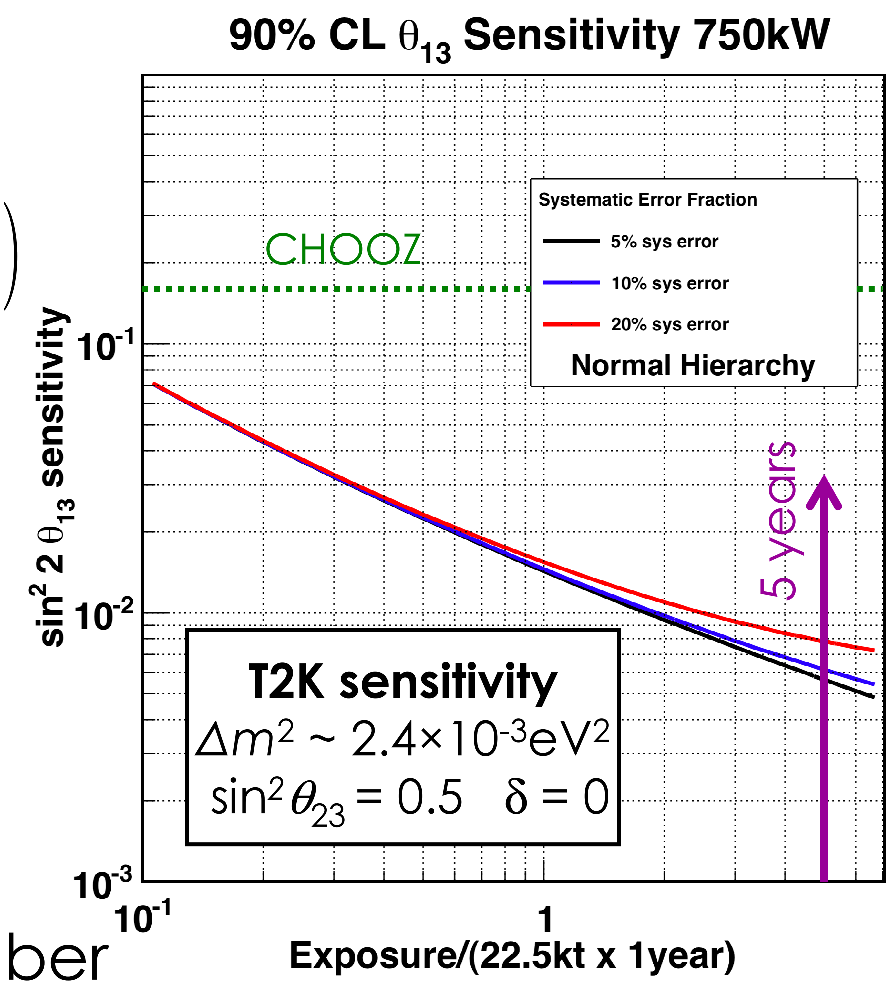
ν_e appearance channel



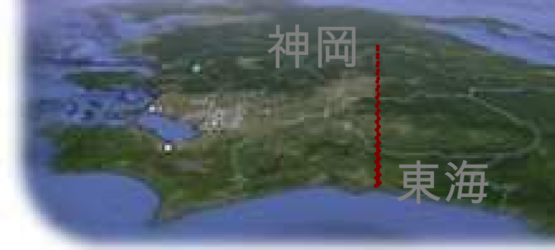
$$P_{\mu e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{atm} L}{4E}\right) + O\left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}} \sin 2\theta_{13}\right) \times \cos\left(\delta + \frac{\Delta m^2_{atm} L}{4E}\right) + O\left(\left[\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right]^2\right)$$

The main goal of T2K is to measure/'improve limit on the magnitude of' U_{e3}

- Nominal sensitivity $O(10^1)$ better than current limits.
- If U_{e3} is measurable the number of event observed also depends on CP-violating phase



The T2K collaboration



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Colorado S. U.
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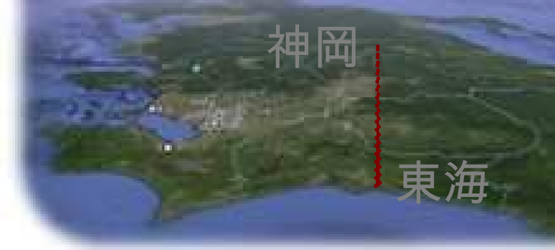
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

Host facilities: J-PARC, KAMIOKA OBSERVATORY

Total:
~500 members
61 institutes
12 countries

The T2K experiment

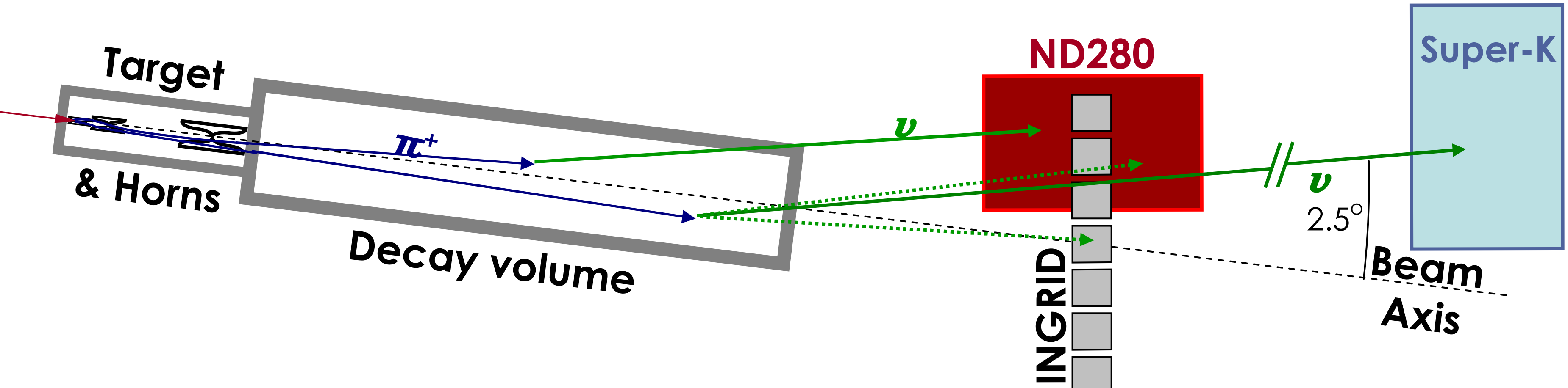


The Tokai to Kamioka experiment is a 'long baseline' experiment.

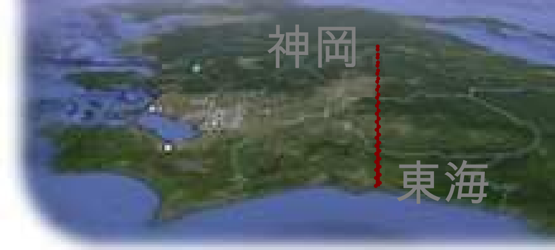
- Distance from target to far detector (Super-K) is 295km.

Neutrino flux falls as $1/L^2$, so a large (massive) far detector is desirable:

- Super-Kamiokande is BIG - 22.5 kilotonnes (fiducial) of water.

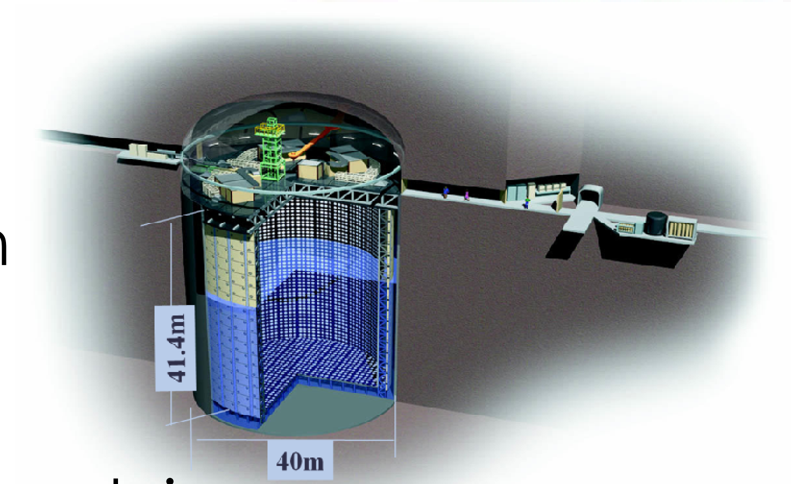


Super-Kamiokande IV



See talk by Hayato-san

- Water-Cherenkov detector
- Good muon/electron separation



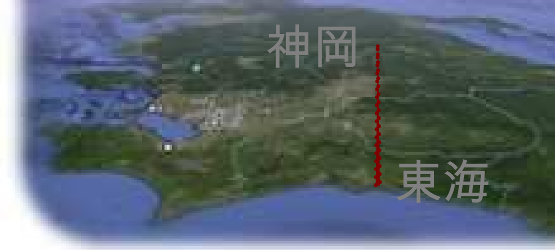
Signal events are charged-current quasi-elastic interactions on ^{16}O nuclei:

$$\nu_\ell + n \rightarrow \ell^- + p$$

Energy resolution from kinematic reconstruction (CCQE):

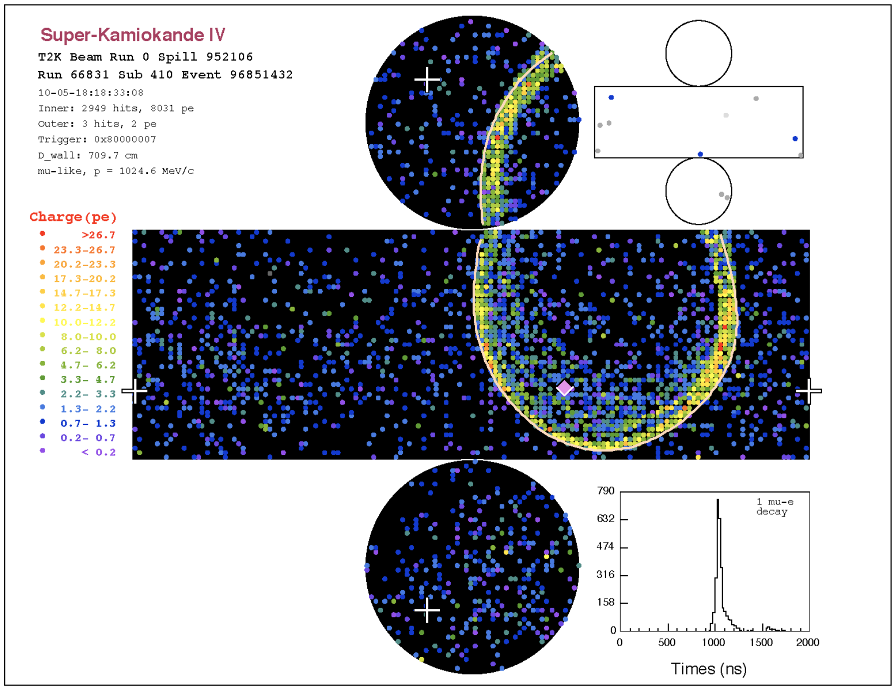
$$E_\nu = \frac{m_N E_\ell - m_\ell^2/2}{m_N - E_\ell + \mathbf{p}_\ell \cdot \mathbf{p}_\nu / E_\nu}$$

CCQE events dominant at E_ν~0.7GeV → Sets choice of E_ν

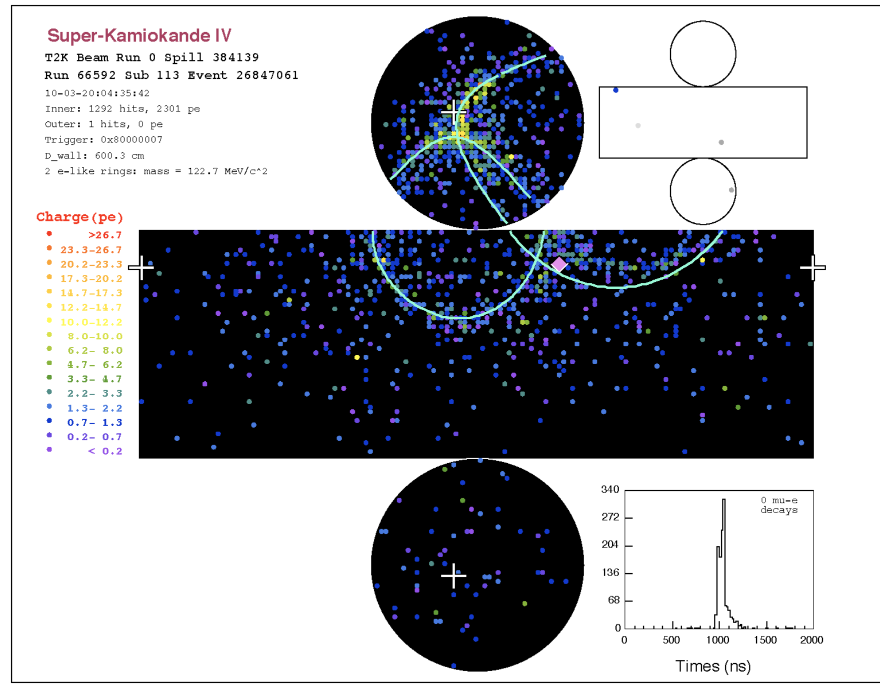


Event displays

Single ring event (muon-like)

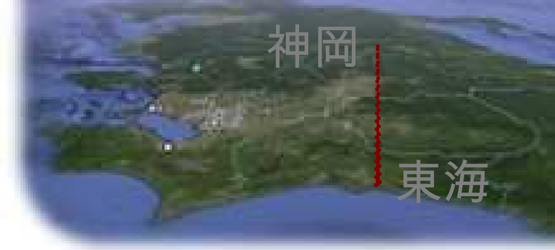


Two ring event



Pink diamond is drawn on the wall at intersection of line in the beam direction starting at the reconstructed vertex

The neutrino beam

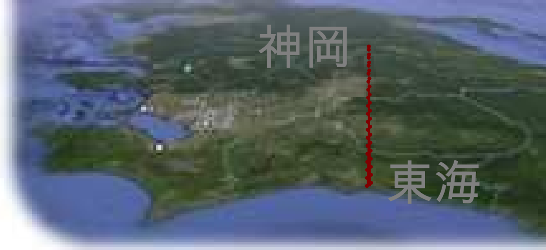


Number 1 consideration: we need **lots of neutrinos**!

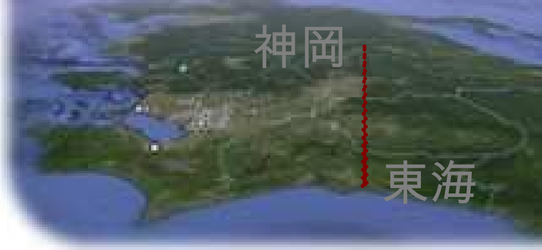
- Neutrino facility incorporated into new high-luminosity accelerator complex at J-PARC.
- Distance to Super-K is a good match for ideal energy regime (~1GeV).
- Conventional neutrino beam: Secondary pions* from proton beam focused by magnetic horns and allowed to decay into muons & muon-neutrinos*.
  - Design power 0.75MW
  - Currently ~55kW (~double in next run)
- Graphite target in T2K phase 1 (may be upgraded)
- Focussing by 3 magnetic horns

*Mostly. Contamination is ~ sub-percent

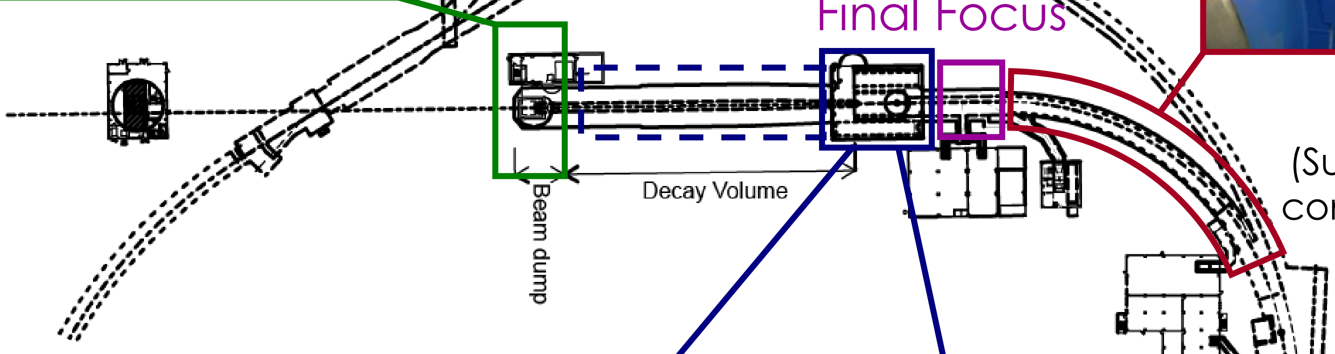
J-PARC facility (KEK/JAEA)



Neutrino beamline



Beam dump & muon monitors



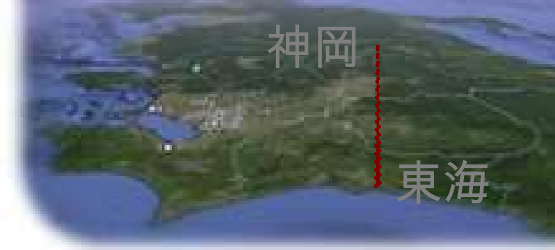
Final Focus

Neutrino arc (Super-conducting combined function magnets)

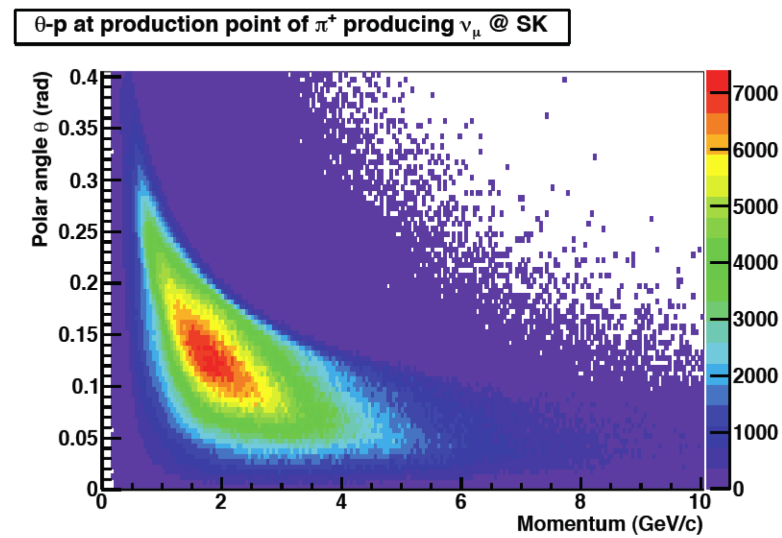
- 6(8) bunch fast extraction
- ϕ2.6 × 90 cm Helium-cooled graphite target
- Horns at 250 (320)kA

Target and horns(3), decay volume (110m)

Hadron production & NA61

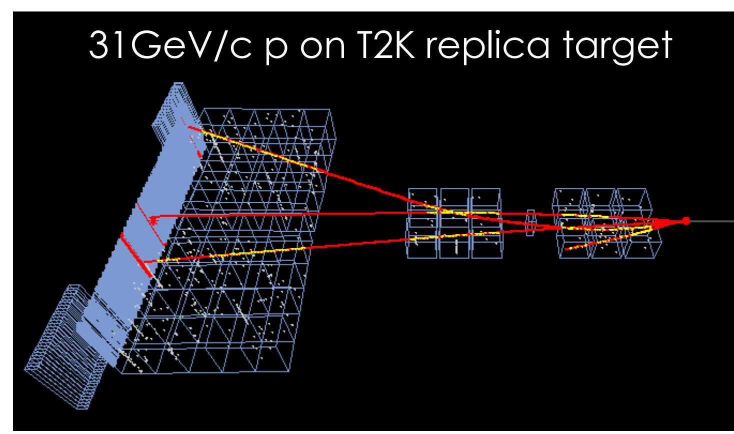


- Hadrons produced at a given momentum and angle
- Horns focus a subset of these down the decay volume.



So neutrino flux depends on:

- Secondary beam geometry
- Hadron distribution off target

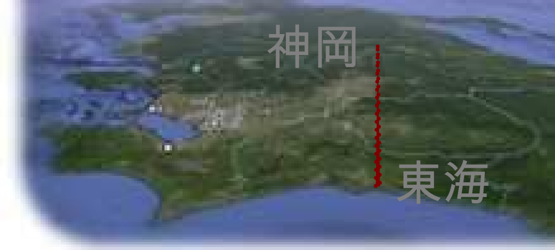


Modelling hadron production is *hard*: T2K will use data from **NA61 (SHINE)**

- Uses thin and T2K replica targets

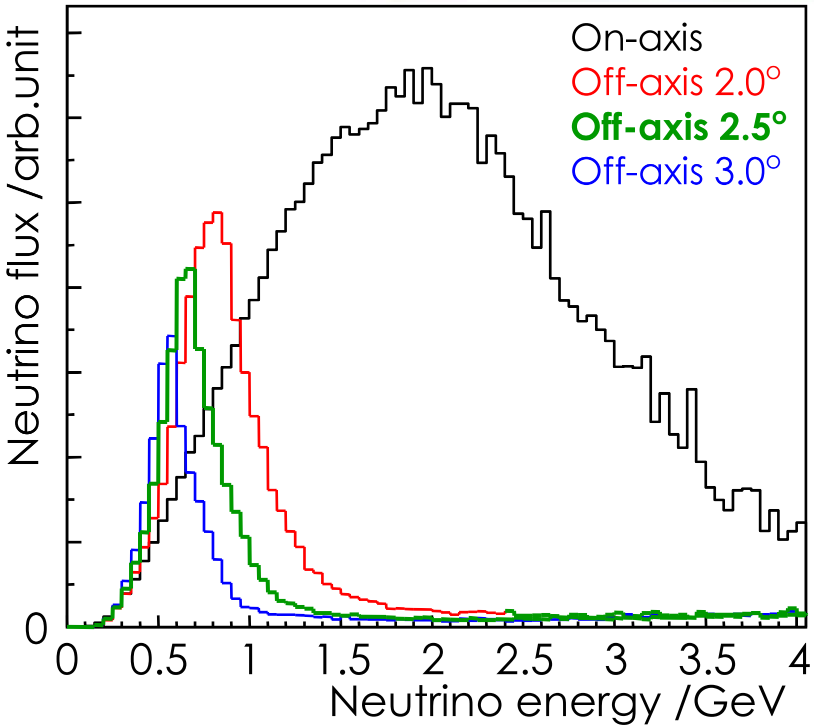
https://na61.web.cern.ch/na61/xc/index.html

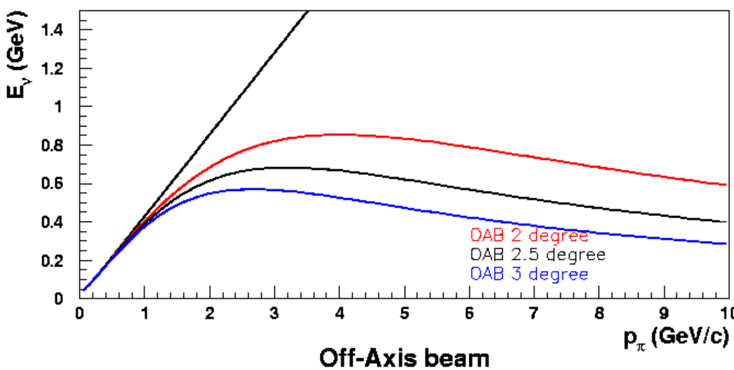
The 'off-axis trick'



Major background for ν_e channel is from higher energy events where some energy is unobserved.

On-axis there is always a large 'tail' ▶ of neutrinos up to high energy





▲ Off-axis, neutrino energy dependence on parent energy is not as strong.

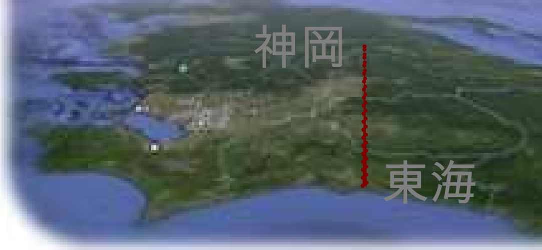
✓ **Nearly eliminates high-energy tail**

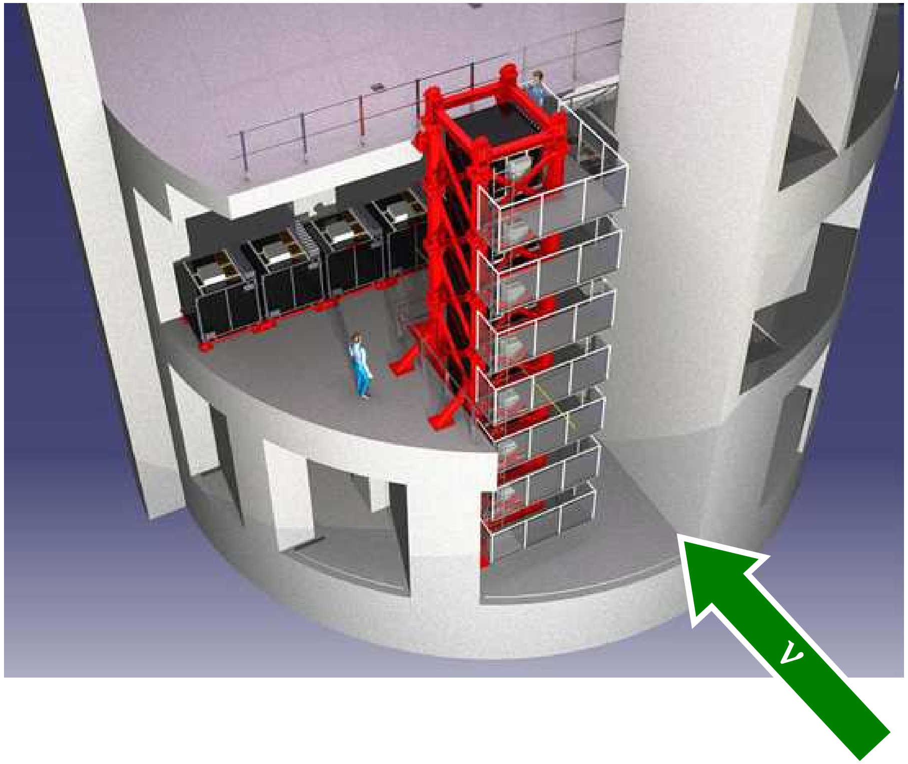
✓ Neutrino peak is narrower

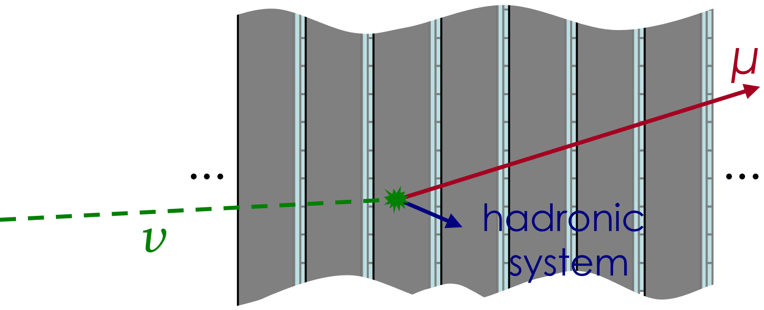
Off-axis beam is **ideal for ν_e appearance** where NC feed-down is a major B/G.

T2K is the 1st experiment to use an off-axis (2.5°) design.

The on-axis detector







Off-axis configuration means you need to know the beam-detector angle to high precision.

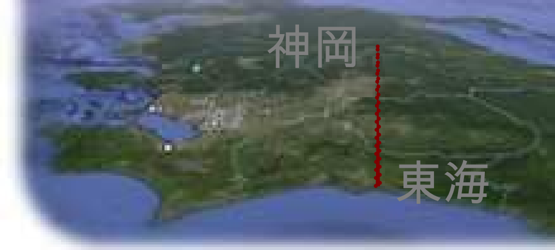
T2K goal is < 1 mrad (0.06 deg)

"On-axis" detector **INGRID** designed to measure beam profile with high statistics.

7 + 7 modules in cross shape, central modules are on-axis

Alternating Iron/ScintX/ScintY modules, 10cm thick iron planes to get plenty of ν_μ interactions

INGRID technology

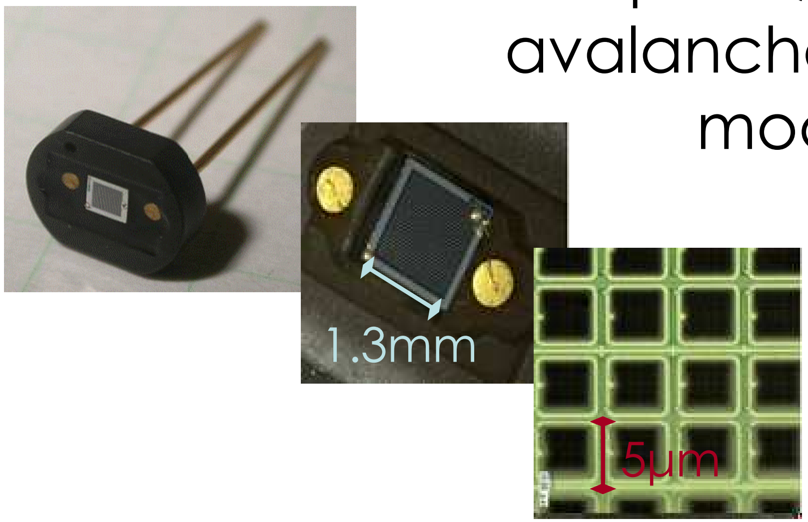


Active material of detector is plastic scintillator bars with WLS fibres in central channels to photosensors.

✓ Well proven & economical: Similar technology used by K2K, MINOS, MINERvA, SciBooNE…

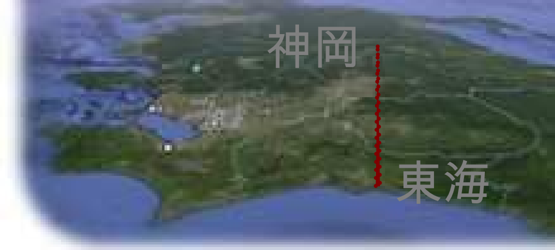
T2K uses innovative readout: **M**ulti-**P**ixel **P**hoton **C**ounters:

667 pixels, each acting as an avalanche photodiode in Gieger mode.



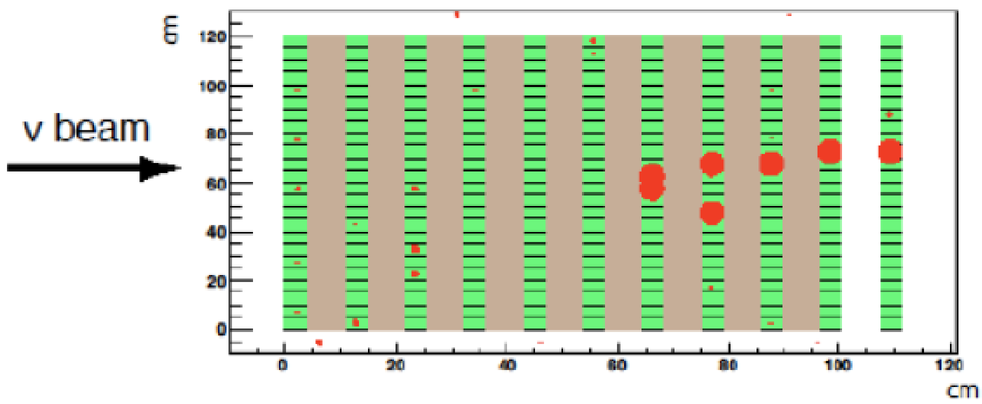
Pixels are read out by a single anode → Charge is proportional to number of photons observed

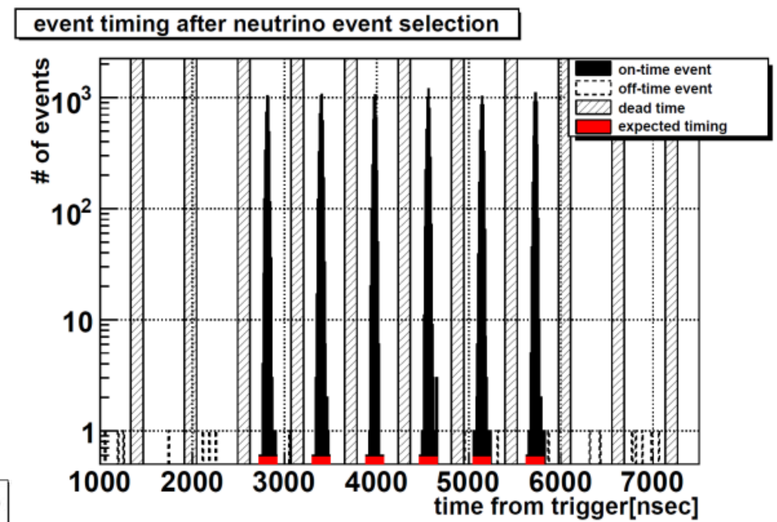
INGRID performance

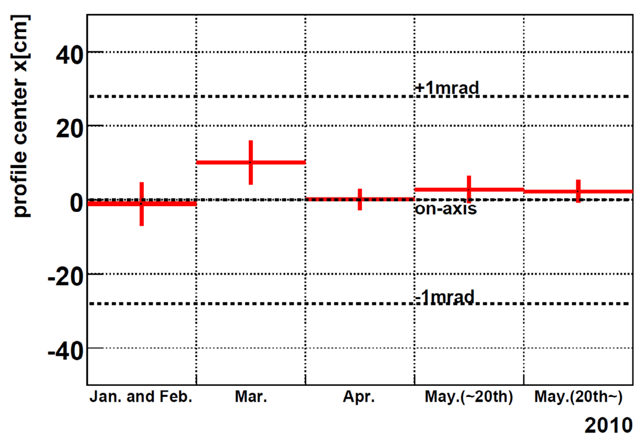


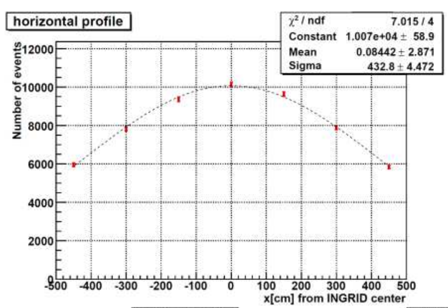
First event

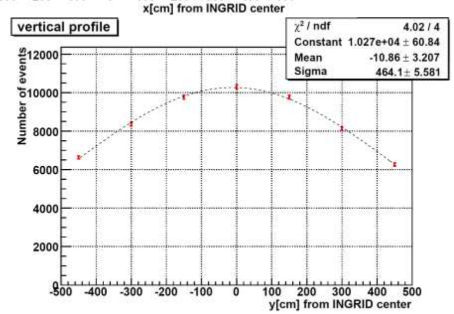
Nov. 22, 2009
20:25:48 JST

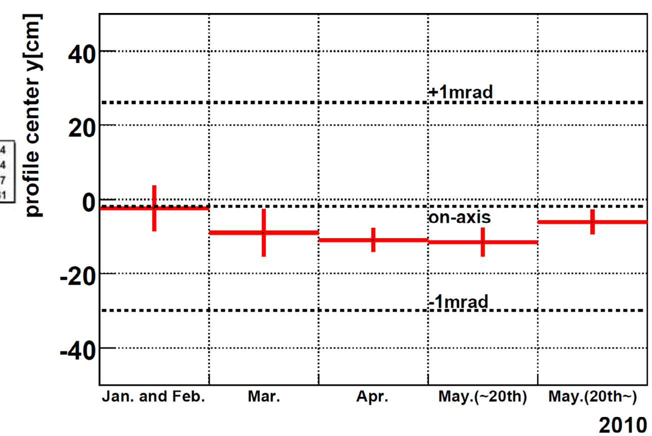




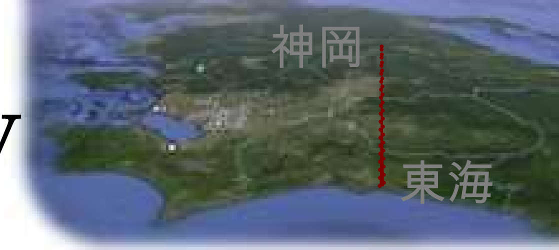




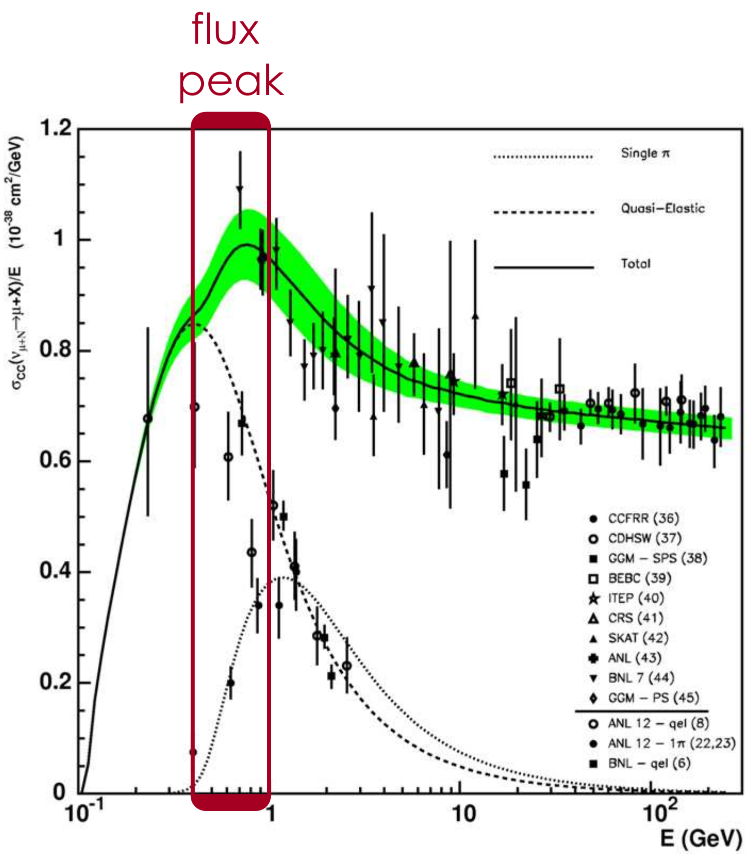




Cross-sections and topology



As well as getting the flux right it is important to get understand the cross sections for neutrinos on oxygen.



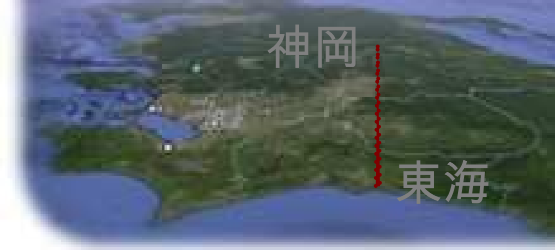
T2K needs to understand exclusive channels:

- CC QE cross-section → events expected per neutrino

Also with regard to backgrounds:

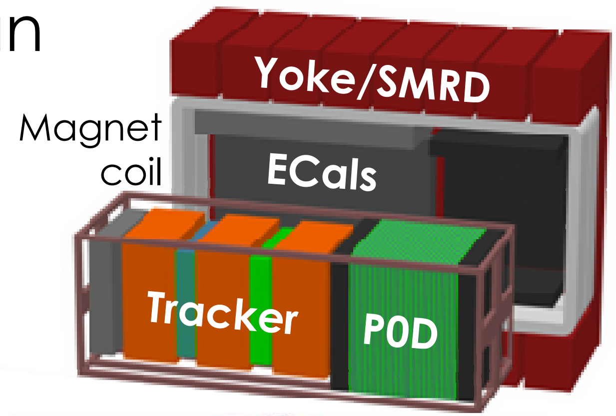
- Non-QE processes where the additional final state particles are unobserved
  ↳ systematically low reconstructed energy.
- NC π^0 events (→ 2γ)can mimic ν_e event if only one ring is resolved.
  ↳ major background for ν_e analysis

The off-axis detectors



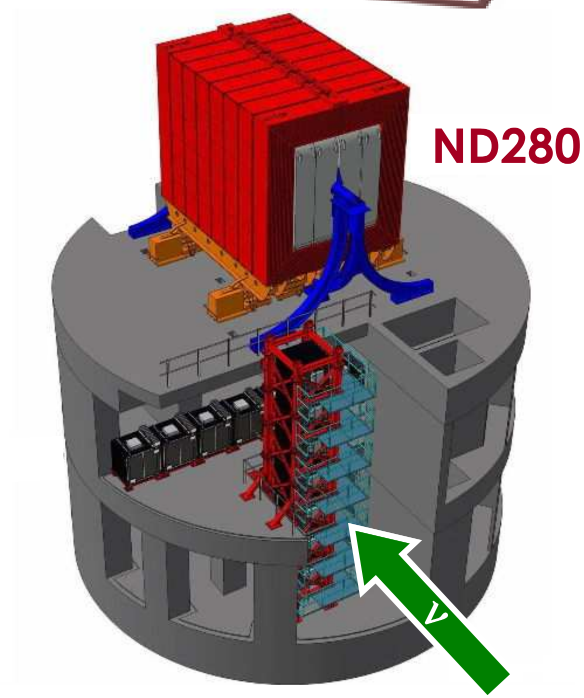
Cross-sections and event topology can be studied with the off-axis **ND280** detector.

- Detector is centred on the same direction as SK so sees a similar flux.

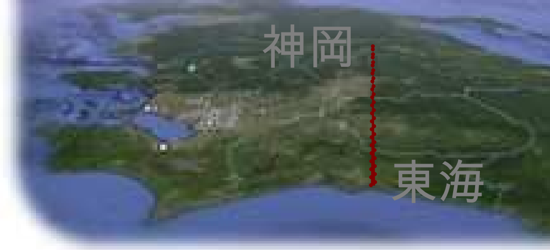


ND280 has two main target regions:

- Pi-0 Detector (**P0D**): optimised to study distribution of (NC) π^0 events
- **Tracker**: Intended for detailed study of charged-particle final states: Better understanding of exclusive processes in the ~1GeV region



ND280 technology



The tracker section consists of two sub-systems:

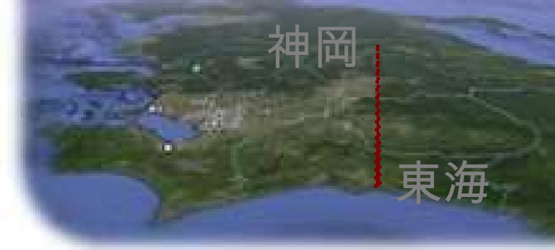
2 **F**ine-**G**rained **D**etectors (target mass) between
3 **T**ime-**P**rojection **C**hambers (particle ID, momentum)

Surrounding the tracker and P0D are **E**M-**Cal**orimeters, and the old UA1/NOMAD magnet (for momentum measurements: B ~ 0.2T). Interleaved in the yoke is the **S**ide **M**uon **R**ange **D**etector which helps identify muons.

Everything except the TPC is based on similar technology (plastic scintillator/WLS fibre/MPPC readout) to INGRID

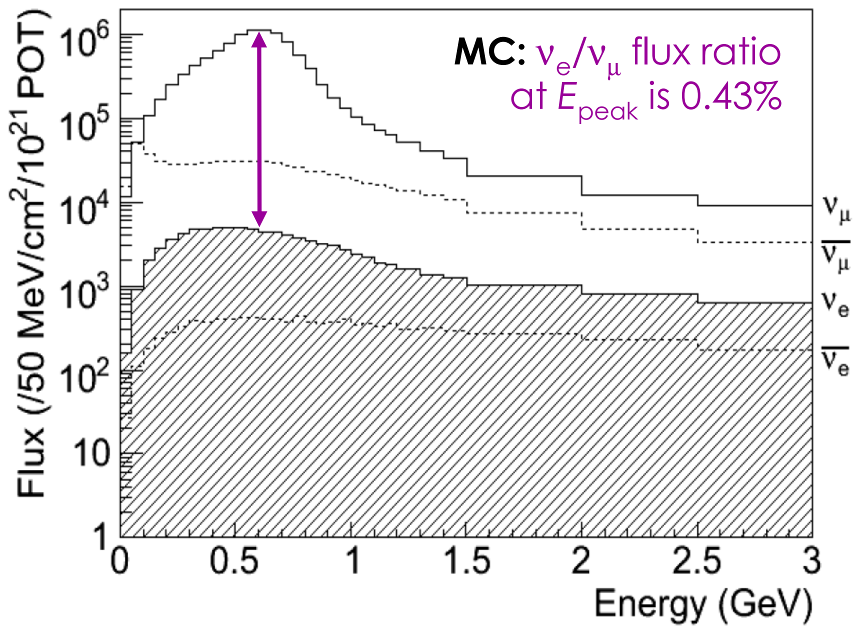
- Small size of MPPCs is great benefit, both for space considerations and because of B-field immunity.

Beam ν_e and the tracker



Another major background is the intrinsic ν_e in the beam.

- ND280 needs to measure this.

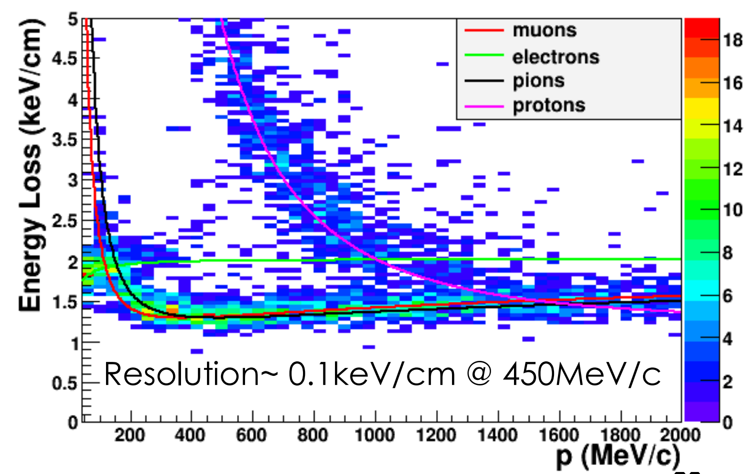


Tracker section is very good for ν_e event identification:

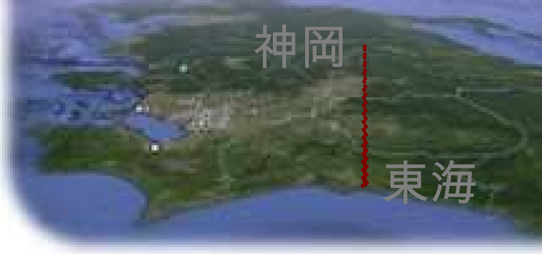
- Electrons leave distinctive tracks in the TPCs.

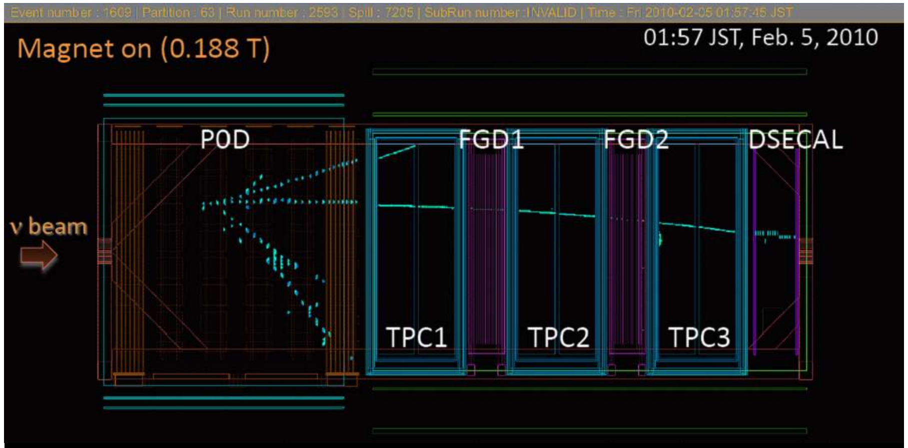
◀TPCs use microMEGAS design (First large scale use of this technology)

Excellent PID via dE/dx ▶ measurements → unusual for a neutrino detector!

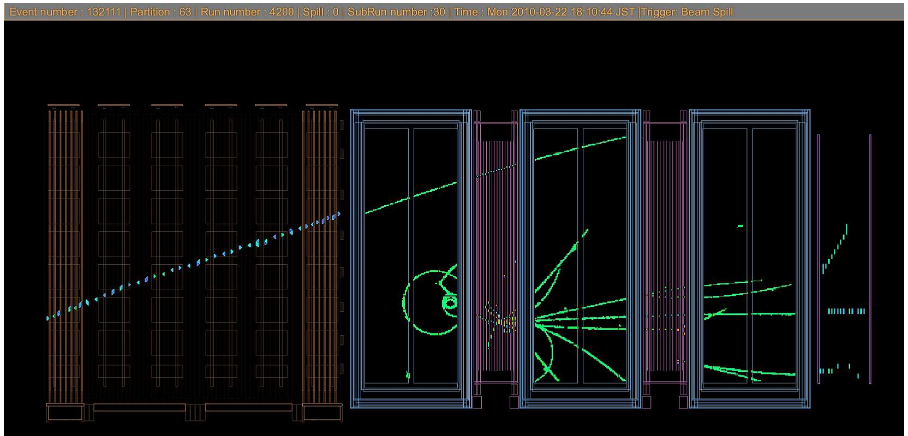


Example ND280 events

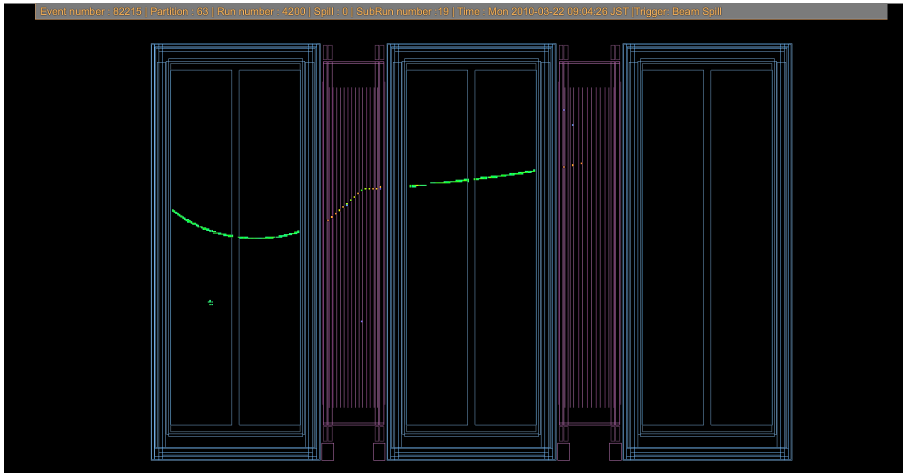




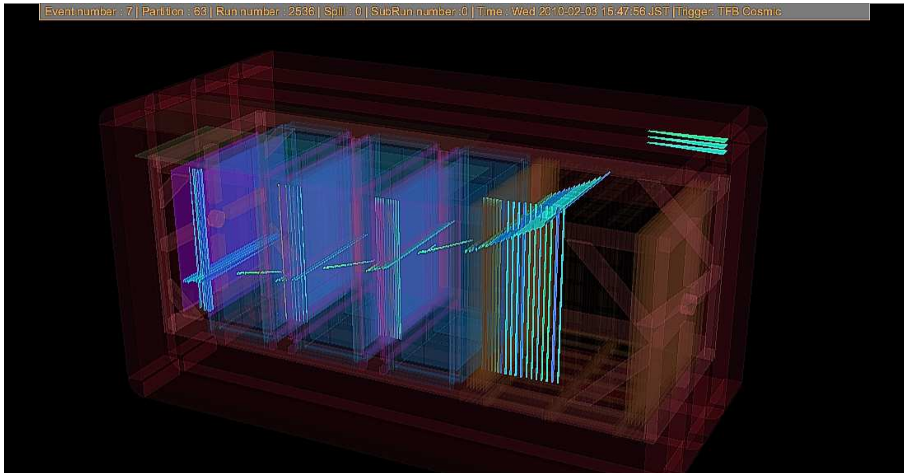
Interaction in P0D: View from (north) side



Sand Muon & FGD interaction

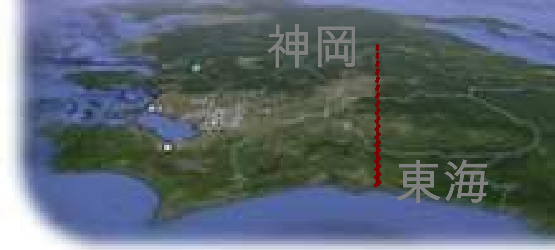


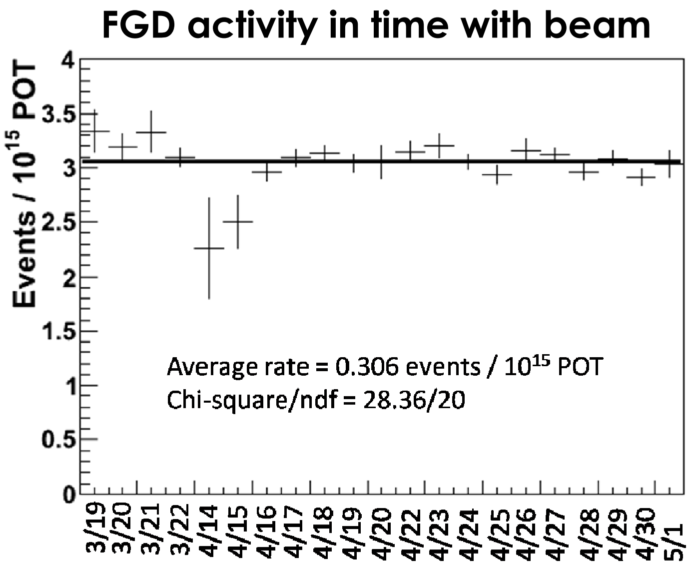
FGD interaction with backward track

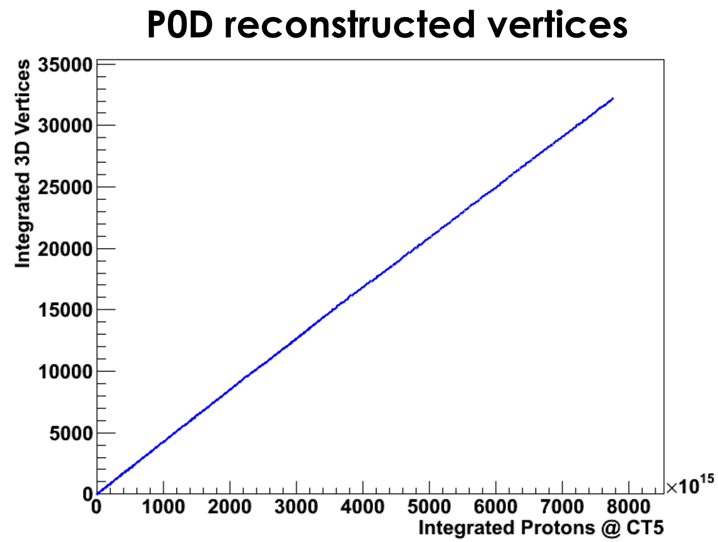


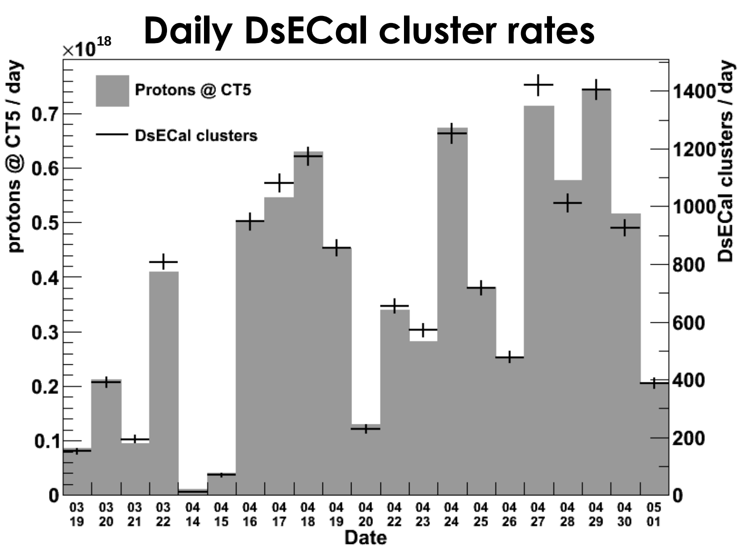
Cosmic ray muon

ND280 performance





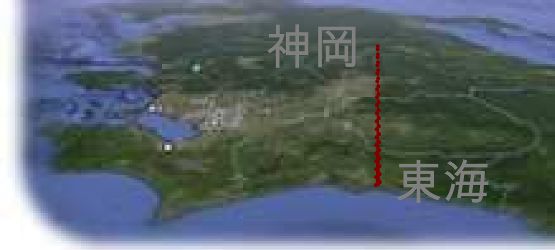


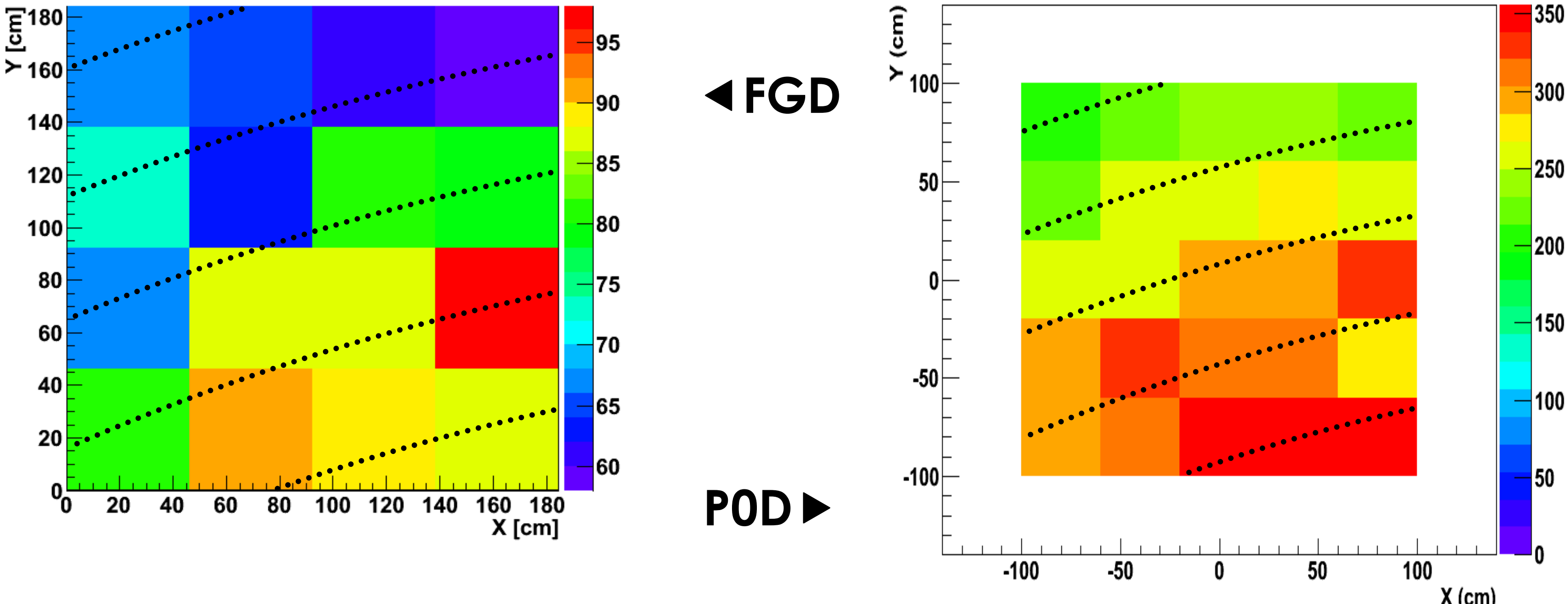


Event rates as function of beam exposure.

- ✓ At all levels of processing (activity, clustering, reconstruction) we see proportionality to the number of protons delivered.

ND280 is off-axis!



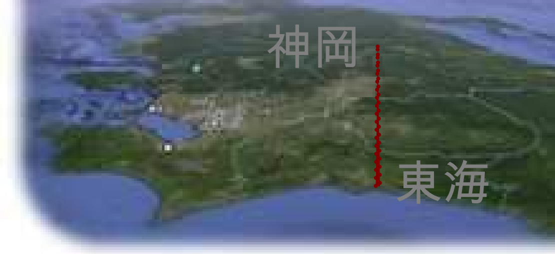


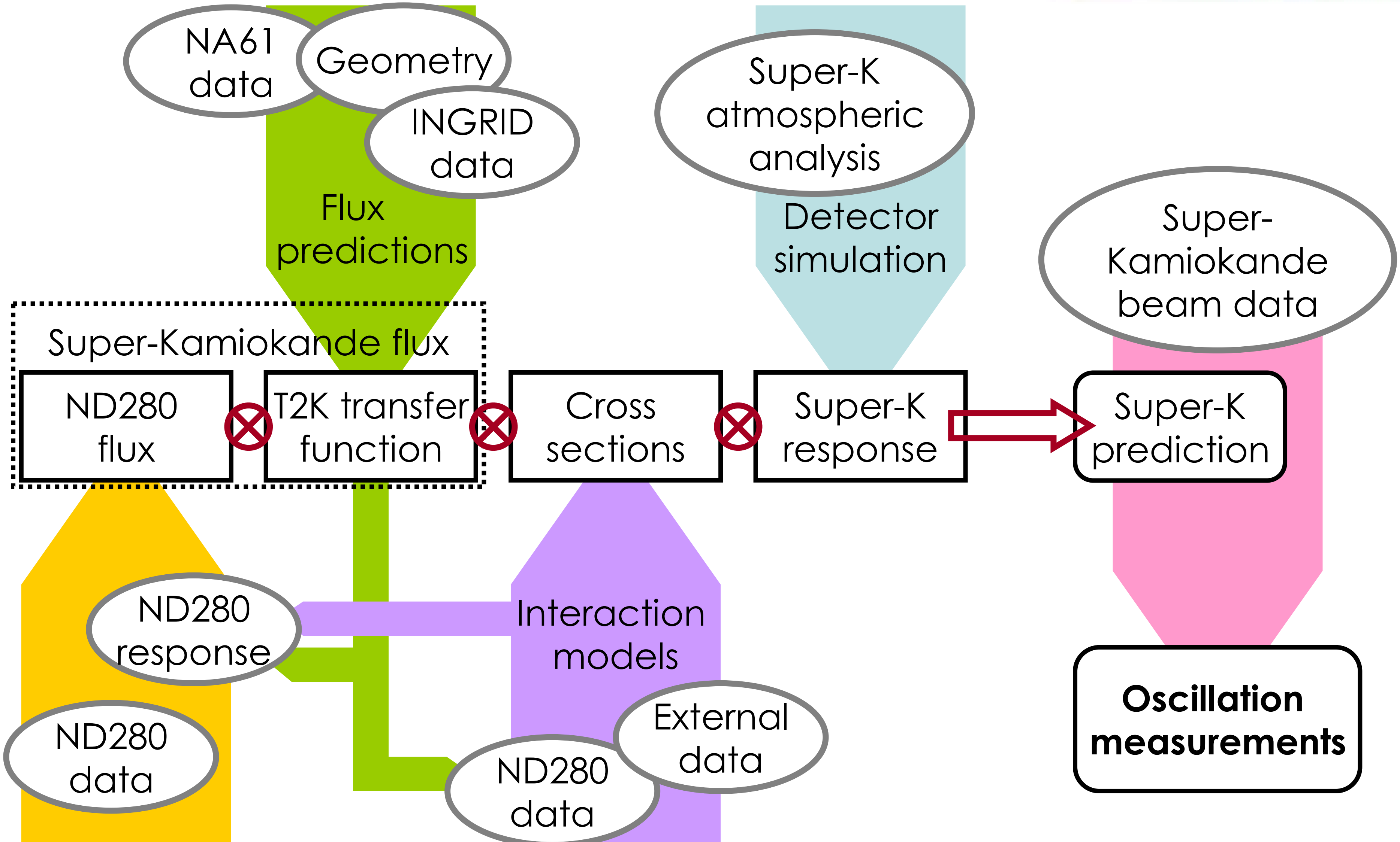
Plots showing contained vertices reconstructed in the 2 'Fiducial' detectors.

Lines show (approximate) iso-contours of off-axis angle.

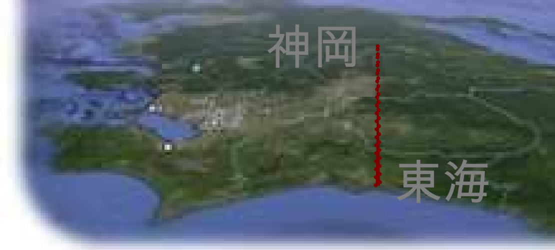
- Outer corner is roughly 20% further off-axis than inner corner.

T2K analysis strategy





Summary



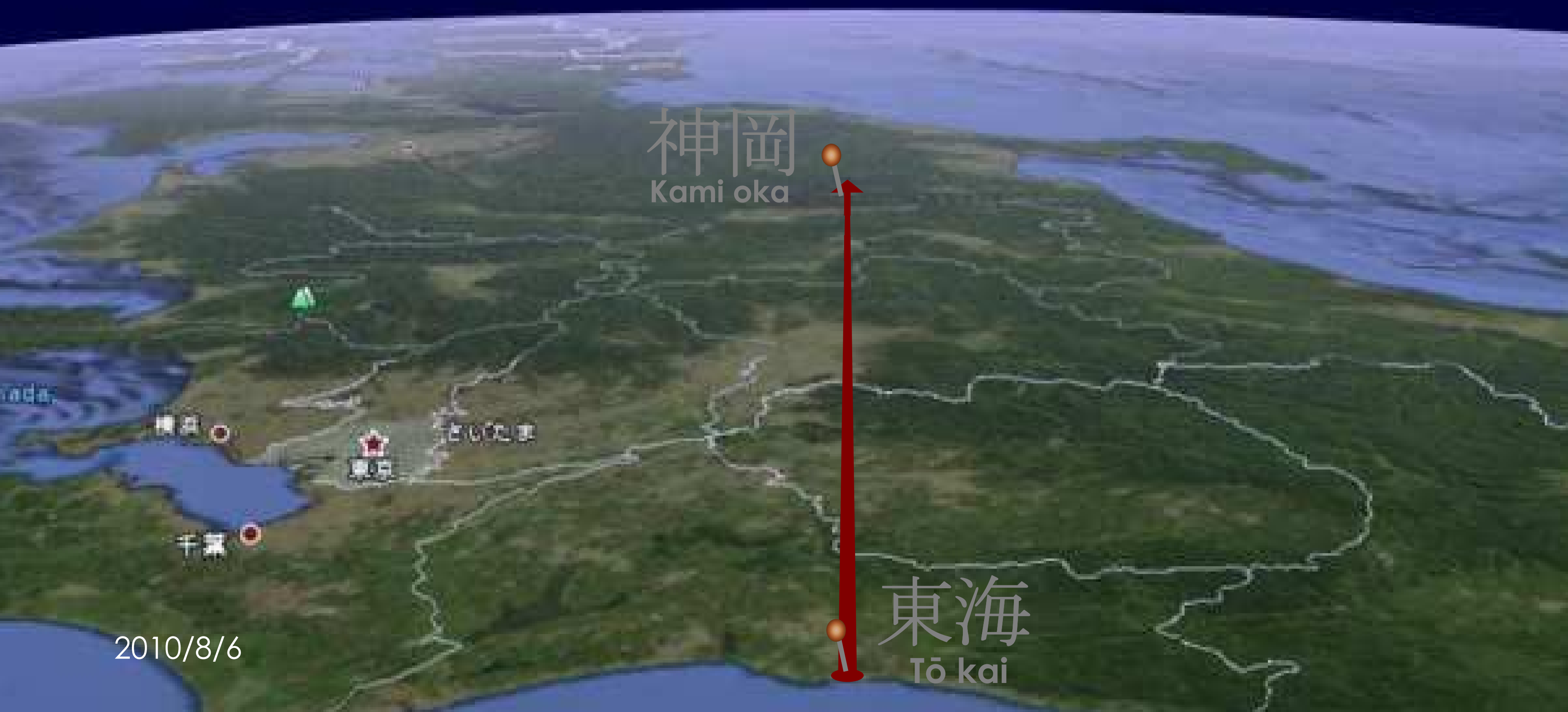
T2K is the most recent in a succession of LBL neutrino oscillation experiments.

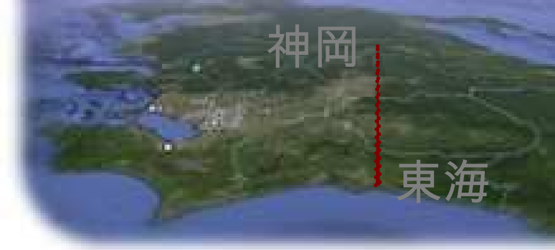
- These are complicated experiments, with many separate parts that must act in concert.
- Shown how each part (beam, near detectors, far detector) has a role, and must be designed to function together.

Timeline:

- 1999 – Initial suggestion (Nishikawa/Totsuka)
- 2001 – Proposal (hep-ex/0106019)
- 2004 – Official approval / T2K collaboration formed
- 2010 – Data taking begins!

Extra slides

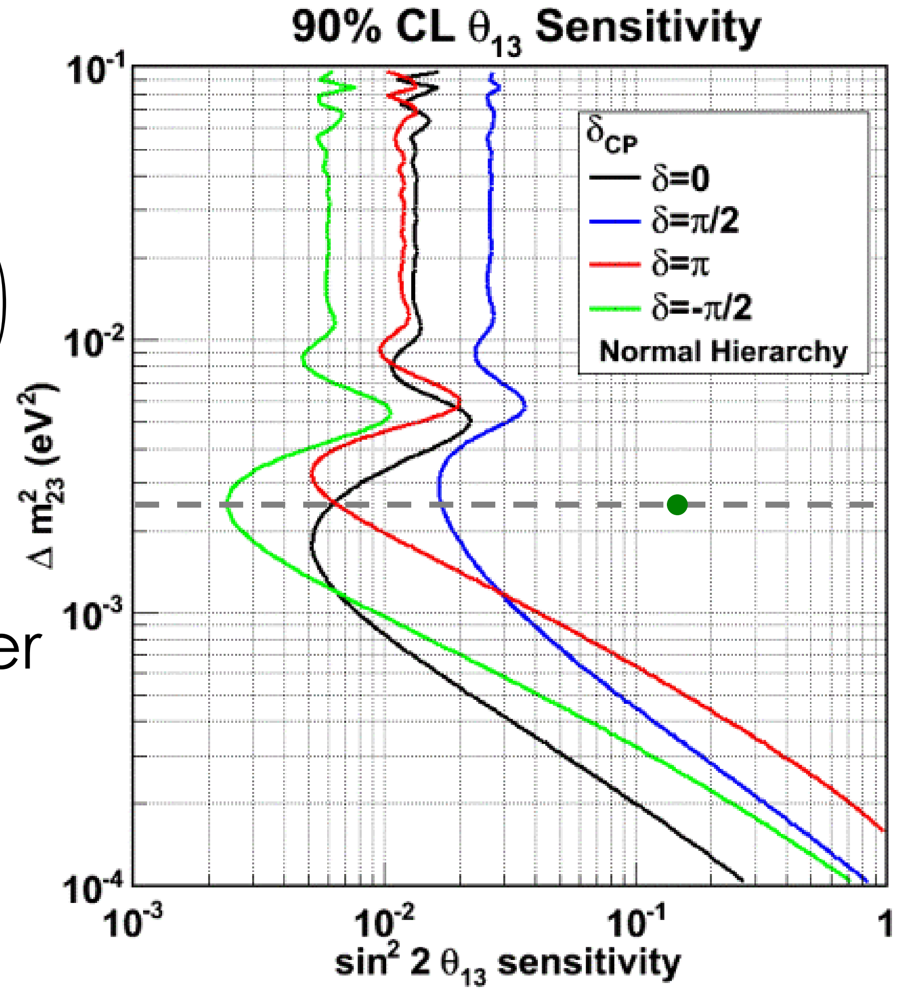




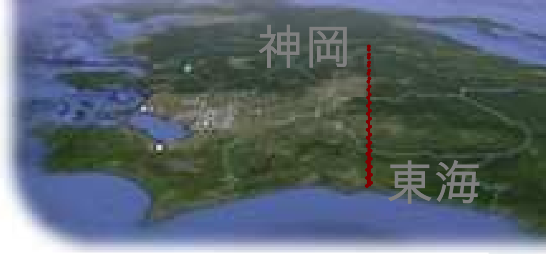
ν_e appearance channel

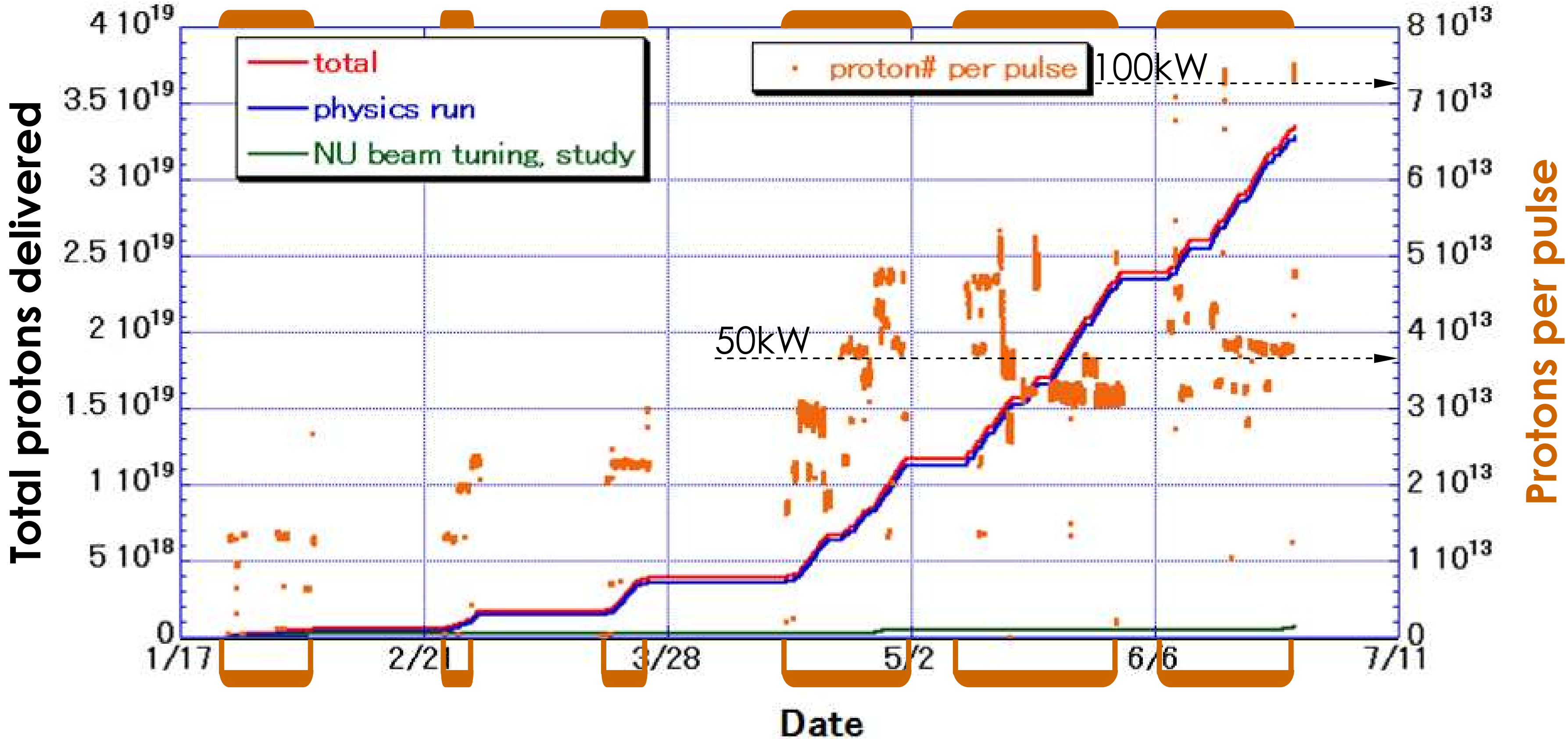
$$P_{\mu e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{\rm atm} L}{4E}\right)$$
$$+ O\left(\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}} \sin 2\theta_{13}\right) \times \cos\left(\delta + \frac{\Delta m^2_{\rm atm} L}{4E}\right)$$
$$+ O\left(\left[\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}}\right]^2\right)$$

If U_{e3} is measurable the number of events observed also depends on the CP-violation parameter, δ.



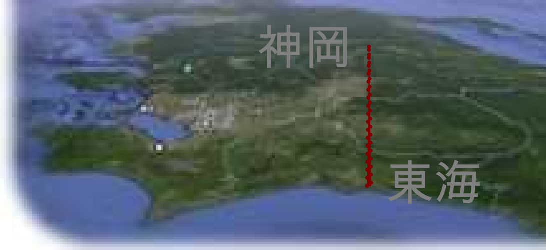
Exposure





- Protons delivered so far: 3.28×10^{19} (Jan-June)
- Continuous running at ~50kW level (up to 100kW in trials)
- Super-Kamiokande live fraction in excess of 99%

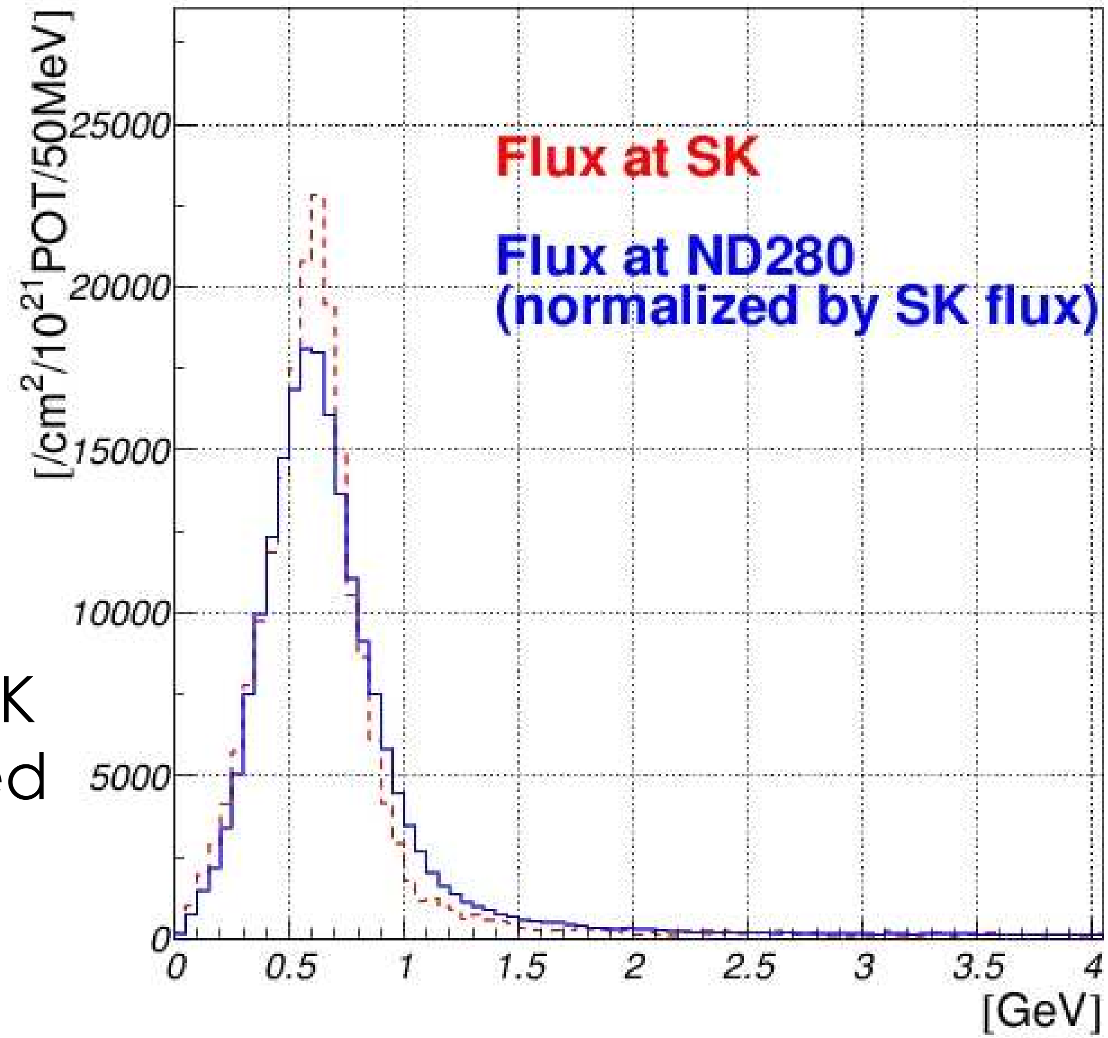
Transfer function



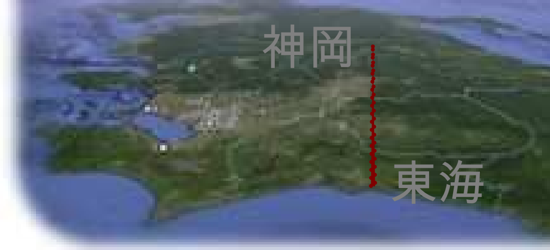
Baseline methods:

- Near/Far flux ratio [used by K2K]
- Matrix Method [used by MINOS]

Development over T2K run period expected



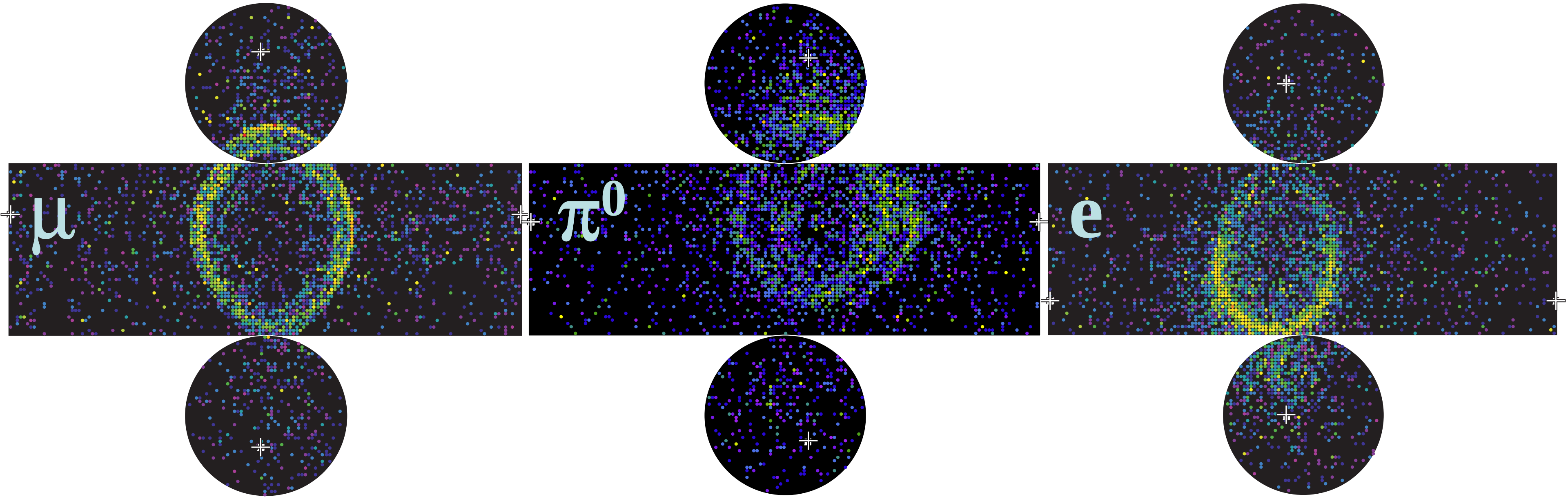
Pi-zero background



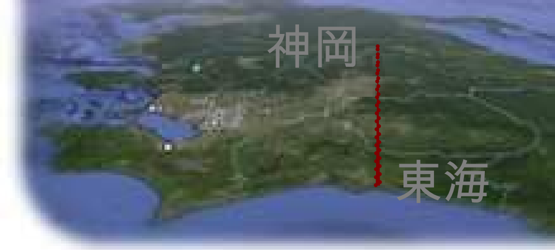
Isolated neutral pions from ν_μ-NC events:

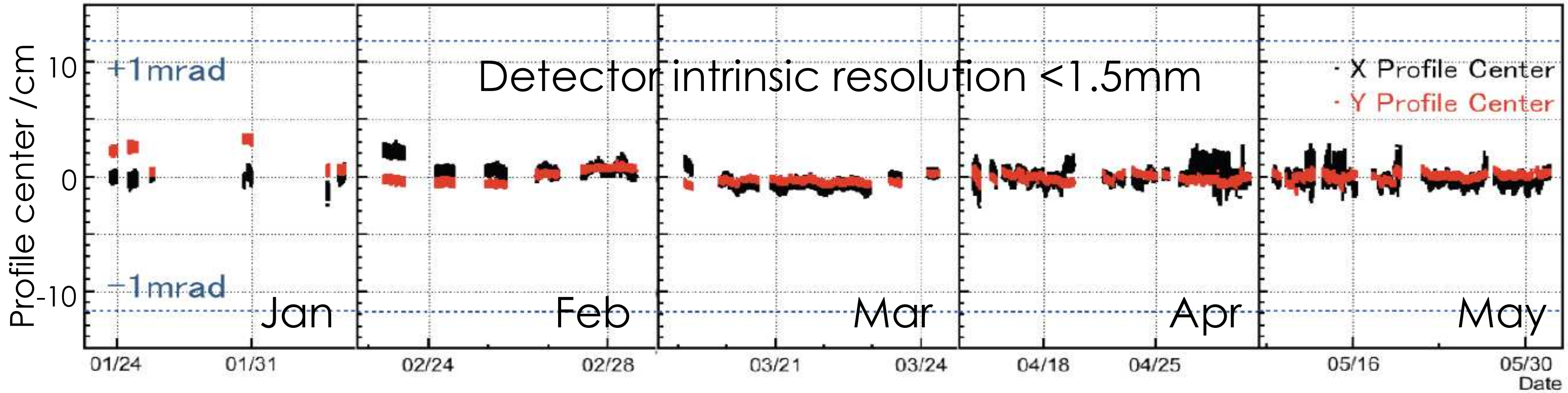
Neutral pion → photon pair → 2 EM showers

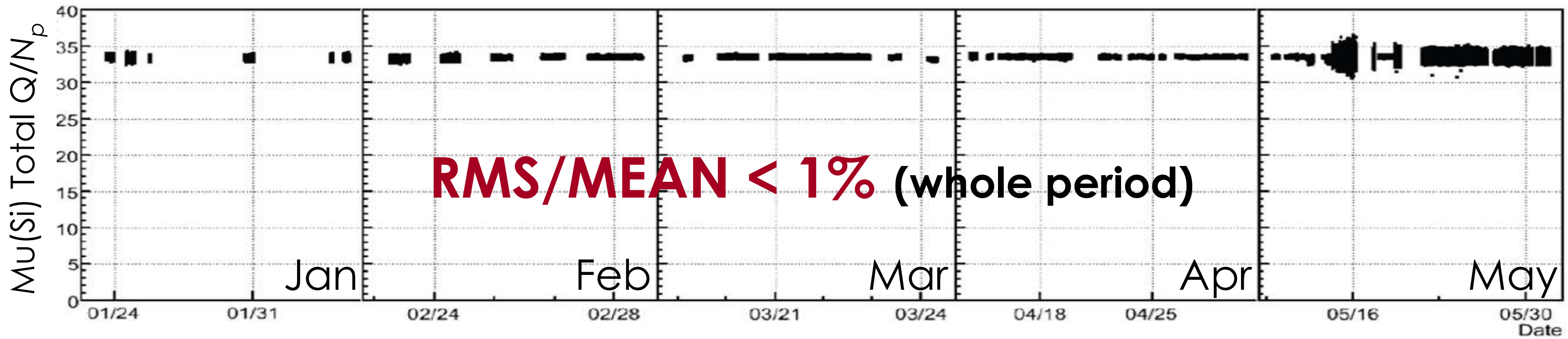
- If the EM showers have same direction they mimic a single EM shower (electron signal)



Muon monitors

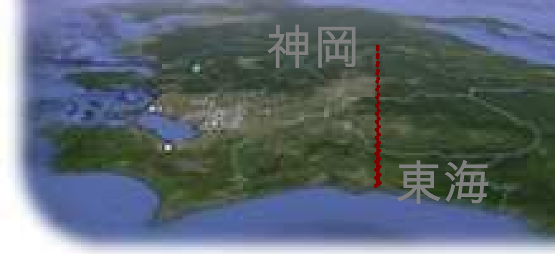






- Secondary/Primary beam intensity stable within 1% (reflects stability of targeting, horn focusing, etc)
- Well within our stability requirements for physics

Unbiased event selection



For initial run, SK event selection was fixed in advance

- Possible because SK is a mature & well understood detector.

<table>
<tr><th>For ν_μ disappearance analysis</th><th>For ν_e appearance search</th></tr>
<tr><td colspan="2">Timing coincident w/ beam time (+TOF)</td></tr>
<tr><td colspan="2">Fully contained (No OD activity)</td></tr>
<tr><td colspan="2">Vertex in fiducial volume (Vertex >2m from wall)</td></tr>
<tr><td>E_{vis} > 30MeV</td><td>E_{vis} > 100MeV</td></tr>
<tr><td colspan="2">nº of rings =1</td></tr>
<tr><td>μ-like ring</td><td>e-like ring</td></tr>
<tr><td></td><td>No decay electron</td></tr>
<tr><td></td><td>Inv. mass w/ forced-found 2nd ring < 105MeV</td></tr>
<tr><td></td><td>E_ν^{rec} < 1250MeV</td></tr>
</table>