

# Towards seeking $\theta_{13}$ : Status and initial data from T2K

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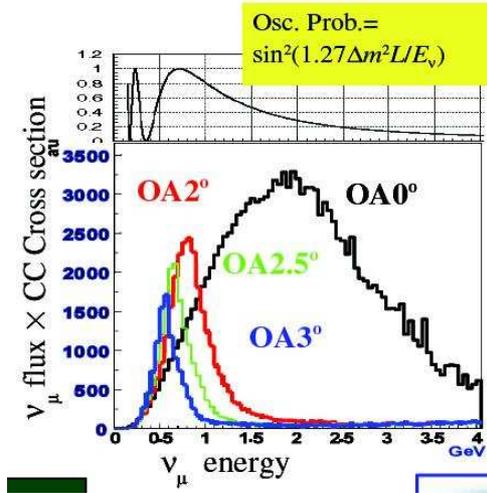
**Abstract.** T2K is a long-baseline neutrino oscillation experiment with the primary aim of measuring the smallest and most elusive neutrino mixing angle,  $\theta_{13}$ . 2010 saw the beginning of the T2K data-taking phase. This paper gives an overview of the T2K experiment, its goals and current status, and will discuss some of the initial data. All parts of the experiment: beamline, near detectors and far detector, are functioning well. In the far detector, 23 events have been selected from the first T2K dataset. Particle identification in the far detector also is discussed in this paper. Detailed analysis has not yet been completed.

## 1. Introduction

Neutrino flavour-changing is well-described by the MNSP mixing matrix [1]. There are at present two parameters in this matrix which are unmeasured,  $\theta_{13}$  and the CP-violating phase  $\delta$ , although other parameters may exist in addition if neutrinos are Majorana particles. The measurement of these two parameters will provide values that are key to understanding not only the behaviour of neutrinos, but potentially will allow us to understand the dynamics of the early universe through which matter gained dominance over antimatter.

The T2K (Tokai to Kamioka) experiment aims to provide the first measurement of the smallest and hence most elusive of the MNSP mixing angles,  $\theta_{13}$ , by searching for the appearance of  $\nu_e$  in a  $\nu_\mu$  beam, as well as to provide a more precise measurement of  $\theta_{23}$  by measuring  $\nu_\mu$  disappearance. In the first case, after  $5 \times 0.75 \text{ MW} \times 10^7$  seconds, corresponding to  $8.3 \times 10^{21}$  protons on target (POT), T2K can measure  $\sin^2 2\theta_{13}$  values as small as 0.008 at the 90% confidence limit in the region of  $0.001 < \Delta m_{23}^2 < 0.004$  assuming systematic uncertainties of 10% or less. This is more than an order of magnitude smaller than the existing best limits which come from the CHOOZ experiment [2]. In the second case, T2K aims to measure  $\sin^2 2\theta_{23}$  with a precision of  $\delta(\sin^2 2\theta_{23}) \sim 0.01$  and  $\delta(\Delta m_{23}^2) < 1 \times 10^{-4} \text{ eV}^2$ . This may help us to determine whether or not  $\theta_{23}$  is maximal, which would have theoretical implications.

T2K consists of three main components: the  $\nu_\mu$  beamline; a suite of near detectors; and a far detector. The T2K collaboration includes approximately 500 members from 61 institutions in 12 countries. In order to accomplish the two main aims stated above, a  $\nu_\mu$  beam is produced at the Japan Proton Accelerator Research Complex (JPARC) on the east coast of Japan near Tokai and directed towards the far detector, Super Kamiokande (SK), 295 km away in the Kamioka mines. A near detector suite is positioned 280 m from the neutrino production target and consists of an on-axis detector, INGRID, and the off-axis ND280 detector. T2K uses the unique off-axis



**Figure 1.** The normalised  $\nu_\mu$  flux as a function of  $\nu_\mu$  energy at different angles off the main axis of the beam.

beam configuration, which is discussed further in Section 2, in order to maximise the  $\nu_\mu \rightarrow \nu_x$  transition probability.

2009 saw the commissioning of the T2K beam and detectors. Data for analysis was obtained during the first half of 2010. Sections 2, 3.1, 3.2 and 4 discuss the commissioning and monitoring data which has been obtained from the beamline, from each of the subdetectors within the near detector suite, and from SK. Future plans are covered in Section 5.

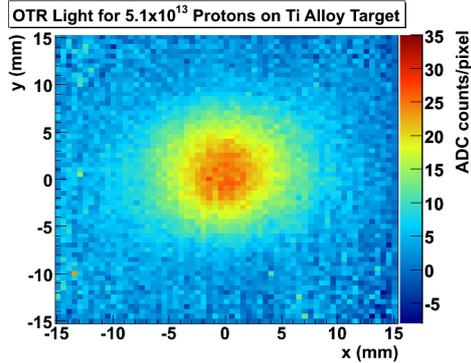
## 2. The T2K beamline

The T2K  $\nu_\mu$  beam is produced by bringing an intense proton beam into collision with a cylindrical, graphite target, thereby producing hadrons consisting of mainly pions with some kaons. The charged pions are focused into a Decay Volume, where they decay almost exclusively via the process  $\pi \rightarrow \mu\nu_\mu$ . This provides the source of  $\nu_\mu$  for the experiment. The beam then proceeds through a beam dump which removes any remaining hadron component, and then through approximately 150 m of rock which removes the muon component, leaving a  $\nu_\mu$  beam with little  $\nu_e$  contamination. The beam is monitored at each stage via proton, muon and neutrino monitors. Monitoring the neutrino beam is part of the function of the near detector suite and is discussed in Sections 3.1 and 3.2. The proton and muon monitoring data is discussed below.

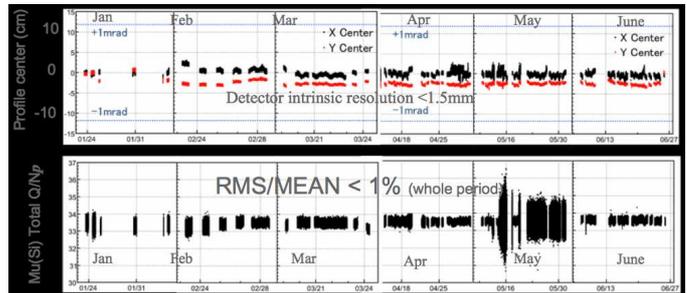
### 2.1. Off-axis beam

Contrary to intuition, the optimal neutrino beam for T2K is obtained by aiming the neutrinos  $2.5^\circ$  away from SK. The reason for this is elucidated in Figure 1 which shows the  $\nu_\mu$  flux versus  $\nu_\mu$  energy at different off-axis angles, where  $OA0^\circ$  corresponds to off-axis  $0^\circ$ , i.e. on-axis. The further off-axis one samples the beam, the lower the neutrino energy and the narrower the energy spectrum. This allows for the beam to be tuned to the energy that corresponds to a maximum oscillation probability, and greatly reduces the number of high-energy neutrinos in the beam which are more likely to result in the production of pions which are difficult to reconstruct in the detectors, particularly in the case of neutral pions in SK, as discussed in Section 4. In addition, the off-axis beam has less  $\nu_e$  contamination simply due to kinematic configurations, and actually has more  $\nu_\mu$  at the energy corresponding to the oscillation maximum.

The first T2K run took place from January through June 2010, during which a total of  $3.23 \times 10^{19}$  POT at 30 GeV were delivered for T2K analysis. The summer shutdown included installing new extraction kickers and making further improvements to the beam system,



**Figure 2.** The transverse position of the proton beam immediately before it hits the target as measured by the OTR monitor.



**Figure 3.** The position of the centre of the muon beam (top) and the beam intensity (bottom) as measured by the muon monitors immediately after the hadron beam dump.

including a change from 6 to 8 bunches per spill, a shorter spill-repetition cycle, and more protons per bunch.

### 2.2. Beamline monitor data

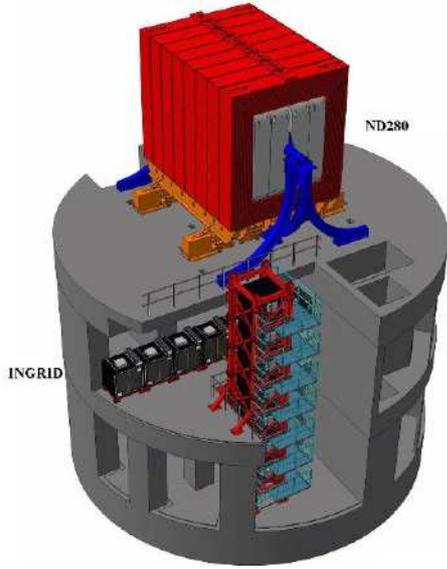
The price to pay for all of the advantages of using an off-axis beam is that the oscillation probability becomes sensitive to the off-axis angle; hence, it is important to monitor the beam position and profile well. At T2K, this is done via a series of various types of detectors placed along the beam path. The Optical Transition Radiation (OTR) Detector monitors the transverse (normal to the beam axis) position and intensity of the proton beam immediately before it impacts the target as shown in Figure 2. The beam profile is approximately Gaussian with a width of approximately 4.2 mm. The radius of the cylindrical target is 13 mm.

The position and intensity of the beam after the hadron beam dump is measured by a set of muon monitors. Figure 3 shows that the centre of the beam (top) for the entire run period was well within the target position, and the intensity of the beam (bottom) remained relatively stable except for a period of beam-testing in May. These examples are representative of the data obtained from many other monitors.

### 3. Near detector suite

The near detectors are situated 280 m downstream of the neutrino production target and serve the purpose of characterising the unoscillated neutrino beam. They consist of an on-axis detector, INGRID, which monitors the neutrino beam flux and profile, and an off-axis detector, ND280, which measures the beam flux, composition, neutrino interaction cross-sections and background processes at the same off-axis angle as SK. This latter detector allows for a partial cancellation of systematic uncertainties when calculating the near/far ratio, i.e. the ratio of the predicted neutrino flux between the near and far detectors, thereby reducing the uncertainties in the  $\nu_\mu$  normalisation used by SK in determining the oscillation parameters. The relative positions of INGRID and the off-axis ND280 are shown in Figure 4 which shows the cross-shaped INGRID below and to the left of the ND280 detector in the ND280 pit.

For all of the T2K detectors, the golden channel for identifying and measuring neutrino interactions and determining the neutrino energy is the Charged-Current Quasi-Elastic (CCQE) interaction, given by  $\nu_l + N \rightarrow l + N'$  where  $l = e$  or  $\mu$  and  $N, N'$  are nucleons within a target nucleus. The lepton in the final state is used to reconstruct the momentum of the incoming neutrino.



**Figure 4.** The relative positioning of the near detectors in the ND280 pit. The off-axis ND280 sits above and to the right of the on-axis INGRID.



**Figure 5.** The INGRID detector, consisting of 16 modules.

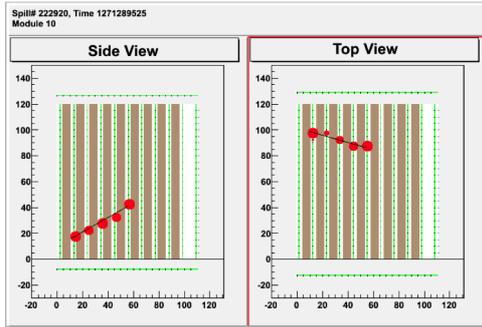
### 3.1. INGRID

INGRID is composed of 16 modules, 14 forming a cross-shape and two sitting at diagonal positions, each composed of layers of plastic scintillator bars interspersed with layers of iron, as shown in Figure 5. The beam goes through the centre of the cross. The long arms of INGRID are ideal for obtaining a good measurement of the beam profile. Each scintillator bar has a central hole through which wavelength-shifting fibre is inserted to carry light from the centre to the ends of the bar, where the fibre is coupled to solid-state photosensors. For the data set presented here, INGRID included the 14 modules in the cross shape. The diagonal modules were added during the summer 2010 shutdown.

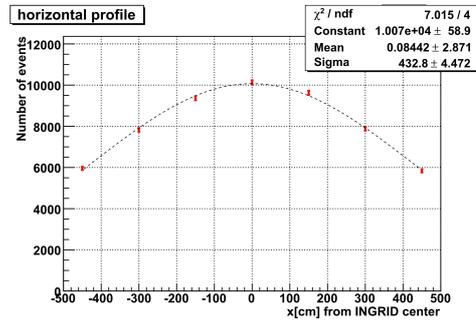
Figure 6 shows a candidate neutrino event in INGRID as seen from the side (left) and top (right) of a module. The red dots correspond to the reconstructed positions of energy depositions or “hits” within the detector, as evidenced by light collected by the photosensors at the ends of the scintillator bars, and indicate the path of the charged lepton produced by the CCQE interaction. The brown shaded layers represent the lead which functions as the interaction target for the neutrinos. The on-axis neutrino beam profile as measured by INGRID is shown in Figure 7. This horizontal profile normal to the beam axis shows the beam well-centred with the beam shape as expected. Similar results have been obtained for the vertical profile.

### 3.2. ND280

The off-axis ND280 detector consists of a dedicated  $\pi^0$  detector (P0D), three Time Projection Chambers (TPCs) interleaved with two Fine Grain Detectors (FGDs), backed by the downstream Electromagnetic Calorimeter (ECal), all contained within a metal framed “basket” as shown in Figure 8. Surrounding the subdetectors inside the basket are the rest of the ECal modules. All of this is enclosed within the recycled UA1 magnet which produces a 0.2 T magnetic field. Although the magnet can be opened, similar to what is shown in the figure, for detector installation and maintenance, during data-taking the two halves of the magnet are brought together. The magnet yoke is instrumented for the purpose of acting as a veto for externally-produced particles, cosmic

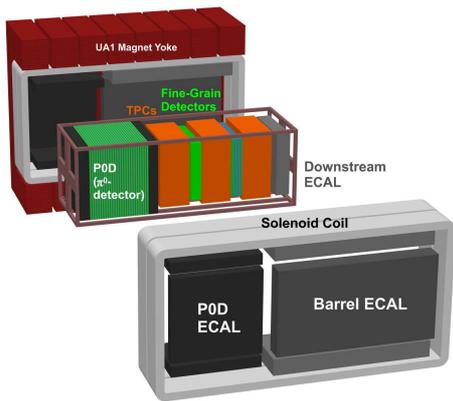


**Figure 6.** A candidate neutrino event detected by INGRID. The red dots represent the positions of hits in the scintillator bars.

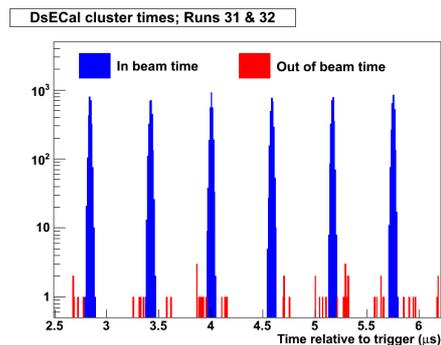


**Figure 7.** The horizontal profile of the  $\nu_\mu$  beam as measured by INGRID.

ray triggering, and muon range measurement, and is called the Side Muon Range Detector (SMRD). The TPCs provide the main momentum measurement for charged particles. The FGDs provide the main target mass for the central region of the ND280 and are optimised for detecting the proton recoil in CCQE interactions. The P0D is optimised for measuring  $\pi^0$  production cross-sections. The ECal modules provide particle identification (PID) and energy measurements for neutral particles. Except for the TPCs, all of the ND280 subdetectors are composed of layers of plastic scintillator bars interspersed with layers of a target material, similar to INGRID. In the case of the P0D and the second FGD, some of the target layers are water. By comparing the interaction cross-sections measured including the water layers, with those measured excluding the water layers, the cross-sections on water will be determined, allowing for a better prediction of the events in SK. For the data set presented here, the ND280 contained all of the subdetectors except for the ECals which surround the basket, which were installed during the summer 2010 shutdown.

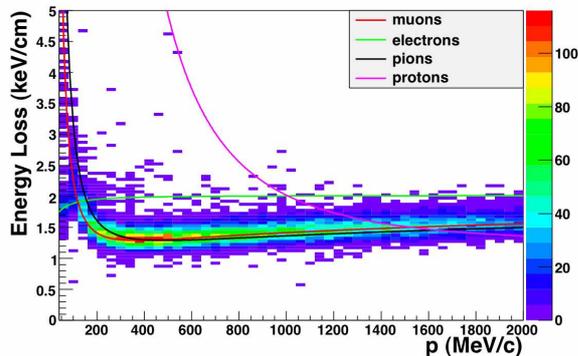


**Figure 8.** The ND280 off-axis detector. The  $\nu_\mu$  beam enters from the left of the figure. Shown are the subdetectors and the open magnet.

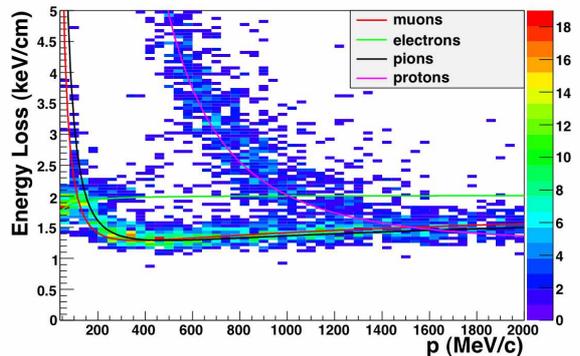


**Figure 9.** The timing structure of the  $\nu_\mu$  beam as measured by the downstream Ecal.

Each of the ND280 subdetectors has accumulated a wealth of commissioning and analysis data. A sample is presented here. Figure 9 shows the 6-bunch structure of the neutrino beam



**Figure 10.** The rate of energy loss,  $dE/dx$ , for negative particles, as measured by the TPCs.



**Figure 11.** The rate of energy loss,  $dE/dx$ , for positive particles, as measured by the TPCs.

as measured by the identification of charge-clusters within the downstream ECal versus time. The blue peaks correspond to clusters identified during the expected bunch-crossing. The small numbers of events between the bunch-crossings are mainly due to misidentified clusters. Figures 10 and 11 show the rate of loss of energy due to ionisation for charged particles traversing the TPCs, for negative (left) and positive (right) particles. The theoretical curves for various particles overlay the data points. As expected for T2K, a large number of events for negative particles are consistent with the muon curve.

Figure 12 shows a typical selection of candidate neutrino events in the ND280 off-axis detector. In each case, the  $\nu_\mu$  beam is entering from the left, although due to the disperse nature of the beam the interaction vertex can occur anywhere within the ND280. The figure shows two inelastic scattering events with the vertex in FGD1 (top left and bottom right), a CCQE candidate (top right), and a candidate CC event which includes a pion (bottom left). The neutrino event in the top left plot also includes an unrelated muon (probably) traversing the detector.

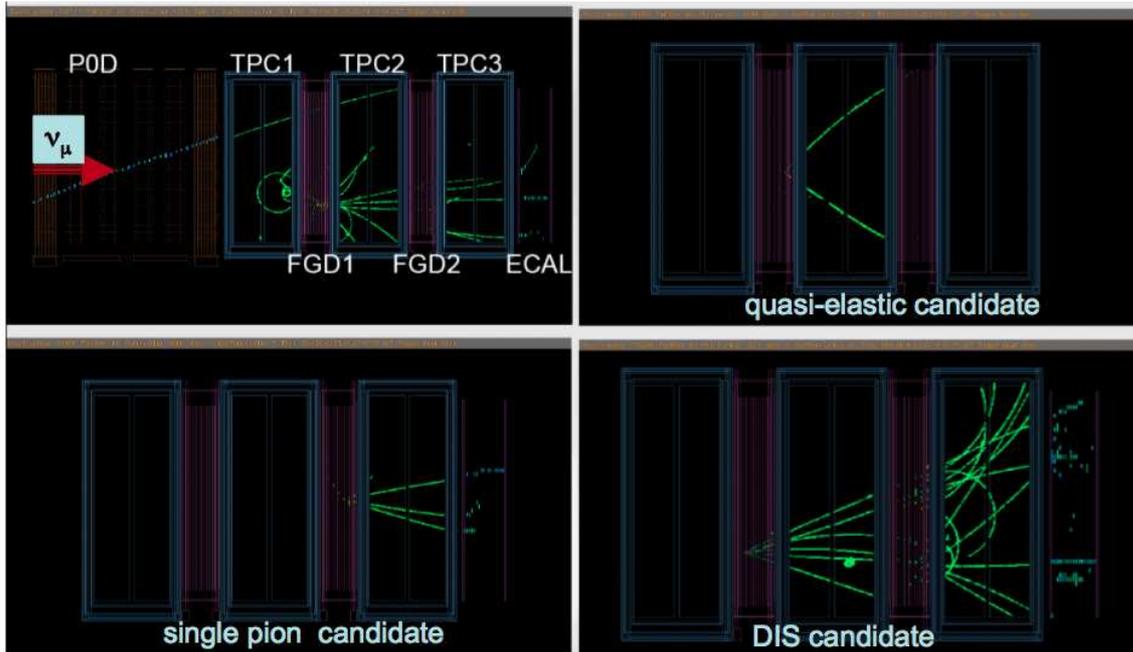
#### 4. Super Kamiokande

SK has been taking solar, atmospheric, and beam neutrino data for over 10 years and is well-described in the literature (see, for example, [3] and references therein). Neutrinos in SK are identified by the Cherenkov rings that are produced by relativistic, charged particles traversing the 50 kT ultra-pure water of the detector. As in the T2K near detectors, the CCQE interaction provides the bulk of the useful events.

In SK, the following criteria are used to select leptons produced via neutrino interactions. The timing of the event must coincide with the beam spill timing. The energy from the event must be fully-contained within the inner fiducial volume of the detector, and the reconstructed event vertex must lie within the fiducial volume. Such events are selected when they have only one reconstructed Cherenkov ring, and if they pass a threshold value for visible energy. PID is achieved by looking at specific properties of the rings. Muons leave a sharp, well-defined ring due to limited scattering within the detector, while electrons produce a more fuzzy, less well-defined ring due to scattering.

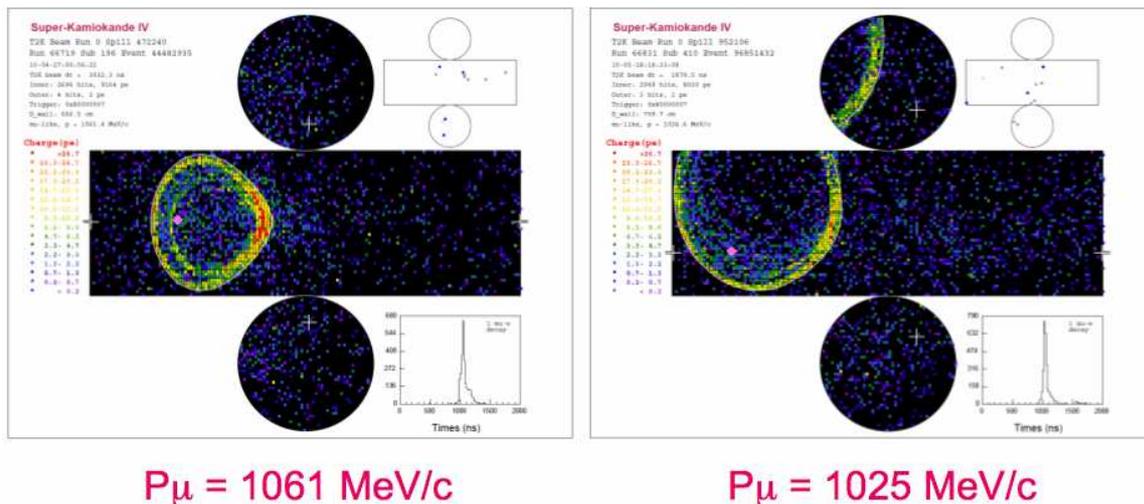
The  $\nu_e$  appearance measurement will be made by counting the number of e-like events in SK and comparing it with the number expected including background  $\nu_e$  inherent in the beam, other sources of electrons, and accounting for misidentified rings. The  $\nu_\mu$  disappearance measurement will be made by counting the number of  $\mu$ -like events and comparing it with the number expected

## A few ND280 neutrino interaction candidates



**Figure 12.** Typical event displays for neutrino interactions in the off-axis ND280. In all cases, the beam enters from the left of the event display.

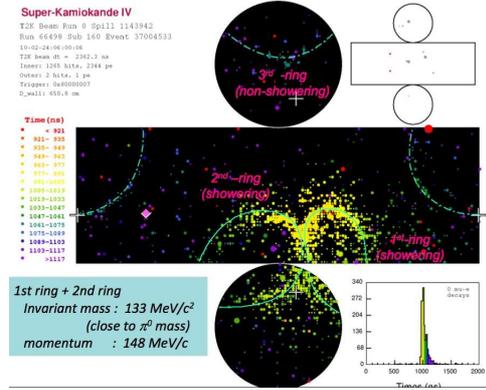
including non-beam backgrounds. Figure 13 shows some typical muon rings in the T2K data. In these figures, the cylindrical part of the detector is mapped flat, while the top and bottom of the cylinder are shown as circles.



**Figure 13.** Typical event displays for  $\nu_\mu$  interactions in SK. The cylindrical detector is mapped flat, with top and bottom of the cylinder represented as circles.

One of the main backgrounds in the appearance measurement is  $\pi^0$  production.  $\pi^0$ s decay to two photons, which produce rings very similar to those produced by electrons. These two

rings may be reconstructed as one e-like ring in cases where the two photons were produced with asymmetric energy leaving only one visible photon ring, or where one ring overlays the other. Figure 14 shows the first T2K event recorded in SK. Interestingly, this event includes a  $\pi^0$ ; however, in this case it is easy to see that there are two e-like rings rather than one.



**Figure 14.** The first T2K event recorded in SK, an event involving a  $\pi^0$ . The two fuzzy rings from the decay photons are visible. The cylindrical detector is mapped flat, with the top and bottom of the cylinder represented as circles.

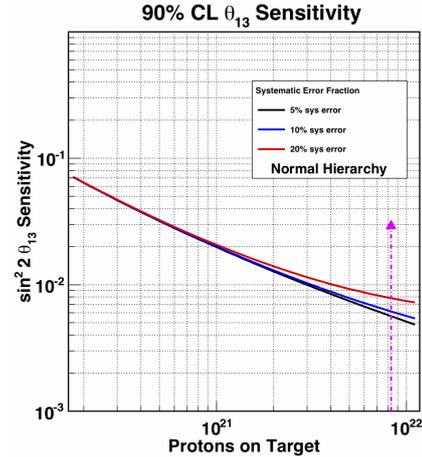
SK, like the near detectors, has also observed the expected 6-bunch neutrino beam structure in their fully-contained events. In total for the January through June 2010 runs, 33 fully-contained events have been observed. Of these, 23 events meet the visible-energy criterion. Detailed analysis of these events has not yet been completed.

## 5. Conclusions

All modules of the ND280 detector, both on- and off-axis, now are installed and working well. The next T2K data-taking period runs from November 2010 through June 2011, during which the aim is to accumulate  $150 \text{ kW} \times 10^7$  seconds ( $\sim 3 \times 10^{20}$ ) POT. Figure 15 shows the expected sensitivity to  $\sin^2 2\theta_{13}$  at T2K as a function of number of POT. The dashed vertical line corresponds to  $8.3 \times 10^{21}$  POT, which is expected at the end of the first phase of T2K. The different curves correspond to different levels of systematic uncertainty. It can be seen that until  $10^{21}$  POT have been delivered, the sensitivity is independent of the differences between systematic uncertainties that are at the level of 5, 10 or 20%. By July 2011, T2K will have increased its dataset by an order of magnitude and will be optimising the analyses.

## References

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- [2] M. Apollonio *et al* (CHOOZ Collaboration) 1999 *Phys Lett B* **466** 415
- [3] Y. Fukuda *et al* (Super Kamiokande Collaboration) 1998 *Phys Lett B* **433** 9; J.P. Cravens *et al* (Super Kamiokande Collaboration) 2008 *Phys Rev D* **78** 032002



**Figure 15.** T2K sensitivity to  $\sin^2 2\theta_{13}$  as a function of POT. The vertical line corresponds to  $8.3 \times 10^{21}$  POT.