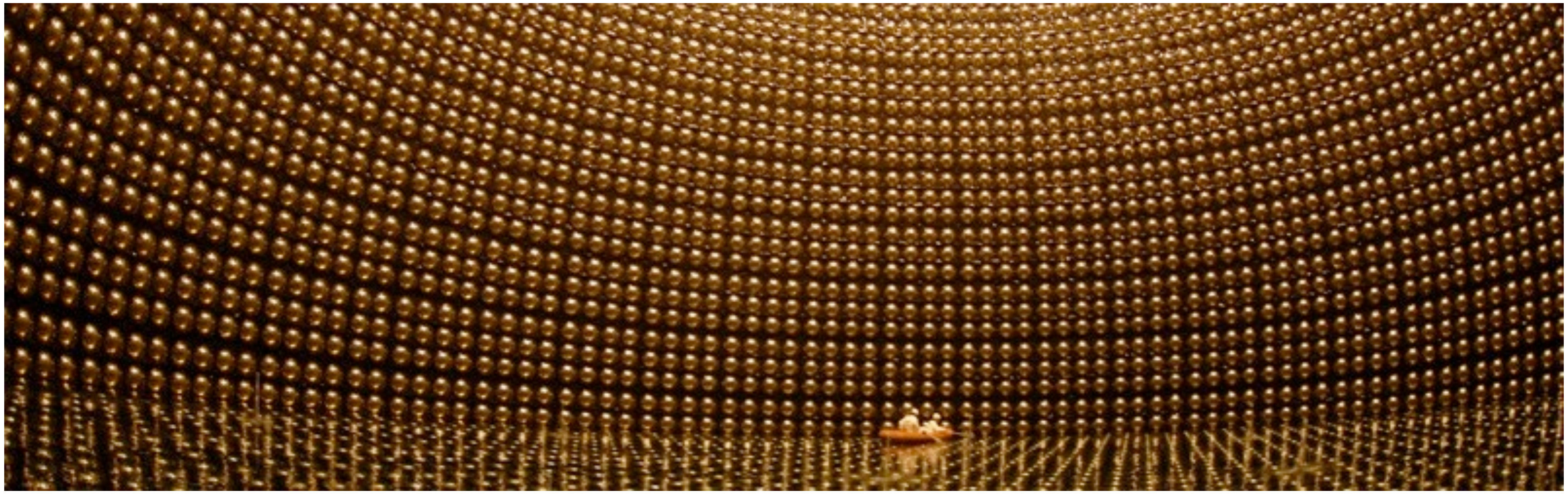


Recent results from T2K

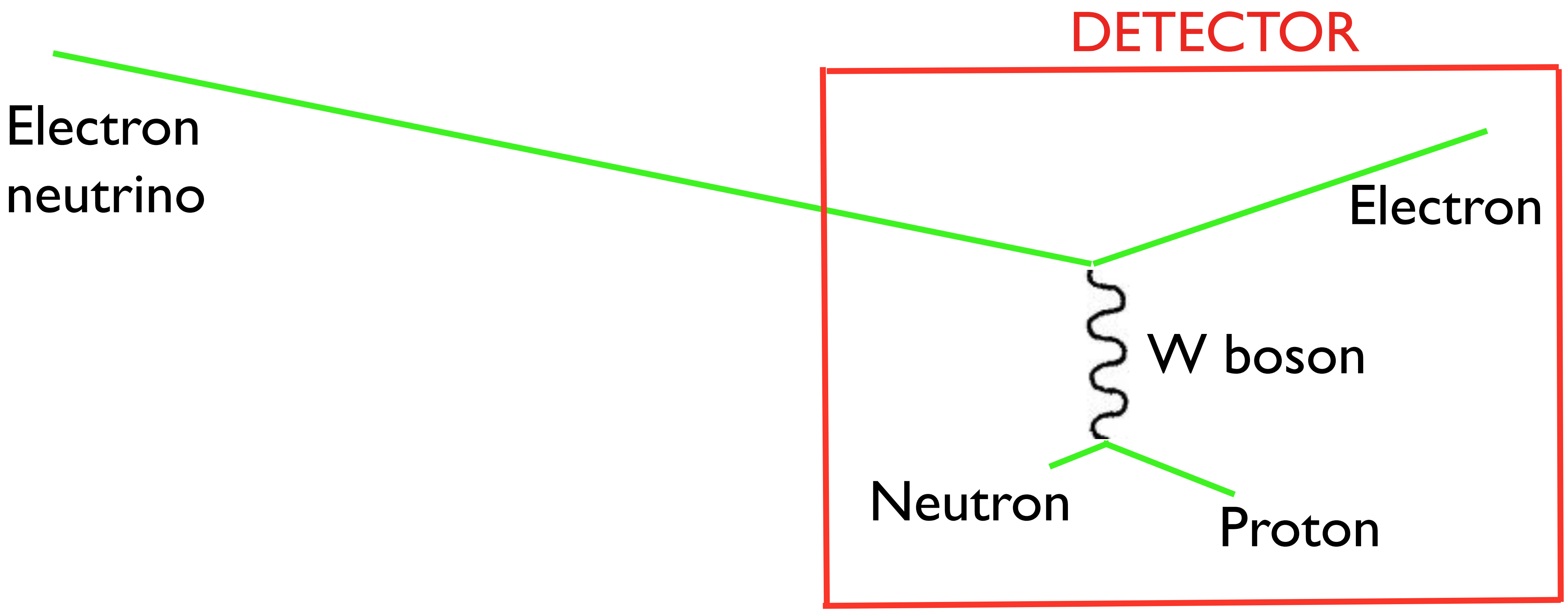
Nick Grant

IVICFA Interdisciplinary Seminar, Valencia

25th October 2013

Neutrino oscillations

Neutrino eigenstates



There are 3 neutrino flavour eigenstates:

1. Electron neutrino (ν_e): interacts with neutron to produce proton and electron.
2. Muon neutrino (ν_μ): same interaction produces proton and muon.
3. Tau neutrino (ν_τ): same interaction produces proton and tau.

There are also 3 neutrino mass eigenstates: ν_1, ν_2 and ν_3.

The PMNS matrix

The flavour eigenstates do not have a one-to-one correspondence with the mass eigenstates, but are related through the PMNS matrix U:

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

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

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

2D rotation matrices

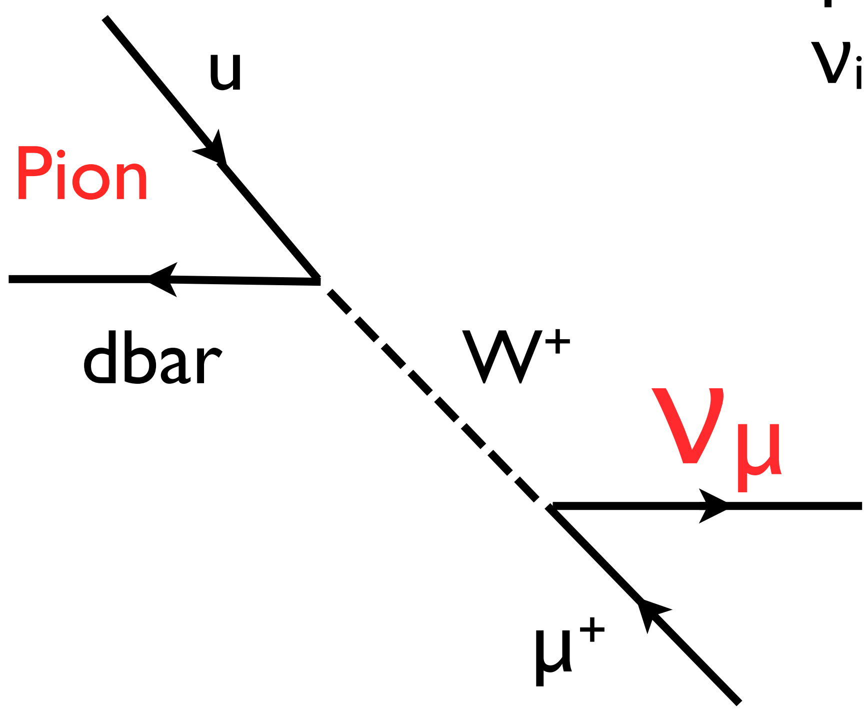
where
$s_{23} = \sin\theta_{23}$
$c_{23} = \cos\theta_{23}$, etc.

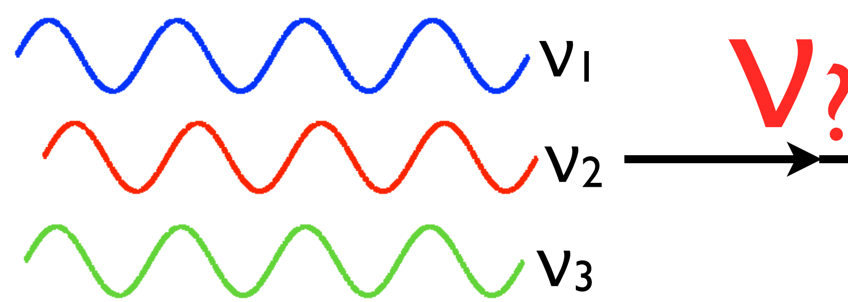
Neutrino oscillations

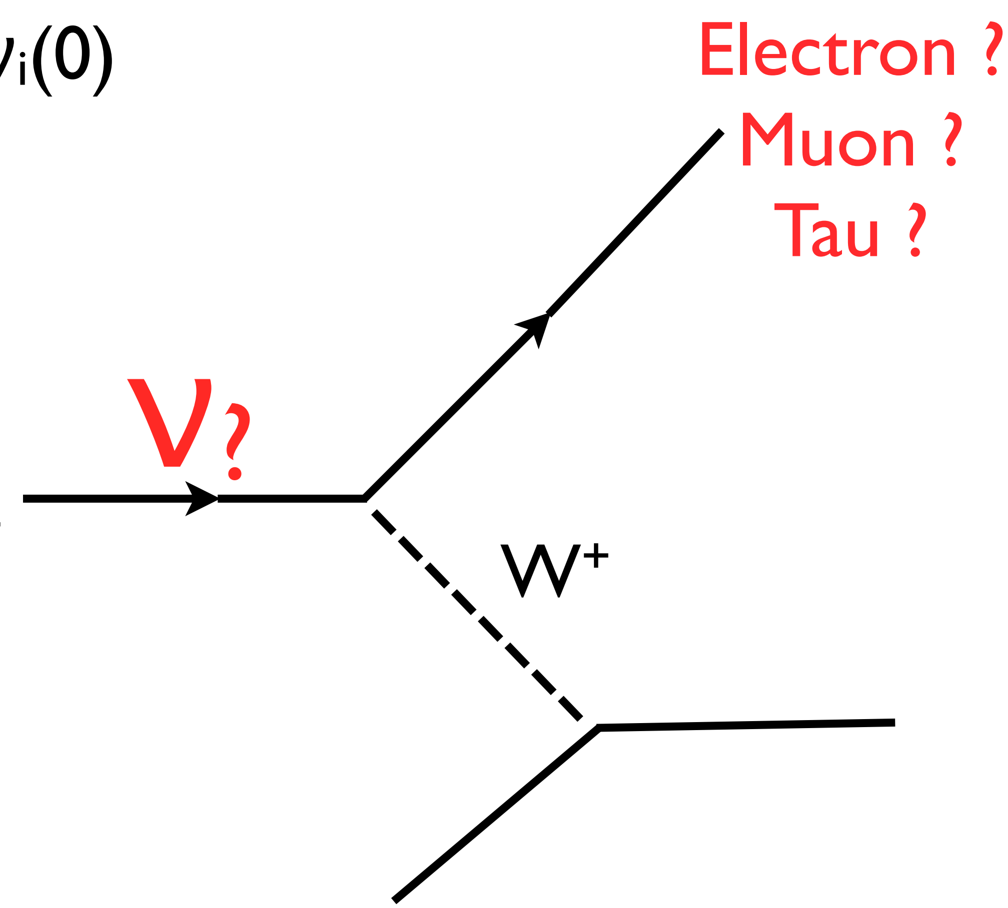
Neutrino created in muon flavour eigenstate

Flavour eigenstate is a combination of 3 mass eigenstates which propagate as plane waves:
$\nu_i(L) = \exp(-im^2L/2E)\ \nu_i(0)$

Neutrino detected as flavour eigenstate



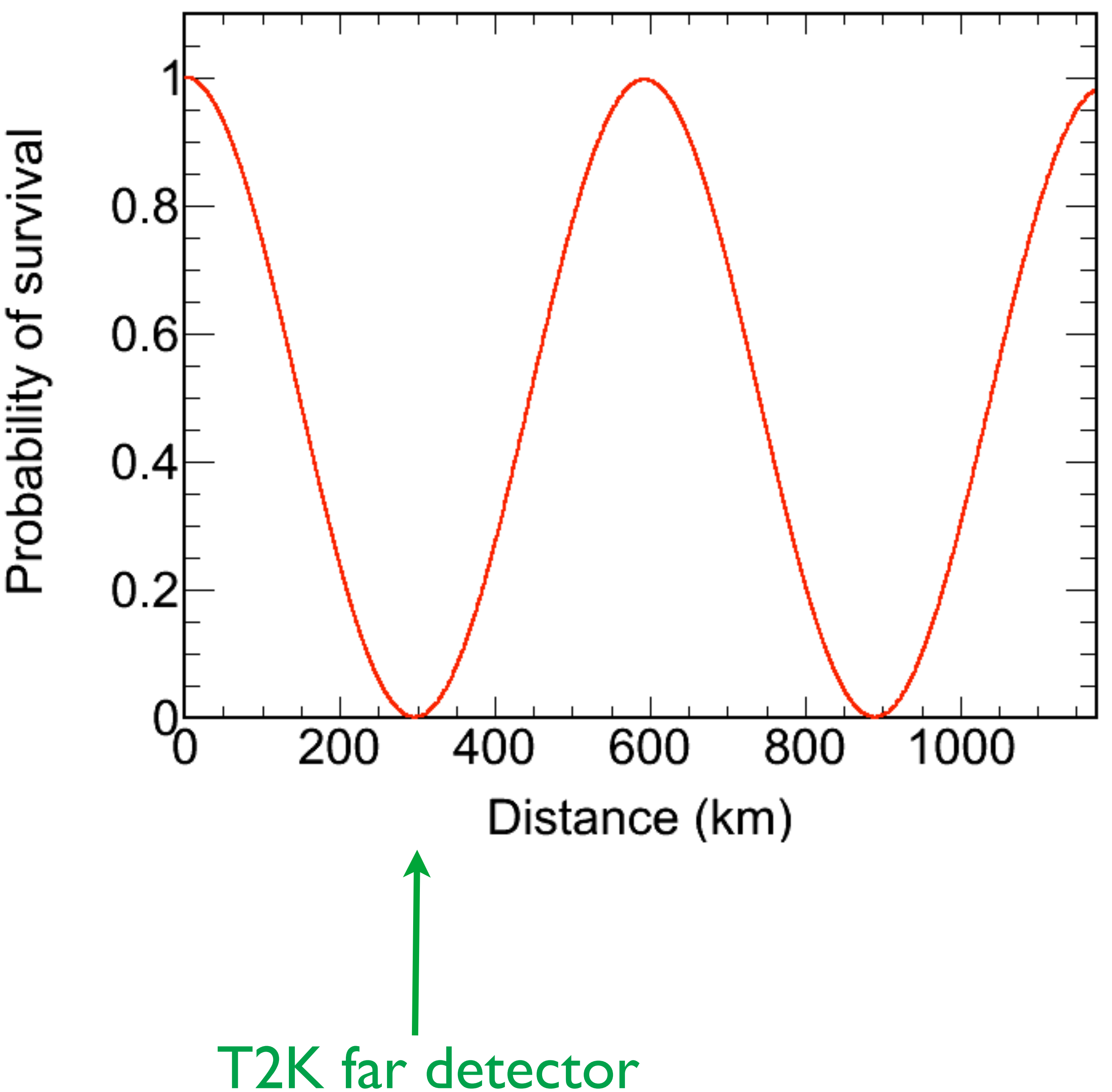




If ν1, ν2 and ν3 have different masses, they also have different wavelengths. As they travel, the relative phases of the 3 mass eigenstate waves change. Then the 3 waves can add to produce a neutrino in a different flavour eigenstate.

Neutrino oscillations

Muon neutrinos with energy $6x10^8$ electronvolts



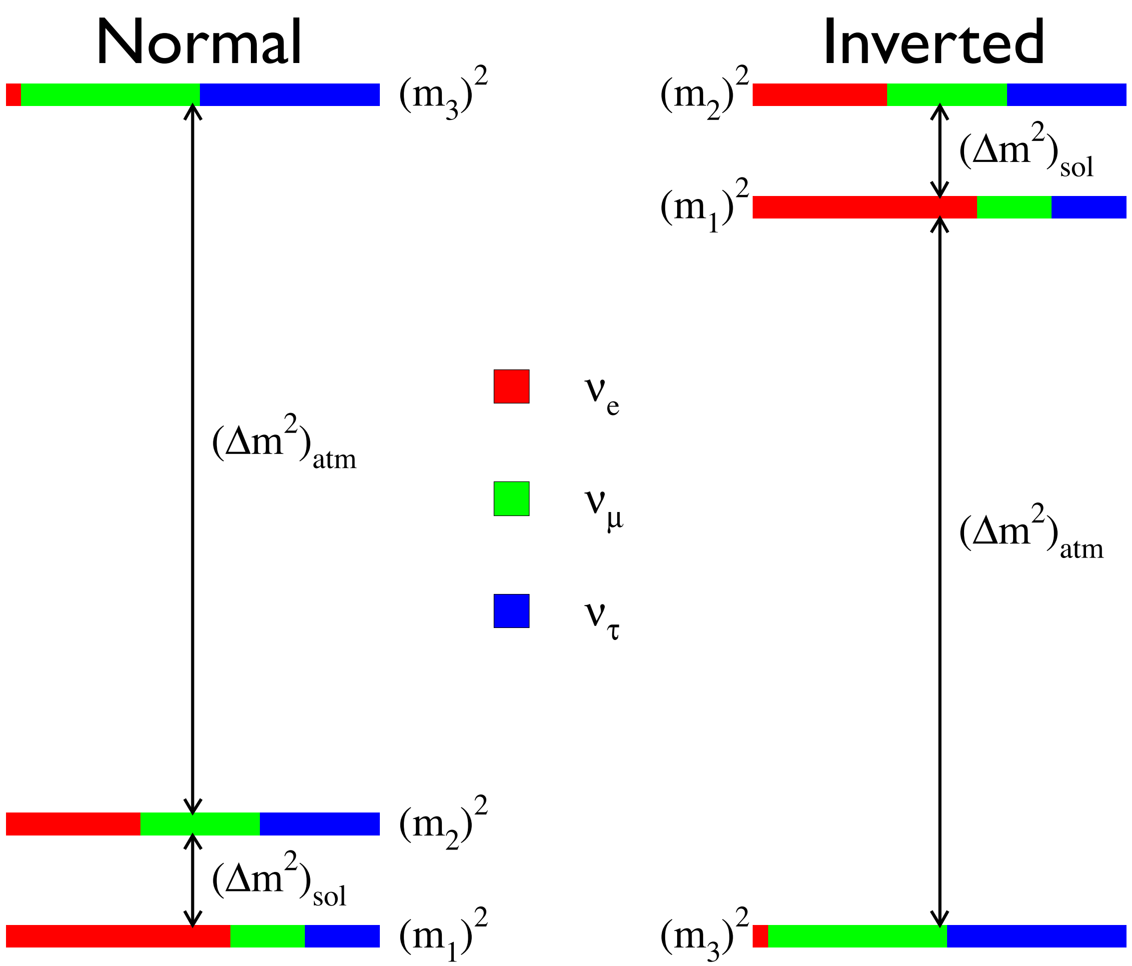
As a result of these changes in relative phases, neutrinos oscillate from one flavour to another as they travel. Low-energy neutrinos oscillate in a shorter distance than high-energy neutrinos.

Another curious aspect of quantum physics is that only the probability of the flavour of neutrino can be known as it travels.

The neutrino only becomes a definite flavour when it interacts in a detector - by finding whether an electron, muon or tau is created.

Neutrino oscillation parameters

Two possible neutrino mass hierarchies



This means that neutrino oscillations can be described in terms of 6 parameters:

3 mixing angles: θ_{12}, θ_{13} and θ_{23}

2 mass-squared differences: Δm_{21}^2 and $|\Delta m_{32}^2|$ (the third mass-squared difference depends on the other two).

1 charge-parity (CP)-violating phase: δ_{CP}

$\sin^2(2\theta_{12})$ and Δm_{21}^2 have been measured by experiments such as KamLAND and SNO:

$\sin^2(2\theta_{12}) = 0.857$ (error≈5%)
$\Delta m_{21}^2 = 7.58\times10^{-5}\ eV^2/c^4$ (error≈3%)

T2K and its neutrino beam and detectors

The T2K experiment

The T2K experiment produces a beam that is mostly muon neutrinos in Tokai and sends it to Kamioka in Japan. Its main objectives are:

1. Search for $\nu_\mu \rightarrow \nu_e$ oscillations and determine the value of θ_{13}.

2. Make precise measurements of ν_μ disappearance and the parameters θ_{23} and $|\Delta m_{32}^2|$.

3. Make measurements of cross sections of neutrino interactions.

The T2K collaboration

~500 member, 59 institutions, 11 countries.

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

CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

RWTH Aachen U.

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

ICRR Kamioka
ICRR RCCN Kavli
IPMU KEK Kobe
U. Kyoto
U. Miyagi
U. Edu. Osaka City
U. Okayama
U. Tokyo Metropolitan
U. U. Tokyo

IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw Warsaw
U. T. Wroklaw U.

INR

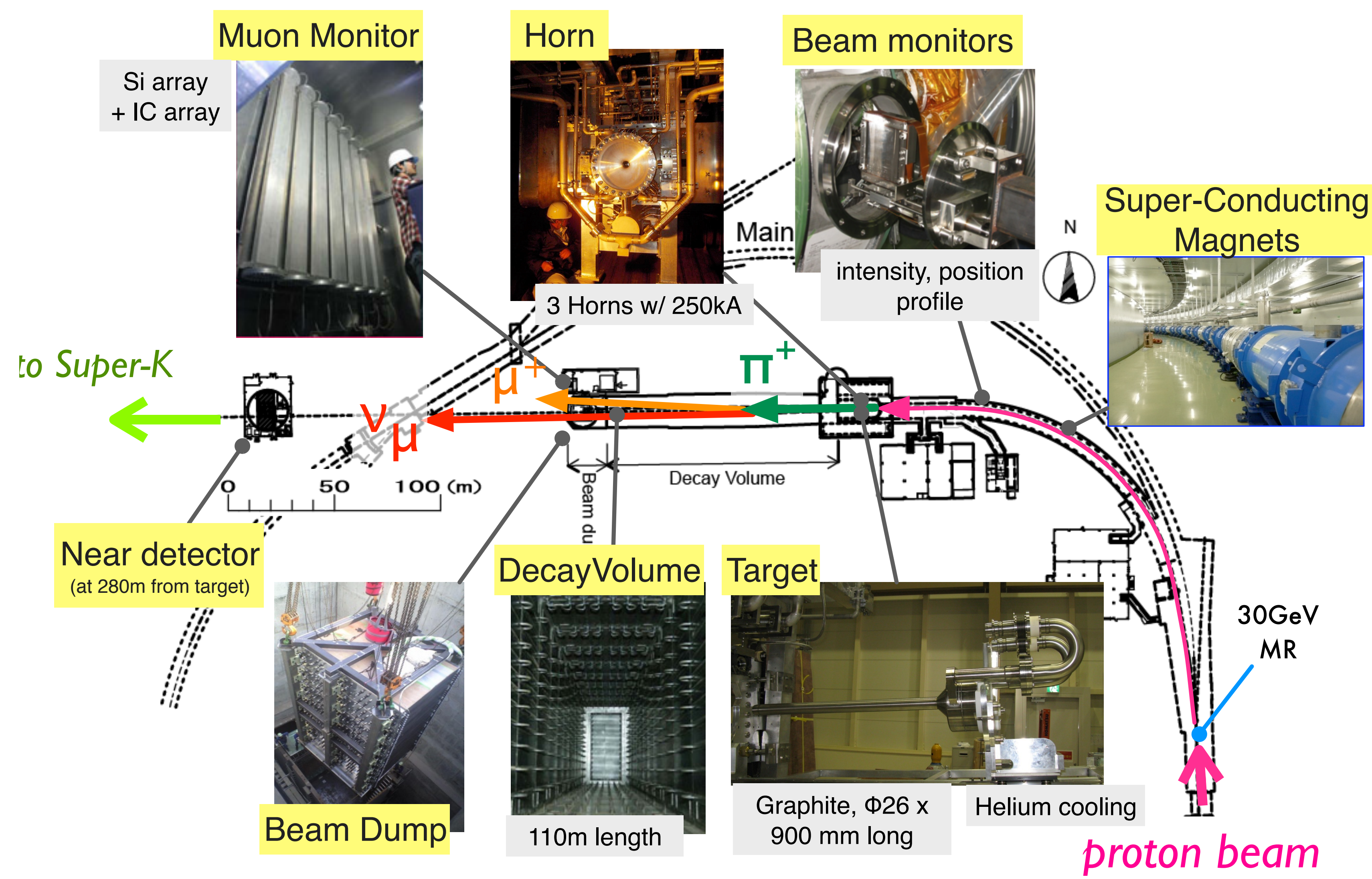
IFAE, Barcelona
IFIC, Valencia

ETH Zurich
U. Bern
U. Geneva

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

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

The T2K neutrino beam

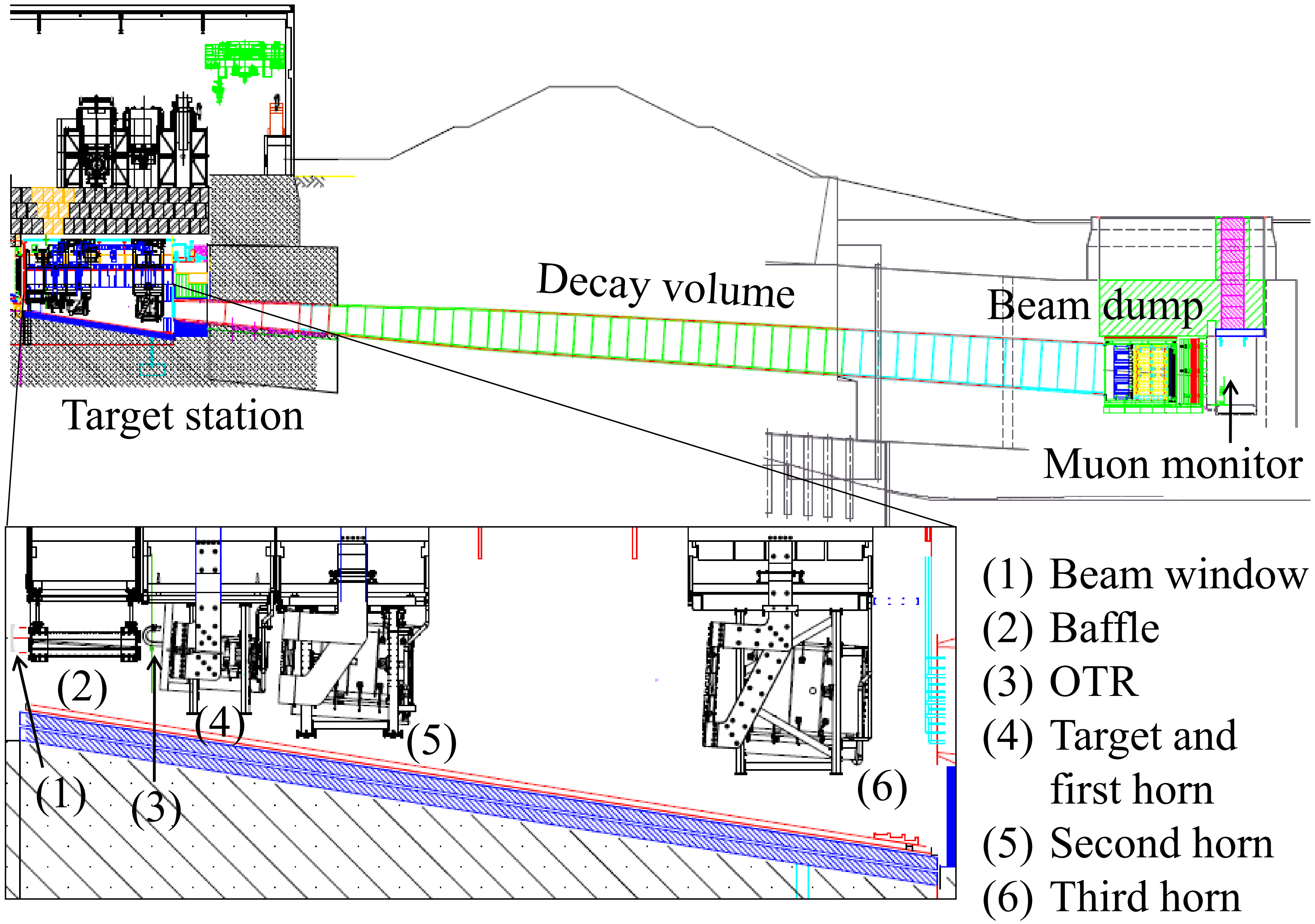


The J-PARC proton accelerator consists of a linear accelerator (LINAC), a rapid-cycling synchrotron and a main ring synchrotron.

8 bunches of protons are extracted from the main ring into the primary beamline within a single turn by a set of 5 kicker magnets.

In the secondary beamline, the protons collide with a graphite target to produce charged pions and kaons.

The T2K secondary beamline

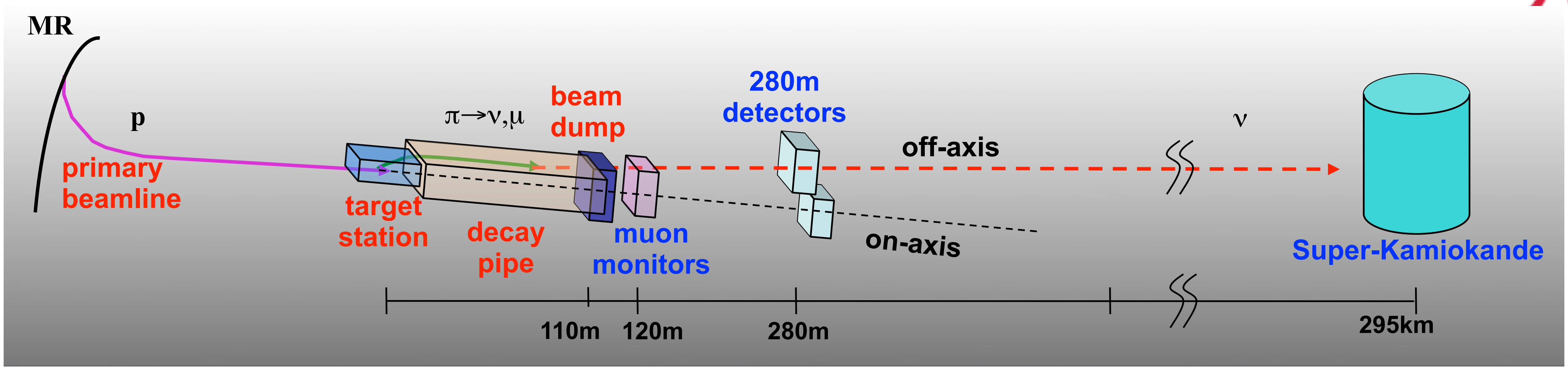


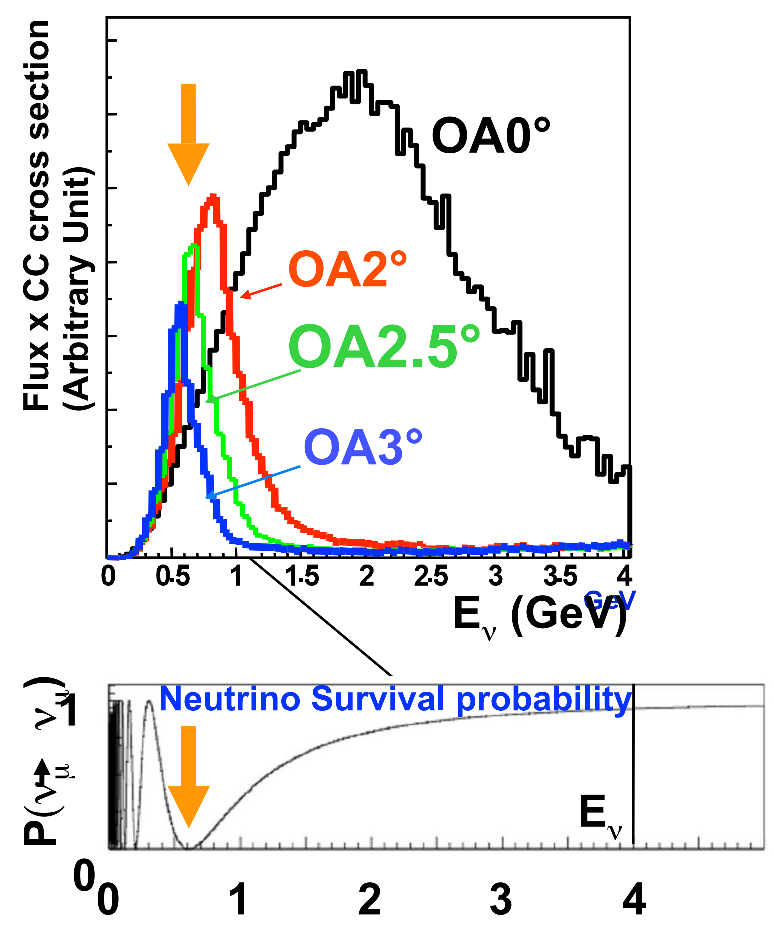
After exiting the target station, π^+ are enhanced in the aimed direction using 3 magnetic horns. The π^+ decay in the decay volume (length 96 metres):

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

All hadrons and low-energy muons are stopped by the beam dump, which is made of graphite, iron and concrete. ν_μ pass through it to form the neutrino beam. Muons with energies > 5 GeV also pass through, and these are used to monitor the direction and intensity of the beam in the muon monitor.

Off-axis experiment

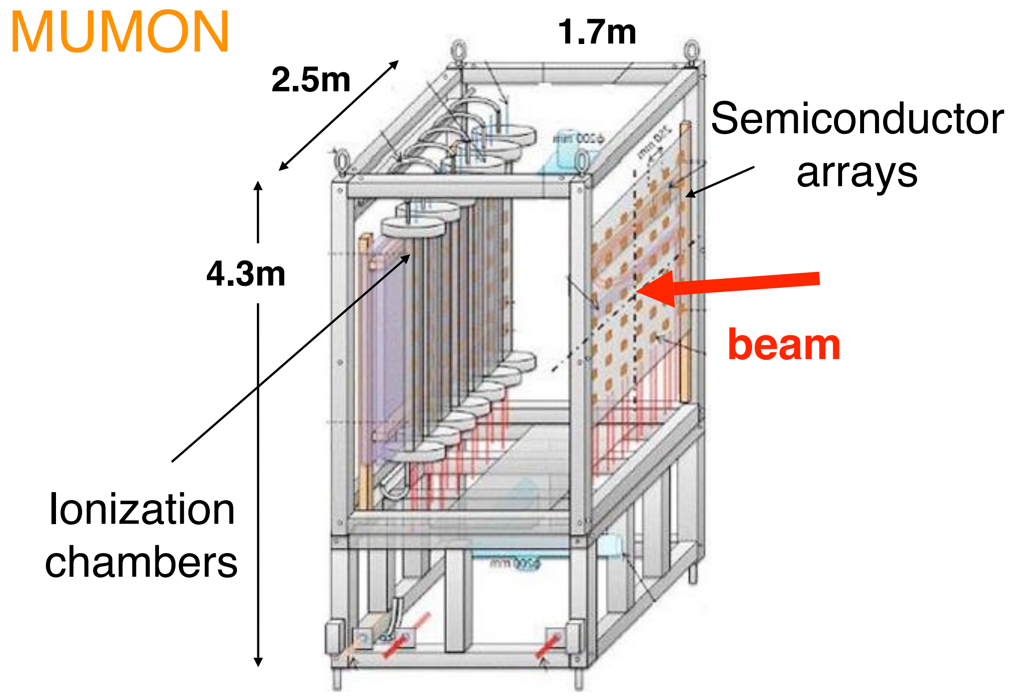




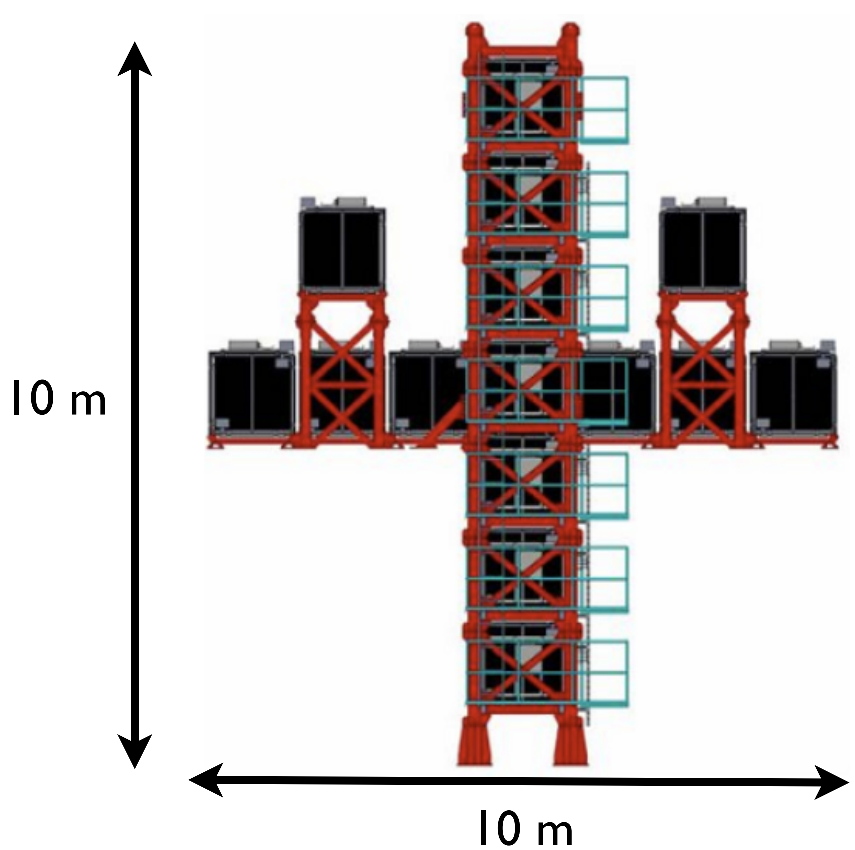
T2K is the first long-baseline neutrino experiment to use the off-axis technique.

The off-axis angle of 2.5° results in a neutrino beam energy spectrum that is much narrower than in an on-axis experiment. This energy spectrum is centered on 600 MeV, the oscillation maximum for a baseline of 295 km. A greater fraction of neutrinos oscillates at the distance of the far detector (Super Kamiokande) than in an on-axis experiment.

MUMON and INGRID



The muon monitor (MUMON) consists of gas ionisation chambers and arrays of silicon photodiodes. It monitors the direction and intensity of the beam on a spill-by-spill basis by looking at high-energy muons. It has done this monitoring for the whole experimental period.

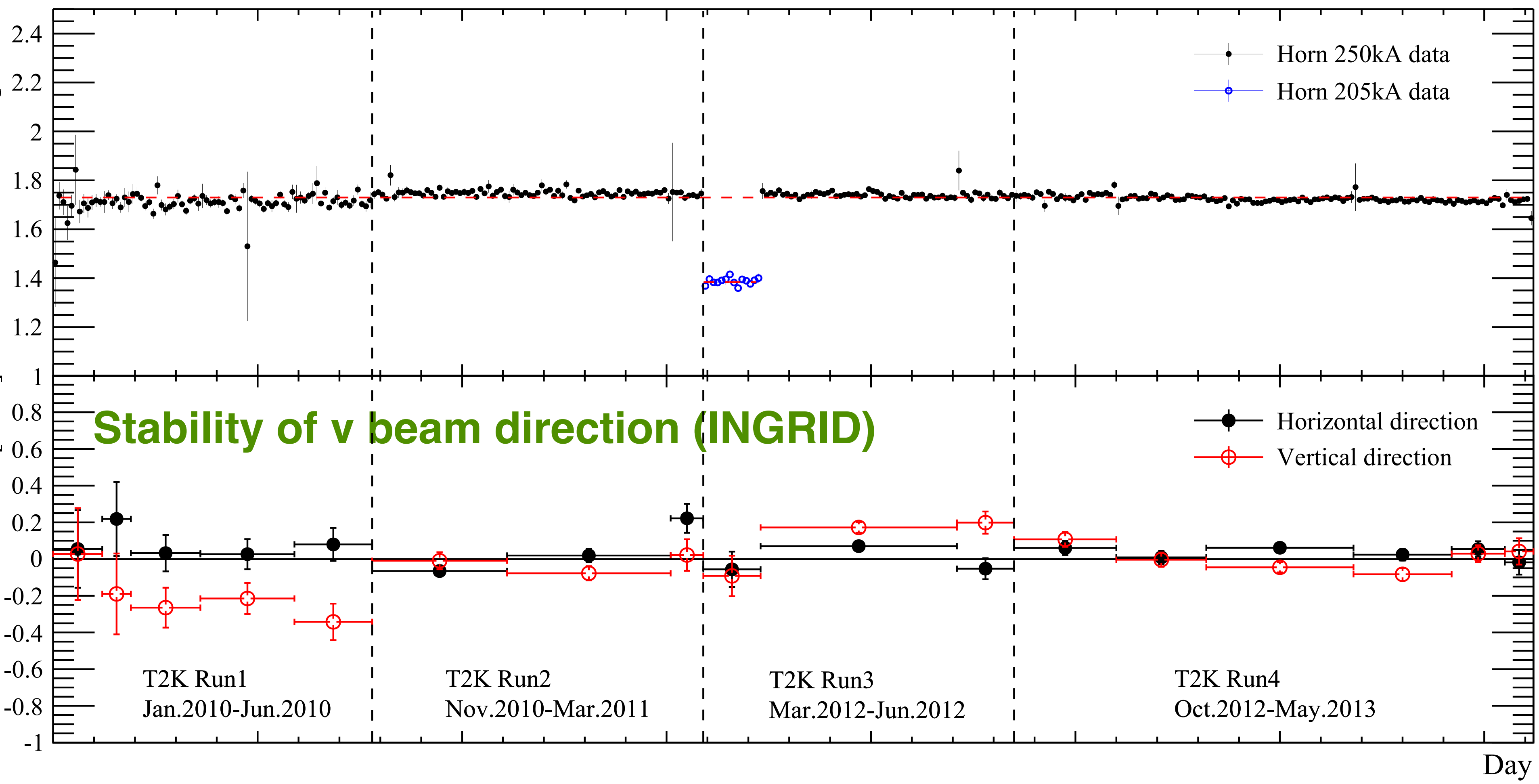


The interactive neutrino grid (INGRID) consists of 16 modules, each of which consists of alternating layers of iron and scintillator. It is on-axis and monitors the direction and intensity of the neutrino beam by checking the number of neutrino interactions in each module on a week-by-week basis.

On-axis near detectors

Stability of ν interaction rate normalized by # of protons (INGRID)

Fluctuation of ν interaction rate (/10^{19}p.o.t) is less than 0.7% whole run period



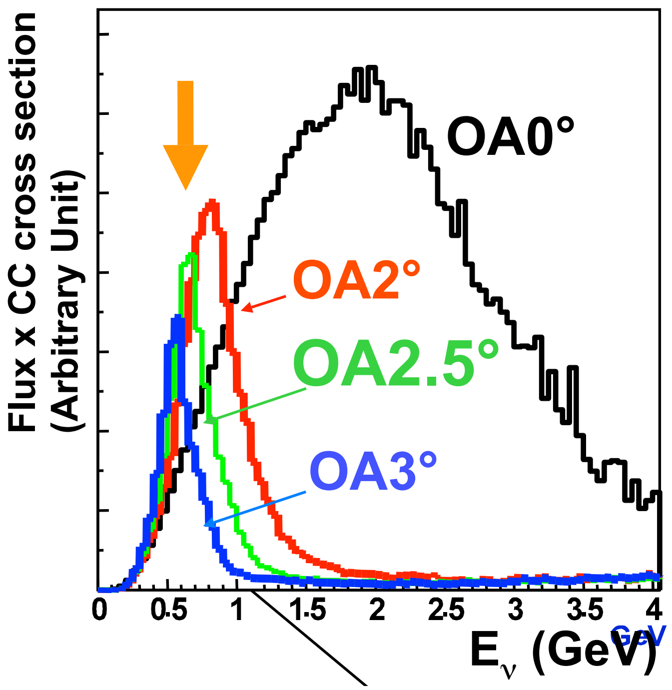
The interaction rate is stable in the INGRID for runs 1-4 except for run 3b (problem with horn power supply).

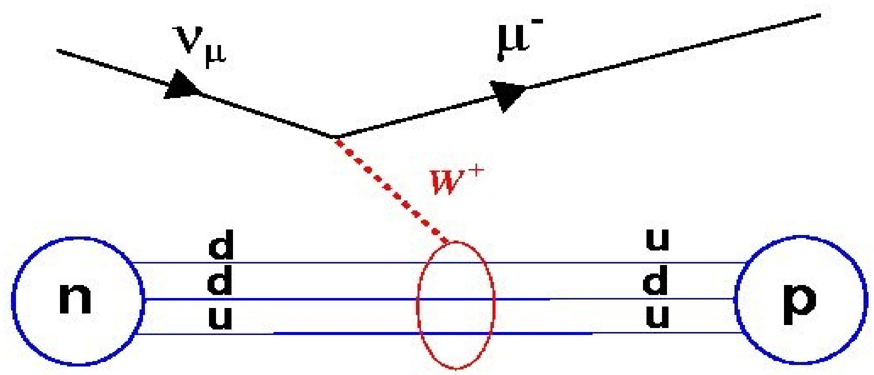
Beam centre well within 1 mrad at INGRID.

Stability of beam direction is much better than 1mrad during whole run period

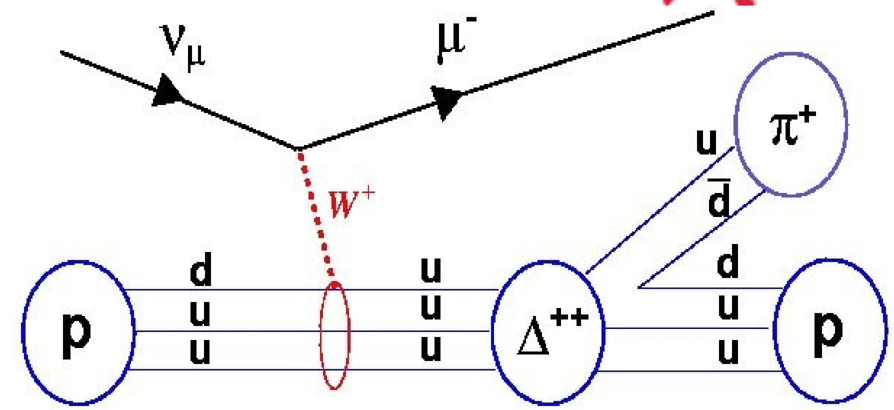
The neutrino energy varies as a function of off-axis angle. We require < 2% uncertainty in energy scale, which in turn requires < 1 mrad uncertainty in beam direction. The beam centre is well within the 1 mrad tolerance at the INGRID.

Off-axis experiment

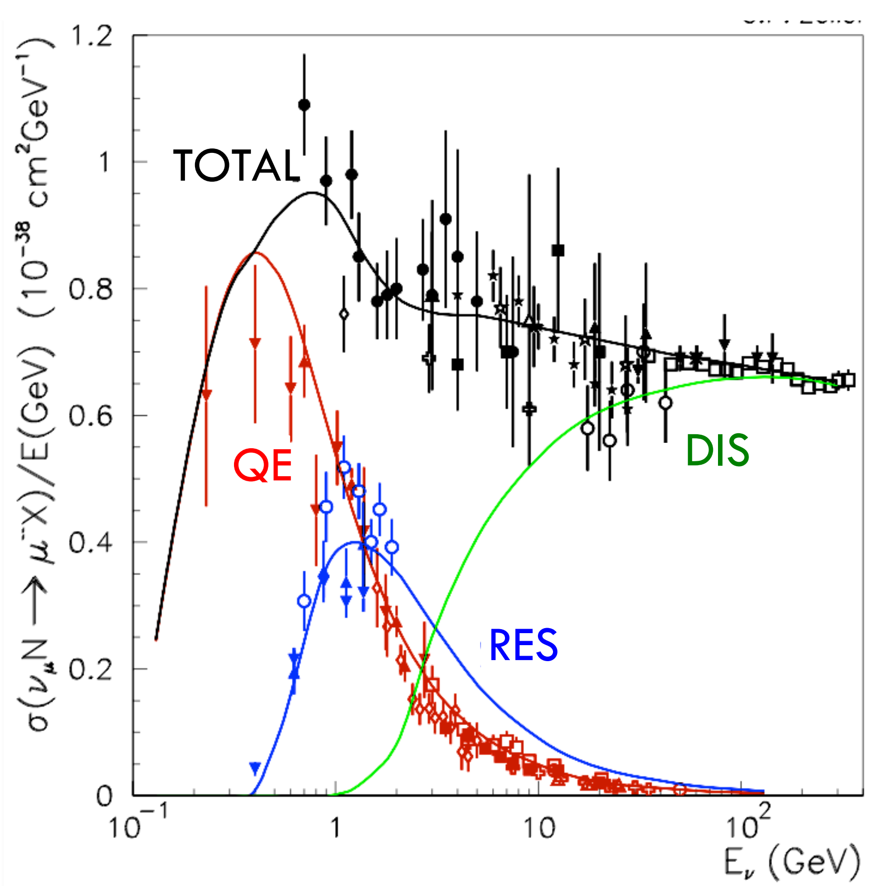




Charged-current quasi-elastic event (QE)



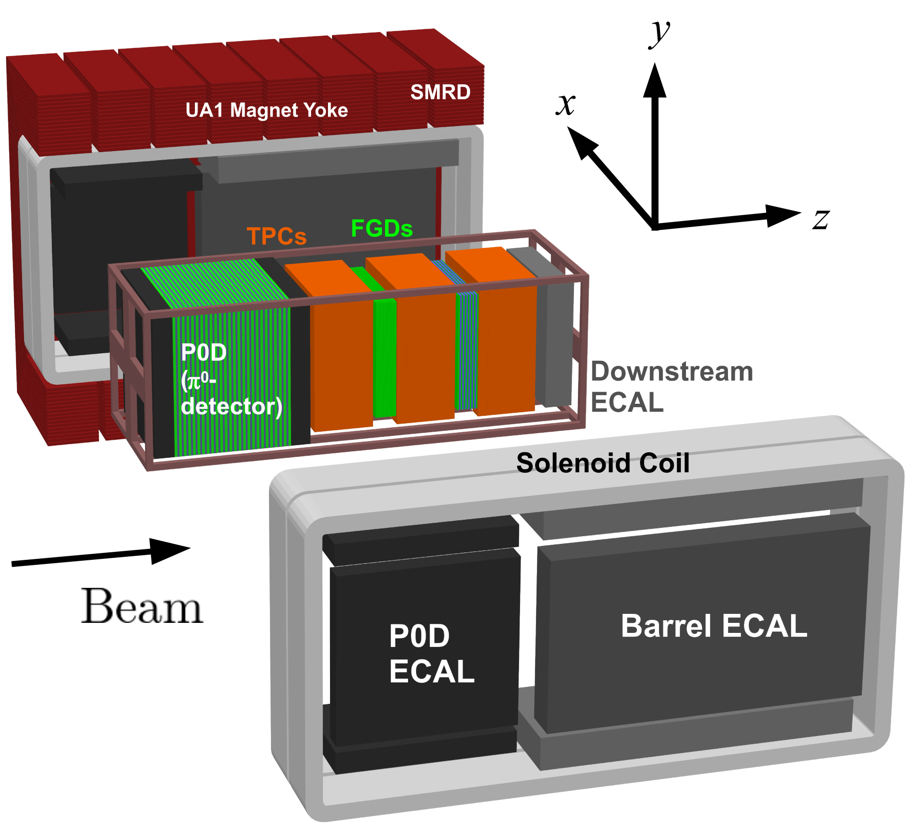
Charged-current π+ production (RES)



The off-axis beam produces in the T2K detectors a greater proportion of charged-current quasi-elastic (CCQE) events. These are our “signal” events because there are only 2 particles in the final state, and we can measure the neutrino energy from them.

It also reduces the proportion of “background” events (i.e. all events other than CCQE) in the T2K detectors.

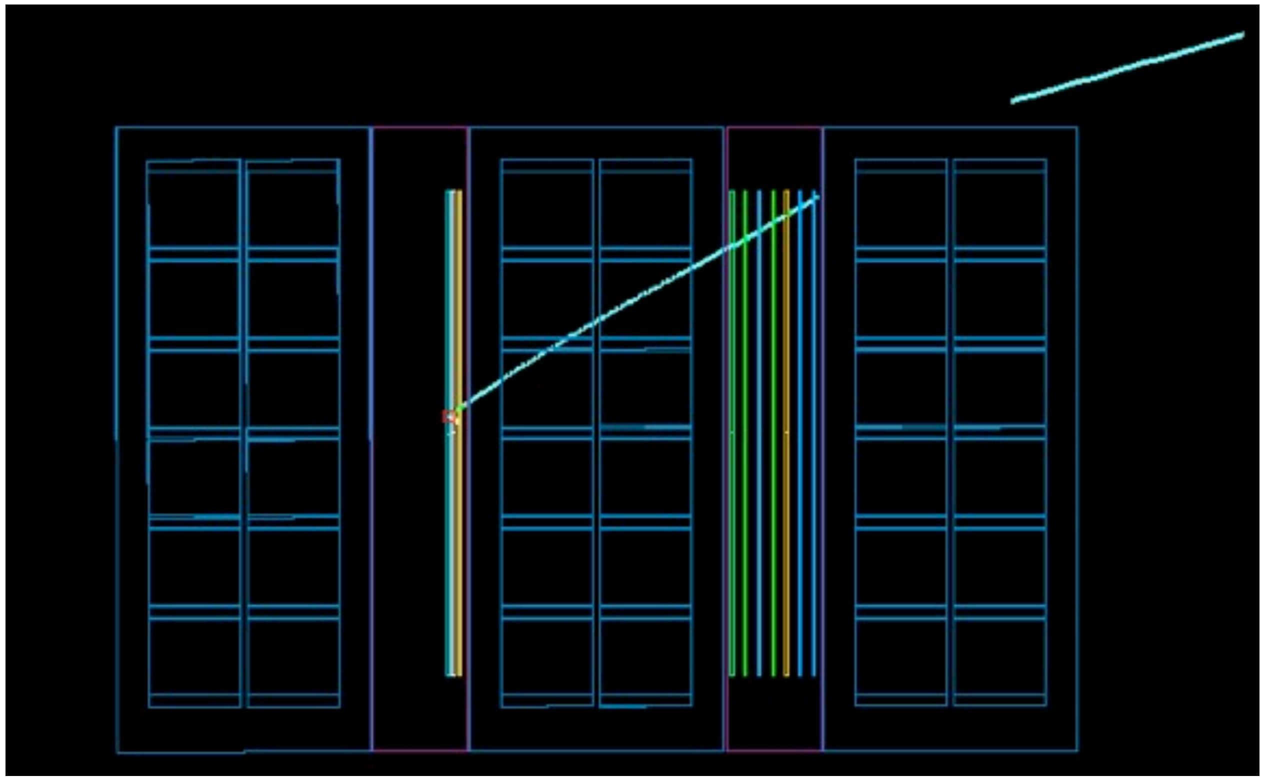
Off-axis near detectors



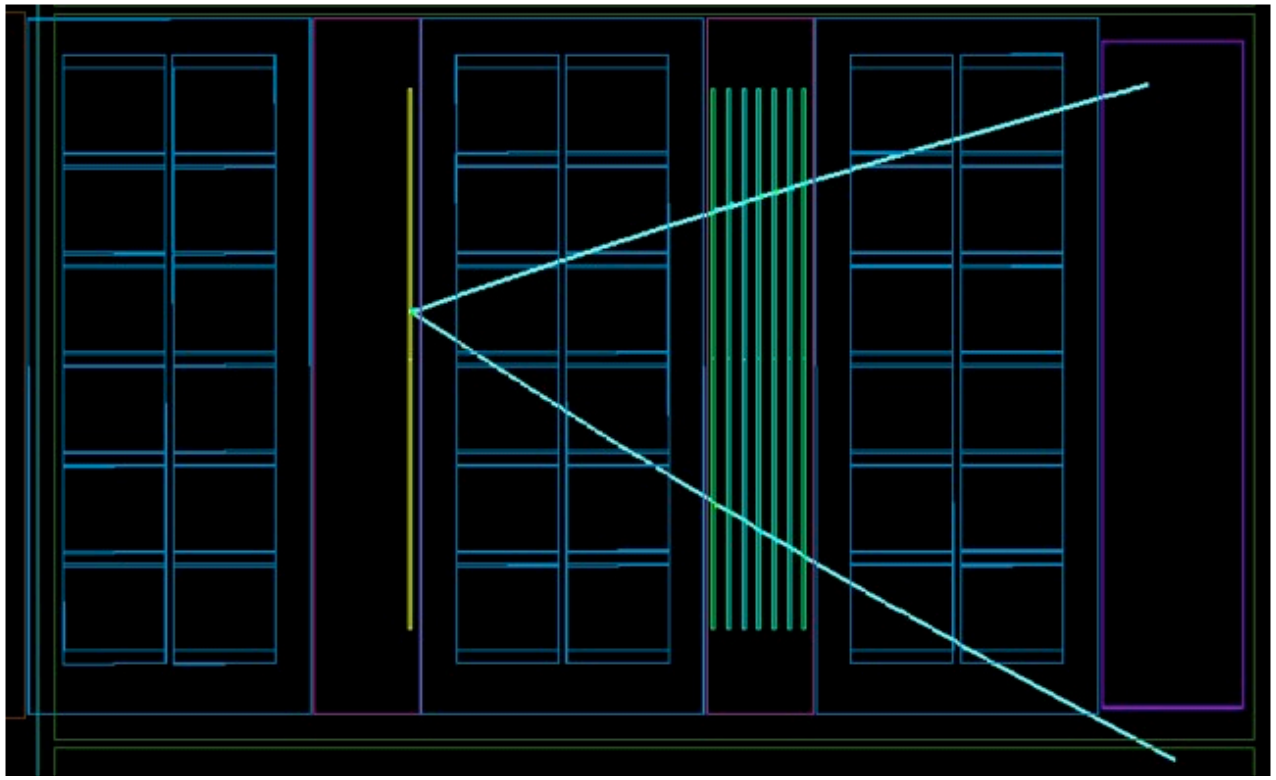
- A π^0 detector consists of alternating layers of water (target), brass (radiator) and scintillator (detector).
- 2 fine-grained detectors provide a target (carbon and water) for neutrino interactions.
- 3 time projection chambers measure momentum and charge of passing particles. They also aid in particle ID through energy deposits of charged particles (dE/dx).
- Electromagnetic calorimeters measure energies of electrons, photons and pions.
- Gaps in the return yoke of the magnet are instrumented with layers of scintillator to act as a muon range detector.

Off-axis near detectors

Charged-current quasi-elastic event in ND280 showing muon track

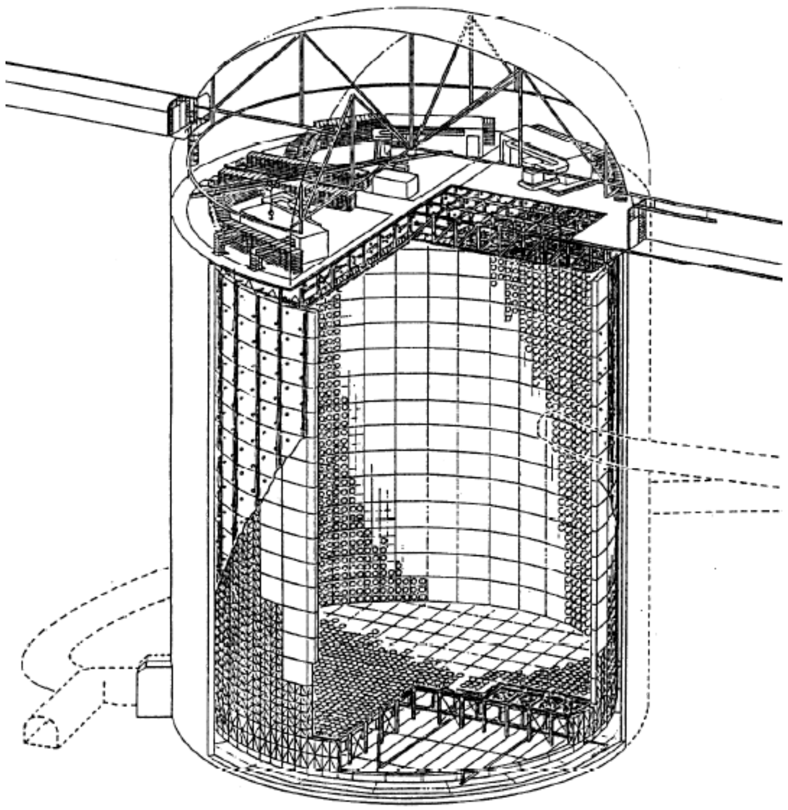


Charged-current single π event in ND280 showing muon and pion tracks

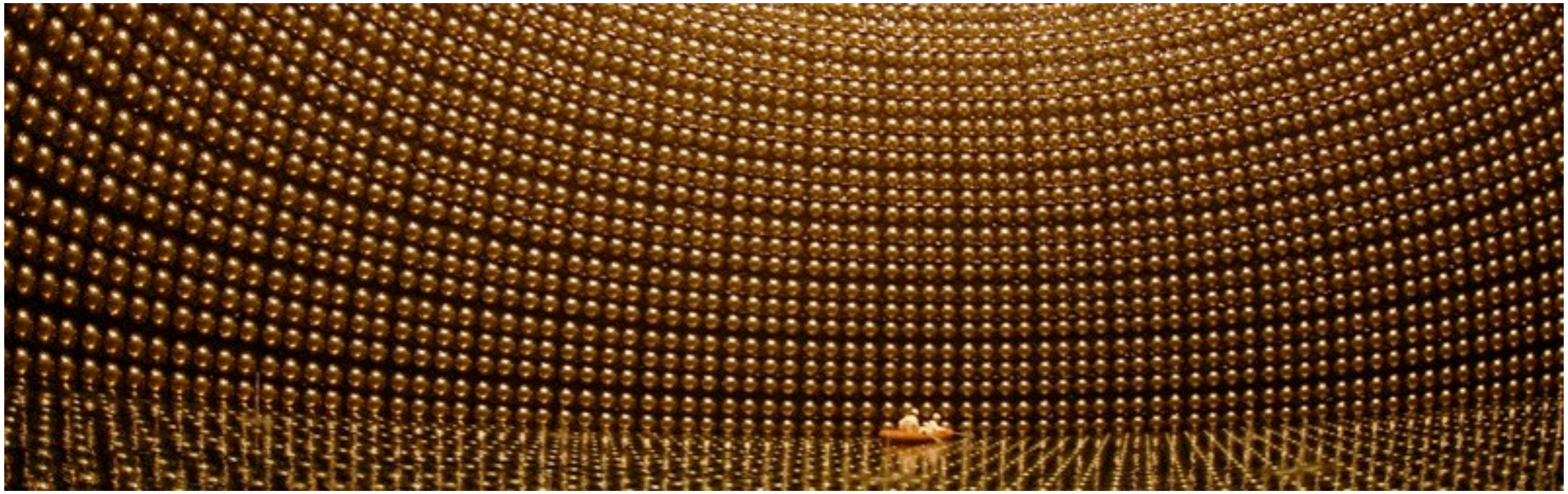


The off-axis near detectors are installed within the UA1 magnet operating at 0.2 T. They measure the ν_μ and ν_e reconstructed energy spectra before oscillations have occurred. Studies are ongoing to measure cross sections of various neutrino interactions including background processes for the oscillation analyses.

Super Kamiokande (far detector)



Super Kamiokande is a water Cerenkov detector located 1000 metres underground. It consists of a large cylindrical tank of ultra-pure water with height 36.2 metres and diameter 33.8 metres (inner detector). The walls of the tank are lined with 11,129 photodetectors of diameter 50 cm.



T2K oscillation analyses

T2K oscillation analyses

Using the ND280, a measurement of the ν_μ content of the neutrino beam is made before any oscillations have occurred. This measurement is used to predict the number of ν_μ that would be seen in Super K if there were no oscillations. The number of ν_μ that is actually seen in Super K is less than this prediction, and this is known as "ν_μ disappearance".

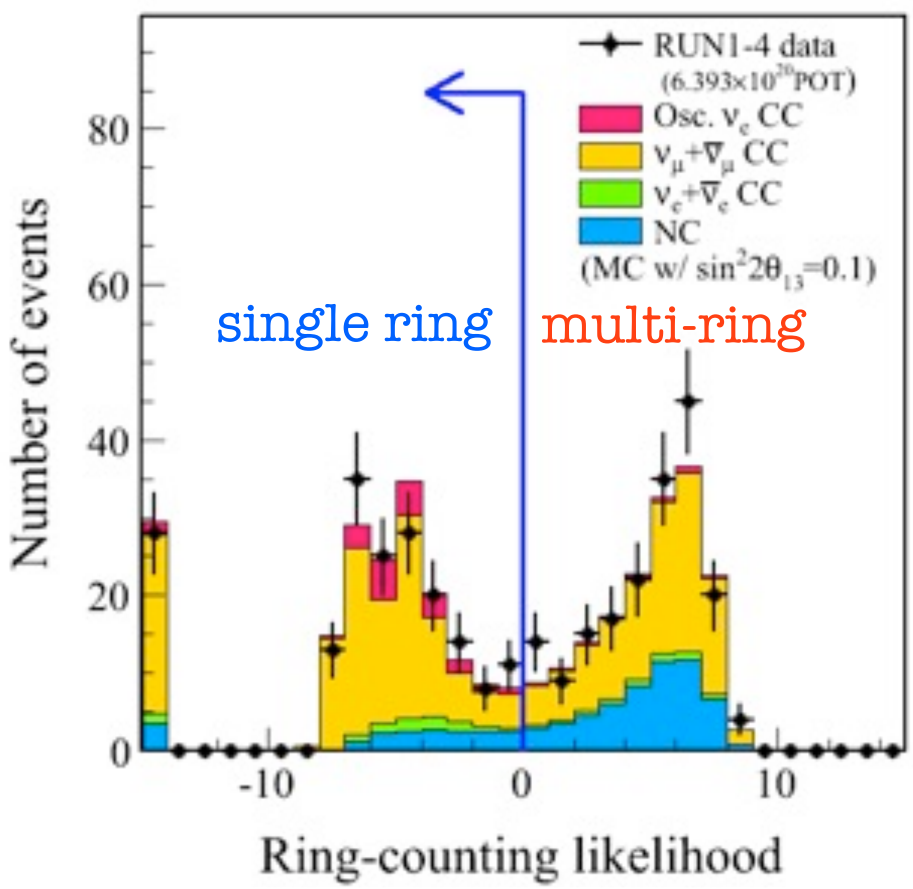
T2K carried out 2 ν_μ-disappearance analyses (2012, Run 1-3):

1. Binned likelihood ratio with events in reconstructed neutrino energy bins
2. Unbinned maximum likelihood using reconstructed neutrino energy

T2K searches for $\nu_\mu \rightarrow \nu_e$ oscillations by seeking ν_e candidates in Super K. This is known as "ν_e appearance". Two ν_e-appearance analyses were made (2013, Run 1-4):

1. Unbinned maximum likelihood using reconstructed muon momentum and angle
2. Unbinned maximum likelihood using reconstructed neutrino energy

Event selection in far detector (Super Kamiokande)



The initial selections are common to both the ν_μ-disappearance and ν_e-appearance analyses:

1. Timing: use PMT hits between -2 and +10 μsec relative to start of beam spill.

2. Reject events with >=16 hits in outer detector as outer detector events.

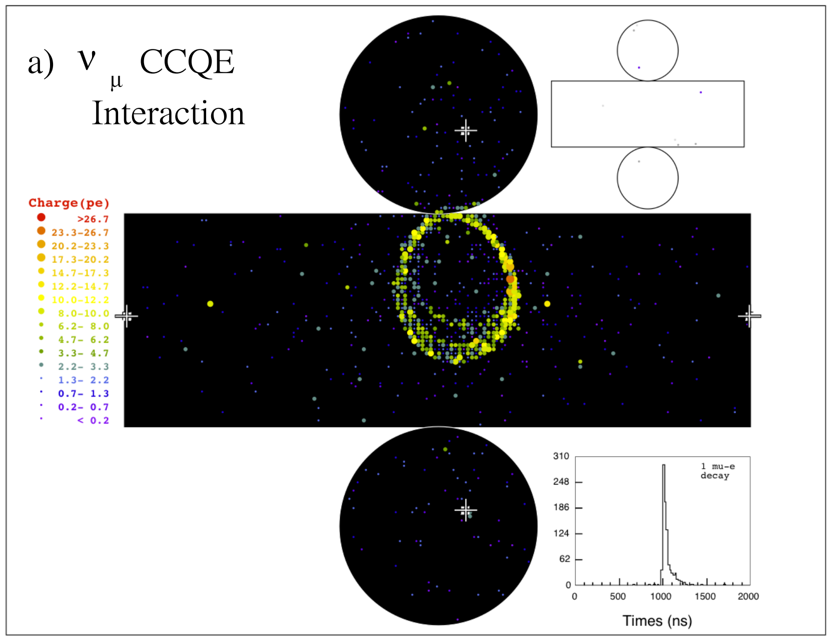
3. Reconstructed vertex in fiducial volume, i.e. > 2 metres from wall of inner detector.

4. Exactly one Cerenkov ring.

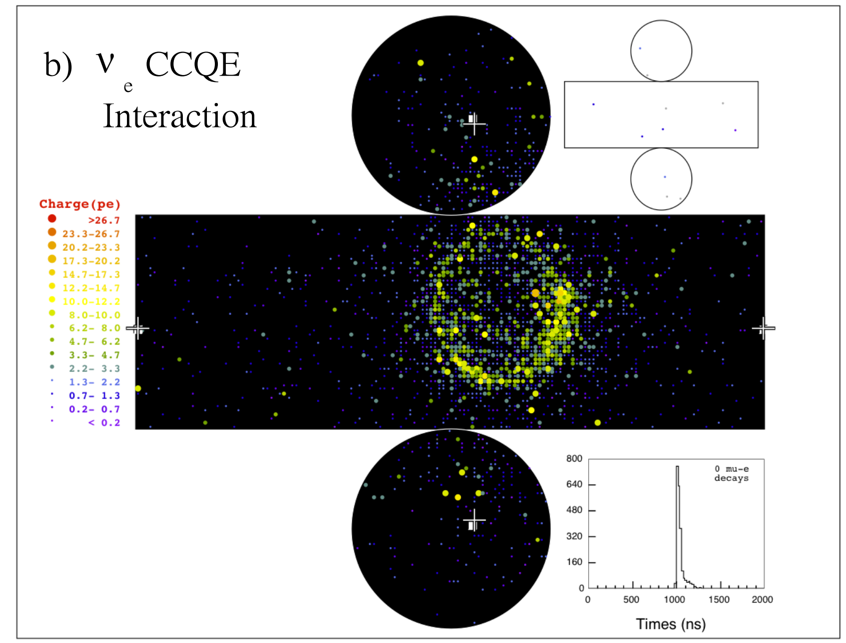
5. The particle ID then divides these events into single μ-like ring and single e-like ring events.

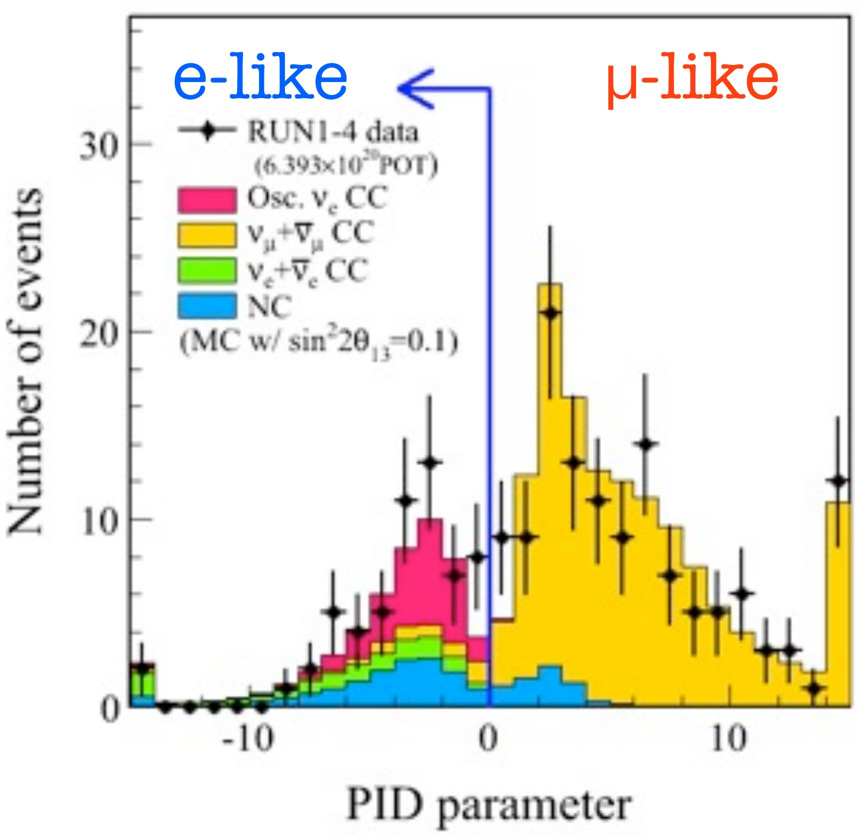
Distinguishing μ-like from e-like rings in Super K

μ-like ring



e-like ring





An electron produces an electromagnetic shower which gives a fuzzy ring. A muon produces a sharper ring. Very good discrimination between muons and electrons: probability of a muon being misidentified as an electron is ≈1%. However Super K cannot distinguish between electrons and photons, which both produce an “electron-like” ring.

Event selection in far detector (Super Kamiokande)

Additional selection criteria for single μ-like ring events are:

6. < 2 Michel electrons (from μ decay)

7. Reconstructed muon momentum > 200 MeV

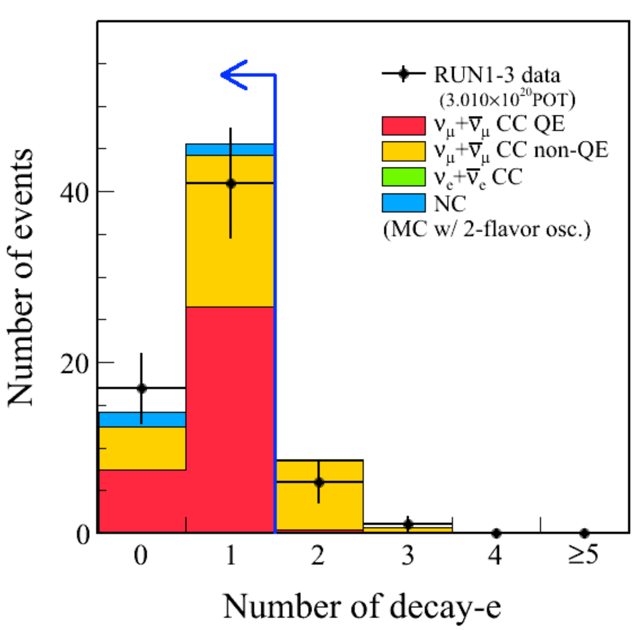
Additional selection criteria for single e-like ring events are:

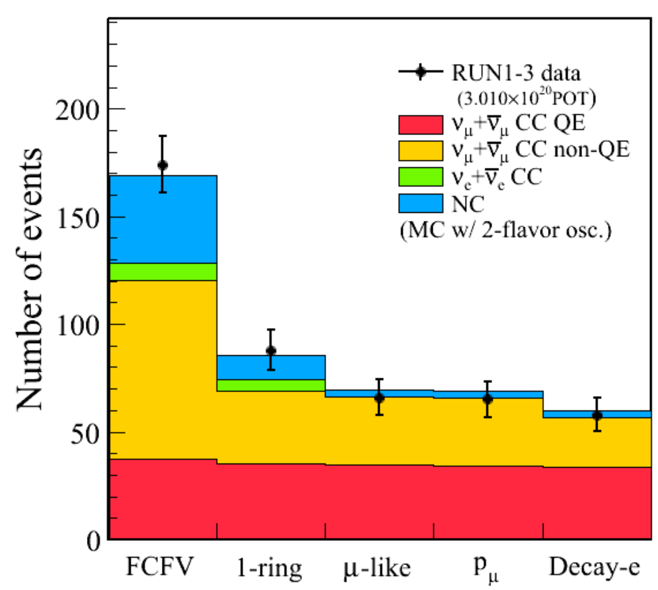
6. Visible energy > 100 MeV

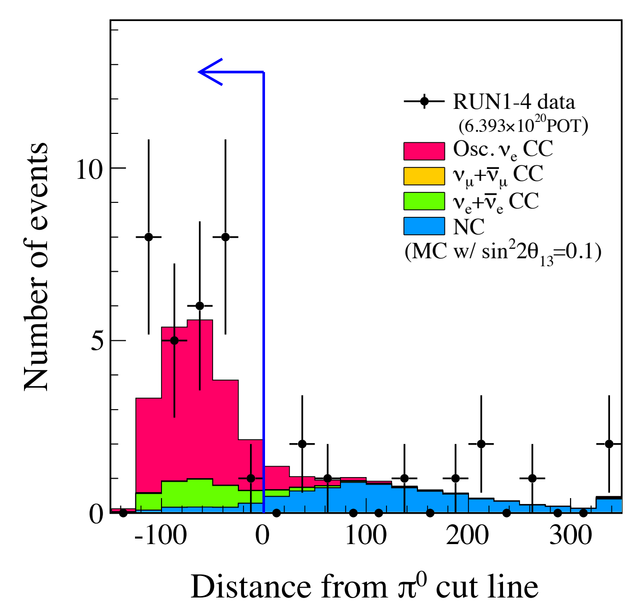
7. No Michel electrons (from μ decay)

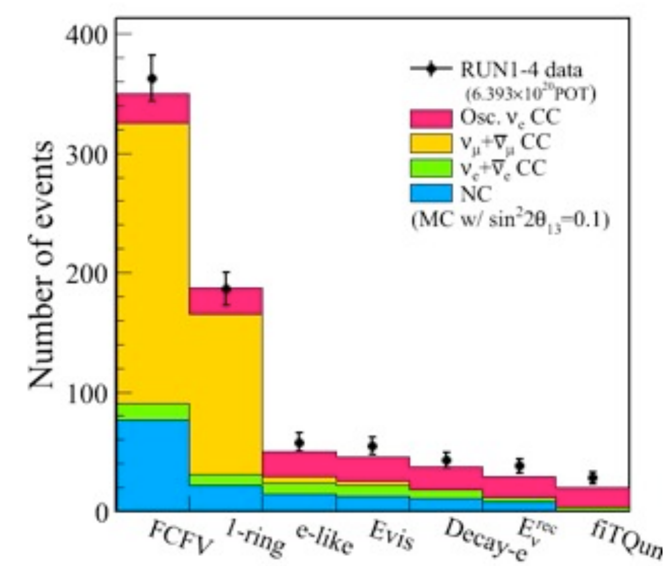
8. π^0 rejection

9. Reconstructed ν_e energy < 1.25 GeV









Backgrounds to ν_μ disappearance and ν_e appearance

ν_μ disappearance

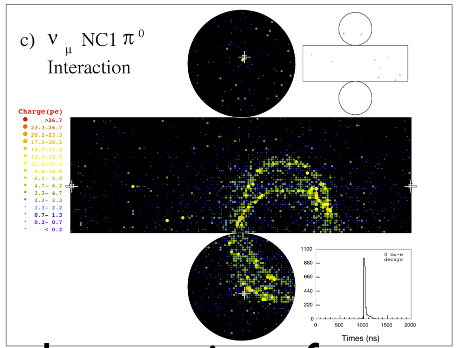
Principal background is CC π+ production.

This is a problem because sometimes (10-20% of the time) the π+ is absorbed in a final-state interaction. If this happens, the CC π+ initial state appears to be a CCQE interaction. This leads to misreconstruction of the neutrino energy.

The problem here is not that we count oscillations when they do not occur, but that we count them at the wrong energy.

ν_e appearance

1. The 1% ν_e component of the neutrino beam: mainly from muon decays, and also some from kaon decays.



2 photon rings from π^0

2. NC π^0 production: π^0 decays to 2 photons. This can mimic a ν_e if two photon rings in Super K overlap or if one is below Cerenkov threshold.

3. Photonuclear interactions: the absorption of a photon by a nucleus. Again a π^0 gives one e-like ring, and appears to be an electron.

Measurement of oscillation parameters

The neutrino oscillation parameters are measured by comparing the predicted reconstructed energy/momentum-angle spectrum in Super K with the observed spectrum. The oscillation parameters are varied in the input to the calculation of the predicted spectrum until the best agreement is obtained with the observed spectrum.

In the binned likelihood ratio ν_μ-disappearance analysis, this is done by minimising

$$2\sum_{E_r}\left[N_{\mathrm{SK}}^{\mathrm{data}}\ln\left(\frac{N_{\mathrm{SK}}^{\mathrm{data}}}{N_{\mathrm{SK}}^{\mathrm{exp}}}\right)+(N_{\mathrm{SK}}^{\mathrm{exp}}-N_{\mathrm{SK}}^{\mathrm{data}})\right] + (\mathbf{a}-\mathbf{a_0})^T\cdot\mathbf{C}^{-1}\cdot(\mathbf{a}-\mathbf{a_0})$$

The sum is over bins of reconstructed energy. $\mathbf{a}$ is a vector of systematic parameters whose nominal values are $\mathbf{a_0}$ and C is the covariance matrix.

The unbinned analyses are done in a similar way except that the multinomial distribution is replaced by a continuous probability density function representing the energy spectrum/momentum-angle distribution of the predicted events.

Systematic uncertainties in predicted single μ-like and single e-like reconstructed energy spectra in Super K

Systematic uncertainties

The predicted number of ν_μ events in Super K is the product of

neutrino flux x interaction cross section x detector efficiency x survival probability,

while the predicted number of ν_e events in Super K is

neutrino flux x interaction cross section x detector efficiency x oscillation probability.

We want to measure the oscillation parameters. But if we use incorrect values for the flux, cross section or efficiency in the calculation of the predicted number of events, we will get incorrect values for the oscillation parameters.

Hence the systematic uncertainties in the oscillation parameters are in the flux, cross sections and detector efficiencies.

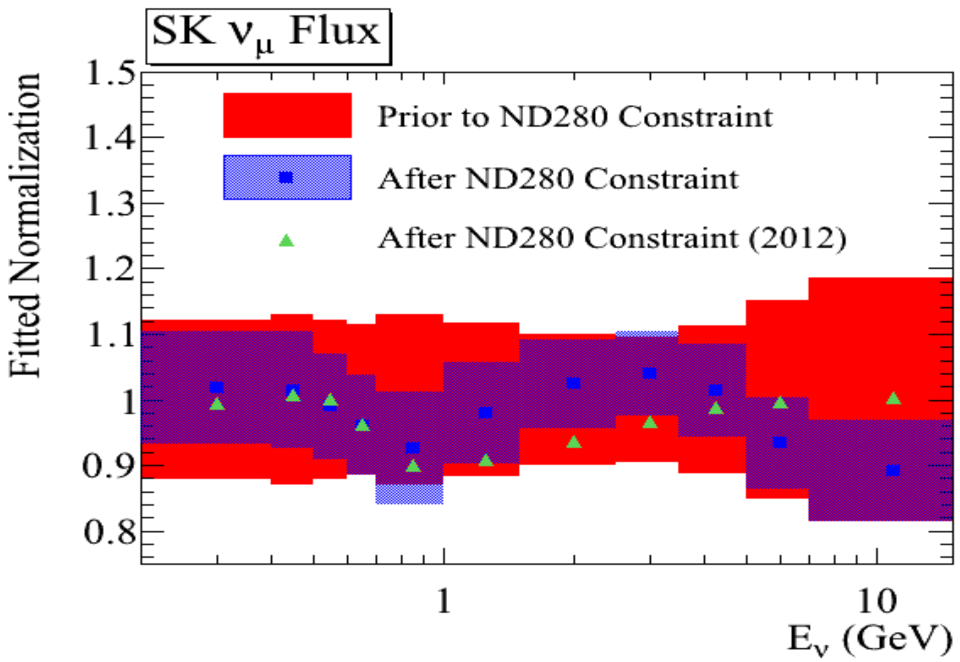
Constraining neutrino flux

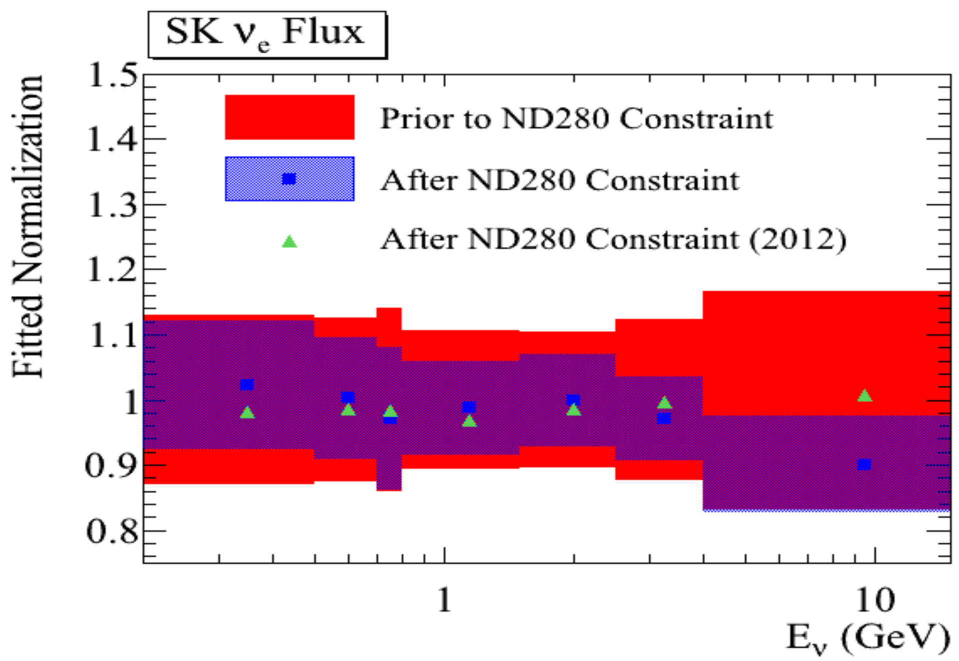
Make initial simulation of neutrino flux based on information from monitors of intensity, position and profile of proton beam (FLUKA).

Reweight this initial simulation so that charged pion and kaon production multiplicities agree with the NA61 measurements of hadron production on a replica T2K carbon target.

This leads to a prediction of the flux for each neutrino species: ν_μ, $\nu_\mu$bar, ν_e and $\nu_e$bar These are turned into event rate normalisation parameters in bins of true energy. For ν_μ disappearance, there are 11 ν_μ bins and 5 $\nu_\mu$bar bins, while for νe appearance there are 11 ν_μ bins, 2 $\nu_\mu$bar bins, 7 ν_e bins and 2 $\nu_e$bar bins.

Fit of flux and cross-section parameters to ND280 data





Uncertainties in neutrino flux parameters are reduced as a result of the ND280 fit.

These flux parameters are combined with 7 cross section parameters that are expected to have some cancellation between the near and far detectors.

We constrain these parameters by allowing them to float in a fit of the ND280 data. We used 2 ND280 data samples in 2012 (ν_μ disappearance results in this talk) and 3 samples in 2013 (ν_e appearance results in this talk).

This has the effect of tuning the flux and "cancelling" cross-section parameters to the ND280 data and reducing the uncertainties in them. It also gives the correlations between these parameters and the "cancelling" cross-section parameters. The Super K Monte Carlo is then reweighted a second time using the the best-fit values of the fitted parameters.

Uncorrelated cross-section parameters

There are also 11 uncorrelated cross-section systematic parameters.

These are not expected to have any cancellation between the near and far detectors since they have different target materials: carbon in the ND280 and oxygen in Super K. For example, the binding energy is different between the two materials.

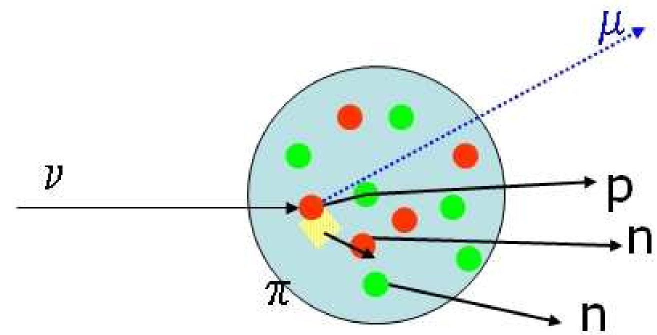
Their effects on the oscillation analysis are evaluated by reweighting the Super K Monte Carlo.

Super K detector uncertainties

Uncertainty in Super K energy scale is estimated as difference in energy loss between data and Monte Carlo for stopping muons and their associated decay electrons from a sample of stopping cosmic-ray muons.

Uncertainties in Super K reconstruction efficiencies are also estimated by comparing atmospheric neutrino data and Monte Carlo control samples.

Final-state interactions



When a pion is produced in the primary interaction between a neutrino and nucleon, it can undergo a secondary interaction before exiting the nucleus in which it was formed. This "final-state interaction" (FSI) can be:

1. Quasi-elastic scattering - modifies its energy and momentum.
2. Charge exchange, e.g. $\pi^+ n \rightarrow \pi^0 p$ or $\pi^- p \rightarrow \pi^0 n$
3. Absorption of the pion.
4. Secondary pion production (if pion has sufficient energy).

Estimate uncertainties due to FSI by simultaneously varying parameters controlling probabilities of each type of FSI, rerunning pion scattering simulation, and comparing with external pion-carbon scattering data.

Systematic uncertainties in numbers of events in Super K

Source of uncertainty	Uncertainty in predicted events
Flux/correlated xsec (without ND280 fit)	21.8%
Flux/correlated xsec (with ND280 fit)	4.2%
Uncorrelated xsec	6.3%
Super K detector	10.1%
FSI + SI	3.5%
Total (without ND280 fit)	25.1%
Total (with ND280 fit)	13.1%

Uncertainties in predicted numbers of single μ-like ring events at Super K

Source of uncertainty	Uncertainty in predicted events ($\sin^2(2\theta_{13}) = 0$)	Uncertainty in predicted events ($\sin^2(2\theta_{13}) = 0.1$)
Flux/correlated xsec (with ND280 fit)	4.9%	3.0%
Uncorrelated xsec	6.7%	7.5%
Super K detector + FSI + SI + PN	7.3%	3.5%
Total (with ND280 fit)	11.1%	8.8%

Uncertainties in predicted numbers of single e-like ring events at Super K

Validation of oscillation analyses

Extensive comparisons are made between the different analyses. The predicted numbers of events and predicted reconstructed spectra are compared for

1. Nominal

2. ±1σ and ±3σ systematic variations of every systematic parameter

3. With and without oscillations

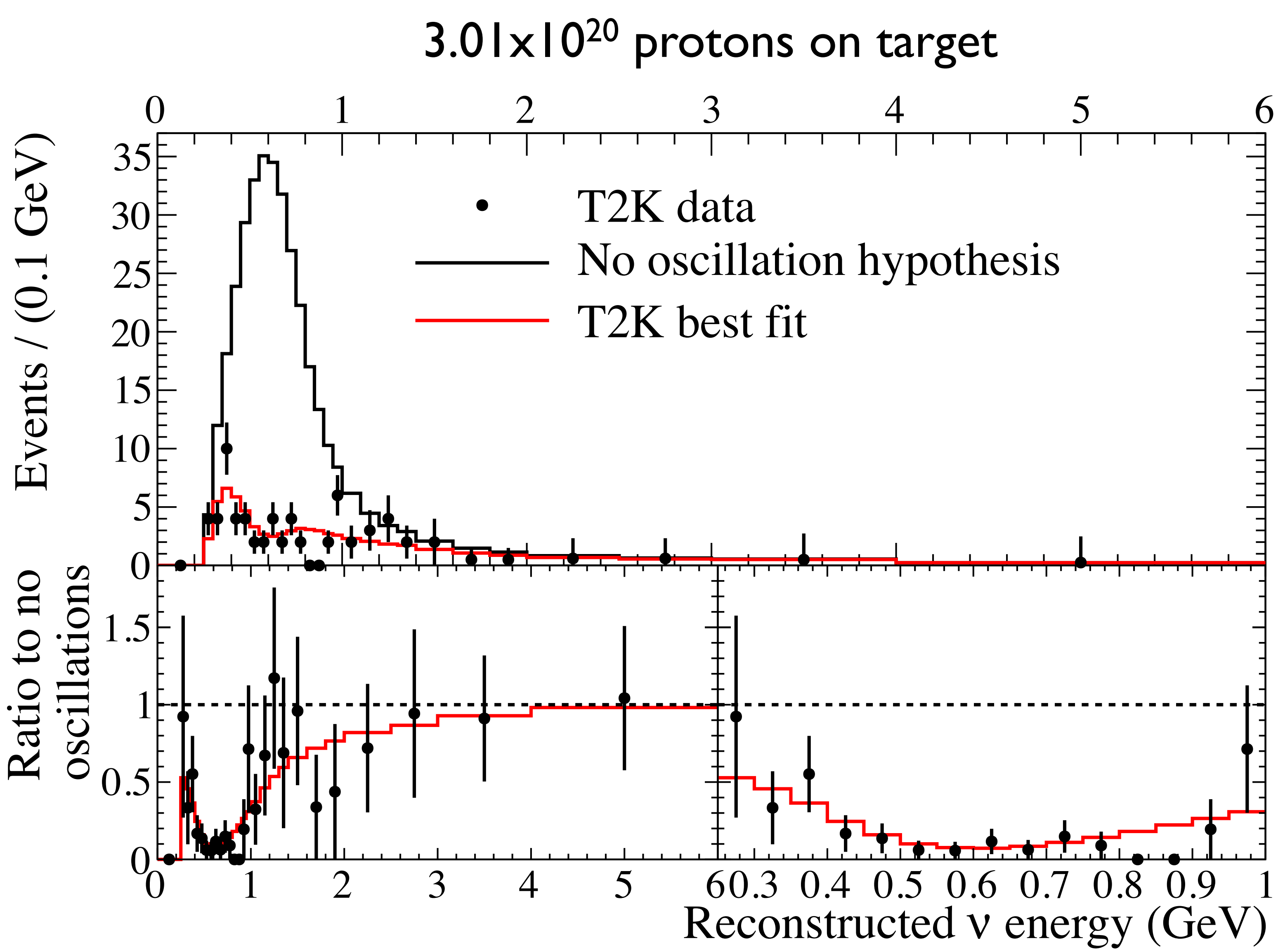
To test the fitters, fit bias studies are made. Also fake datasets are made for which the input oscillation parameters are unknown to the analysers. Each analysis fits these fake datasets, and the results are compared between the analyses.

Results of T2K oscillation analyses

Single μ-like ring Super K data and best-fit spectrum

We predict 205±17 (syst) single μ-like ring events in the absence of oscillations, but observe only 58.

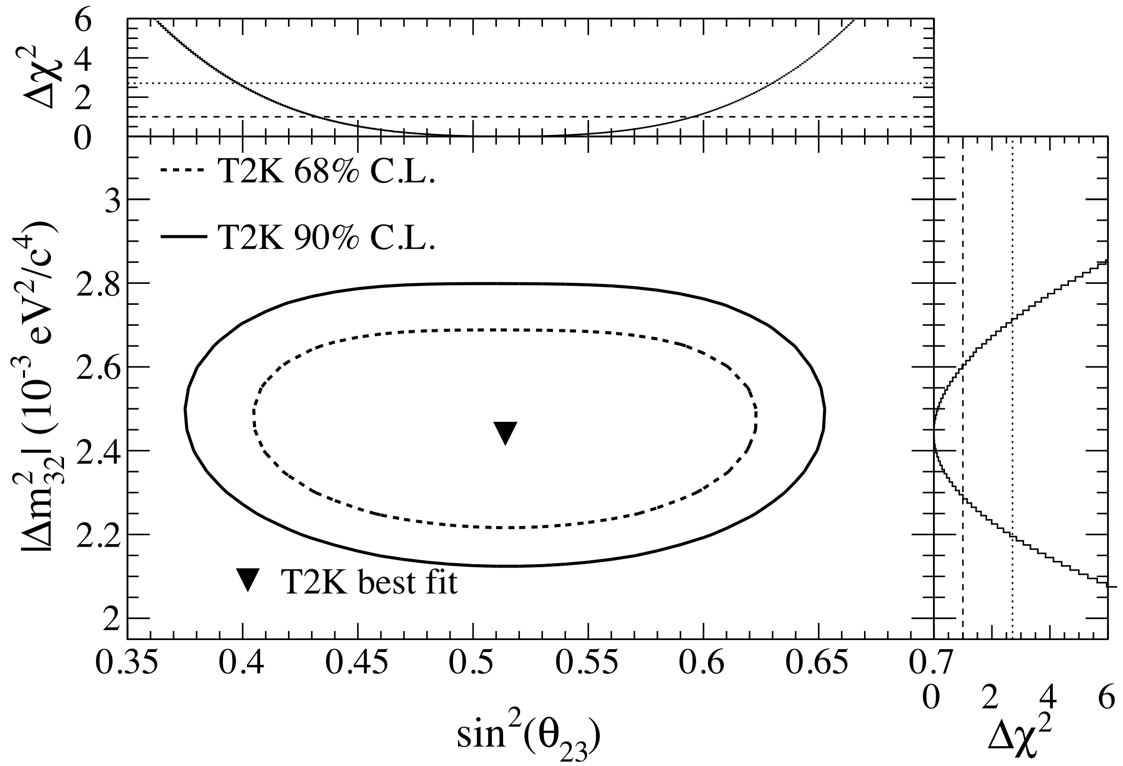
Best-fit parameter values are $\sin^2\theta_{23}$ = 0.514, $|\Delta m_{32}^2|$ = 2.44x10^{-3}eV^2/c^4.



Run 1-3 single μ-like ring dataset (3.01x10^{20} protons on target), best-fit reconstructed energy spectrum and expected spectrum for no oscillations

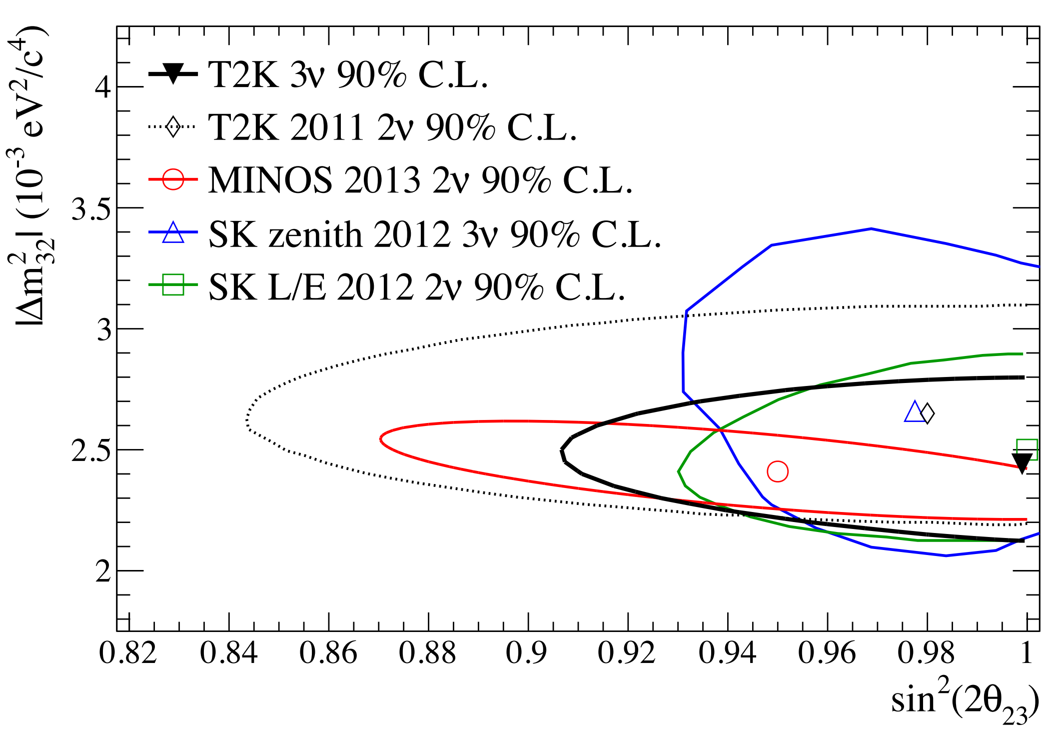
Ratios of Run 1-3 data and best-fit spectrum to expected spectrum for no oscillations

90% confidence contours in $\sin^2\theta_{23}/\sin^2(2\theta_{23})$ and $|\Delta m_{32}^2|$



$P(\nu_\mu \rightarrow \nu_\mu) \approx$
$1 - \sin^2(2\theta_{23}) \sin^2(1.267\ \Delta m_{32}^2\ L / E)$

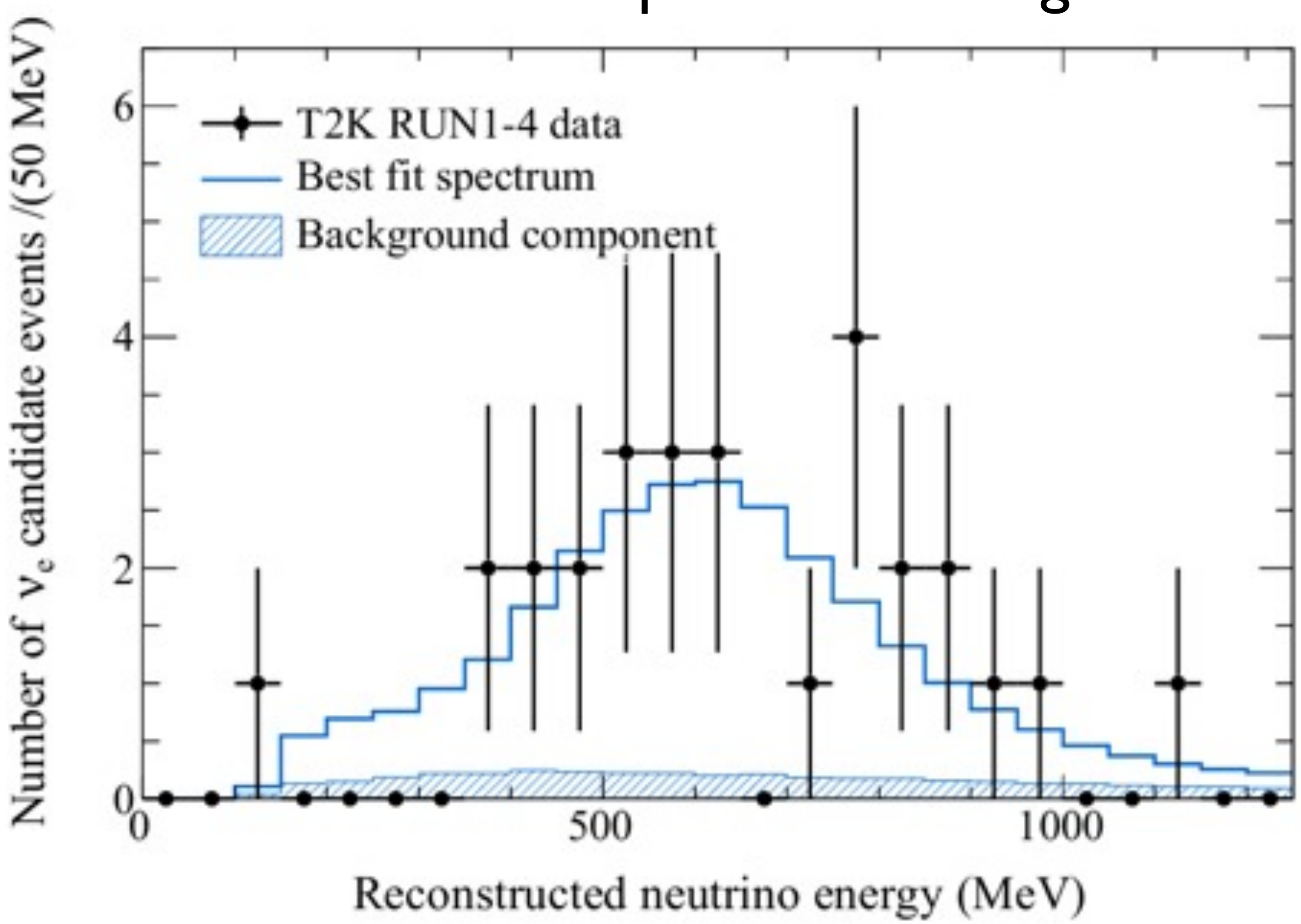
2D 90% confidence contours in $\sin^2\theta_{23}$ and $|\Delta m_{32}^2|$.



2D 90% confidence contours in $\sin^2(2\theta_{23})$ and $|\Delta m_{32}^2|$; these are compared with 2-flavour 90% contours from MINOS and the Super K L/E analysis and 3-flavour contours from the Super K zenith angle analysis.

Single e-like ring Super K data and best-fit spectrum

6.57x10^{20} protons on target



Run 1-4 (6.57x10^{20} protons on target) single e-like ring dataset, best-fit reconstructed energy spectrum and background component.

We observe 28 candidate events in Super K when 4.64±0.53 background events are expected.

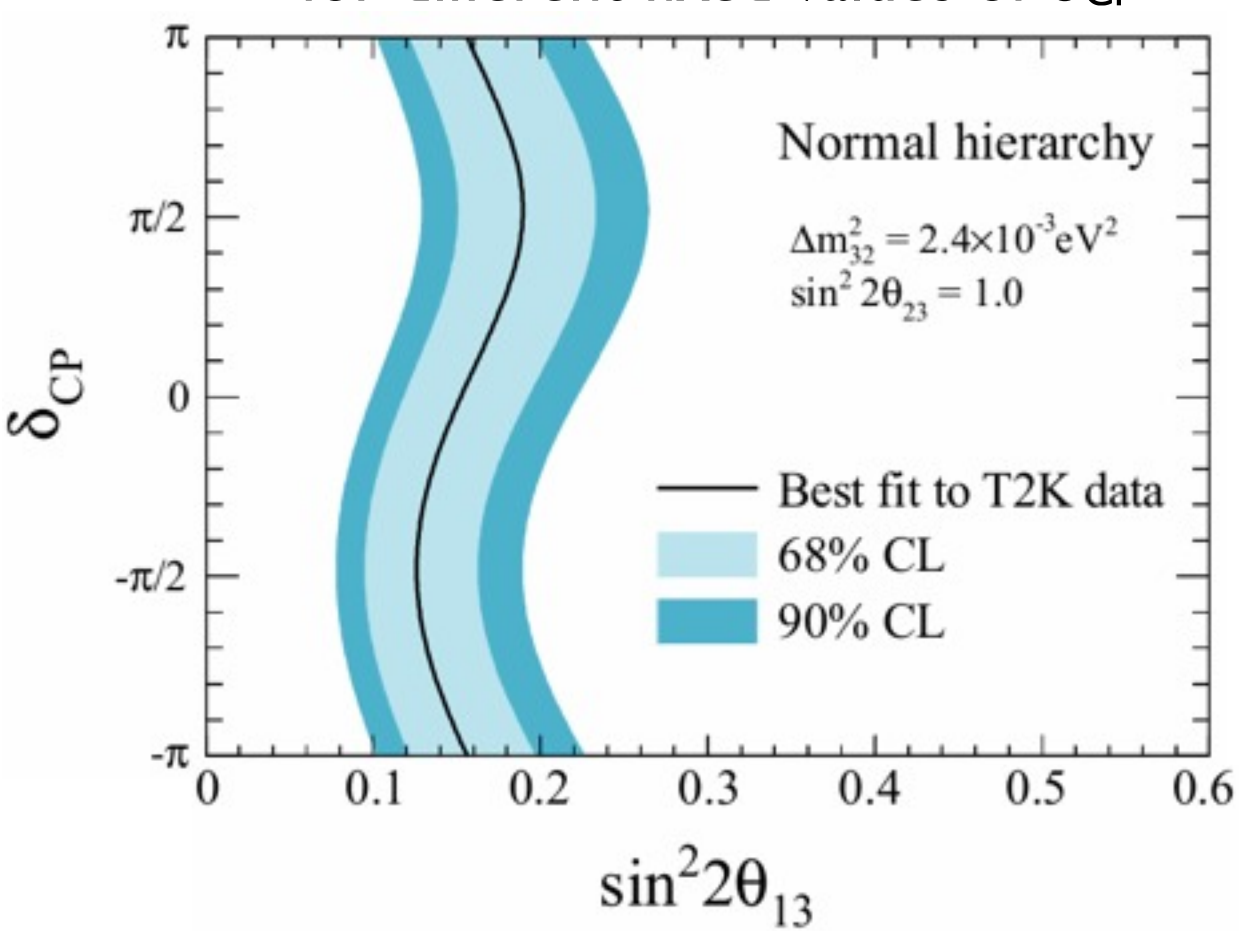
Best-fit values and confidence intervals for $\sin^2(2\theta_{13})$

$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2(2\theta_{13}) \sin^2(1.267\ \Delta m_{31}^2\ L / E)$

Normal hierarchy

Best-fit value of $\sin^2(2\theta_{13})$ is
0.152 +0.041 -0.034 assuming $\delta_{CP} = 0$

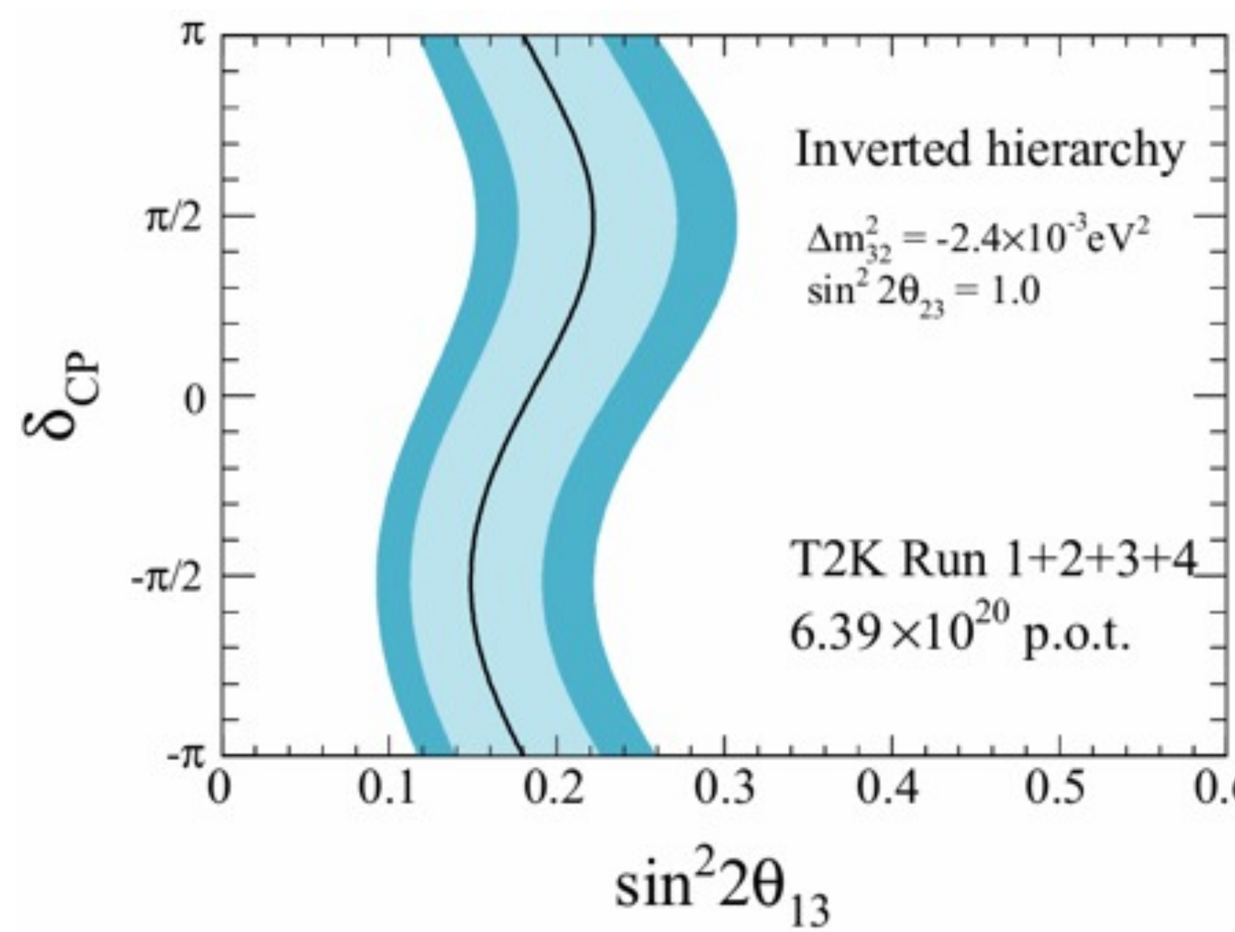
1D confidence intervals for $\sin^2(2\theta_{13})$
for different fixed values of δ_{CP}



Inverted hierarchy

Best-fit value of $\sin^2(2\theta_{13})$ is
0.184 +0.046 -0.041 assuming $\delta_{CP} = 0$

1D confidence intervals for $\sin^2(2\theta_{13})$
for different fixed values of δ_{CP}



p-value for null hypothesis $\sin^2(2\theta_{13}) = 0$

Many simulated experiments were generated assuming a null hypothesis of $\sin^2(2\theta_{13}) = 0$, i.e. no oscillations from ν_μ to ν_e.

The p-value for this null hypothesis is 10^{-13}; this is much lower than the value of 3×10^{-7} which is the standard p-value for claiming a discovery.

T2K has made the first observation of a neutrino of one flavour appearing in a neutrino beam of another flavour !

Searching for CP violation

This also means that it will be possible in the future to search for charge-parity (CP) violation in neutrinos.

A charge (C) transformation changes a neutrino to an antineutrino or vice versa. A parity (P) transformation reverses the directions of the 3 space coordinate axes, and changes a left-handed particle to a right-handed one or vice versa. A CP transformation changes a left-handed neutrino to a right-handed antineutrino or vice versa.

CP violation means that the laws of physics are different for left-handed neutrinos and right-handed antineutrinos, e.g. Prob($\nu_\mu$bar$\rightarrow$ $\nu_e$bar) $\neq$ Prob($\nu_\mu \rightarrow \nu_e$)

If θ_{13} = 0, we cannot search for CP violation since δ_{CP} is always multiplied by sin θ_{13} in the PMNS matrix:

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

But we now know that θ_{13} is non-zero, and will be able to search for CP violation !

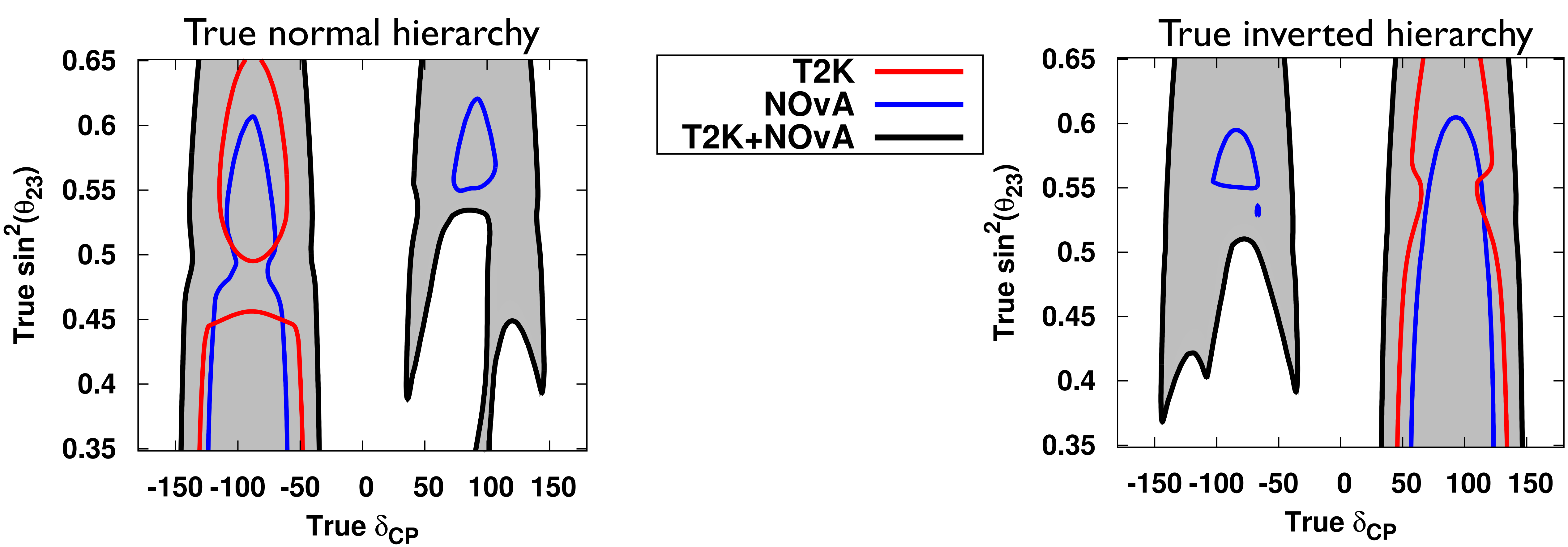
Outlook

T2K will continue to improve the measurements of θ_{23}, Δm_{32}^2 and θ_{13} with ν_μ-disappearance and ν_e-appearance analyses of data taken in neutrino mode.

It will also continue to measure interaction cross sections.

There is a possibility of running in antineutrino mode, and also a possibility of combining results with NOvA to search for a non-zero δ_{CP}.

True values of $\sin^2\theta_{23}$ and δ_{CP} for which a non-zero δ_{CP} can be found at 90% confidence



BACKUP SLIDES

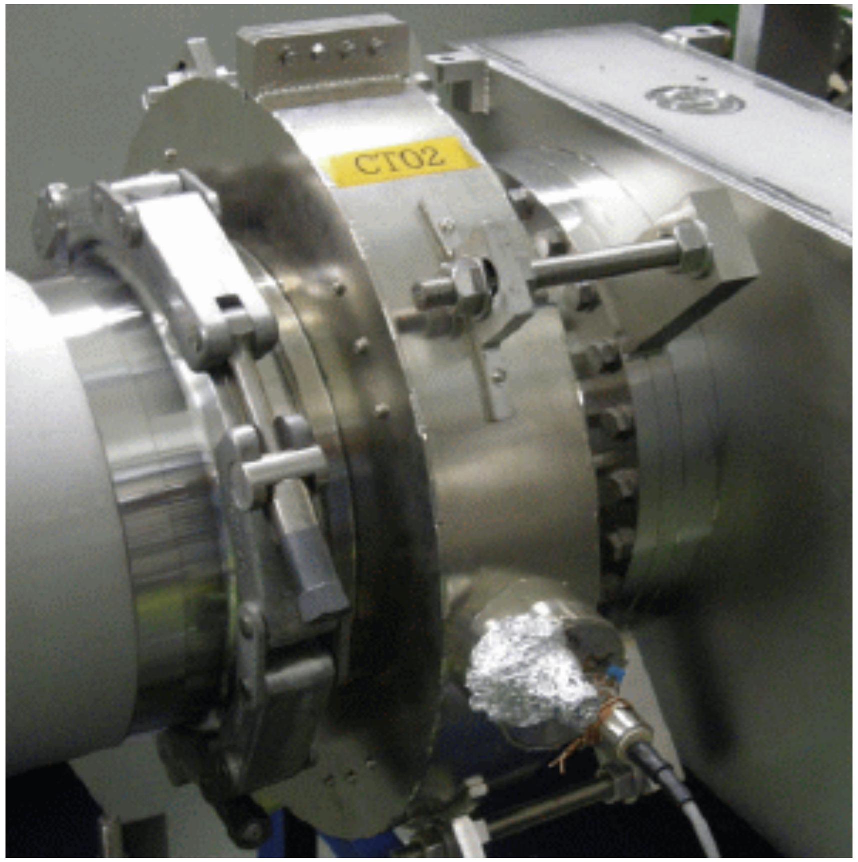
Monte Carlo simulation

The interactions of the primary beam protons with the graphite target are modelled with FLUKA 2008.

Any particles exiting the target are passed into a GEANT3 simulation that tracks particles through the magnetic horns and decay region, and decays hadrons and muons to neutrinos.

The interactions of hadrons in the GEANT3 simulation are modelled with GCALOR.

Measurements of proton beam

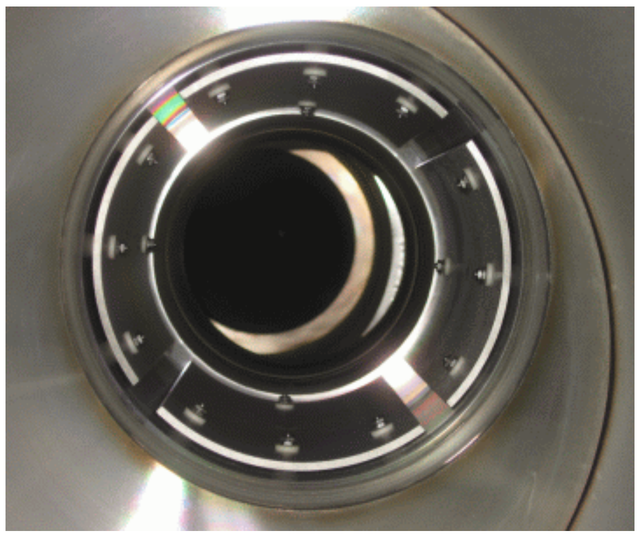


Beam intensity monitor (CT)

The intensity of the proton beam is measured using 5 current transformers (CTs). Each of these is a 50-turn toroidal coil around a cylindrical ferromagnetic core.

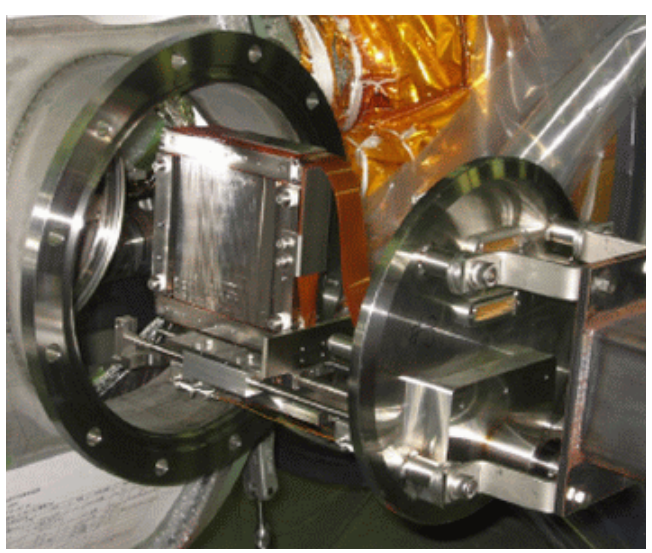
There are also electrostatic monitors (ESM) of the beam position and segmented secondary position monitors (SSEM) of the beam profile.

Measurements of proton beam



Electrostatic monitor (ESM)

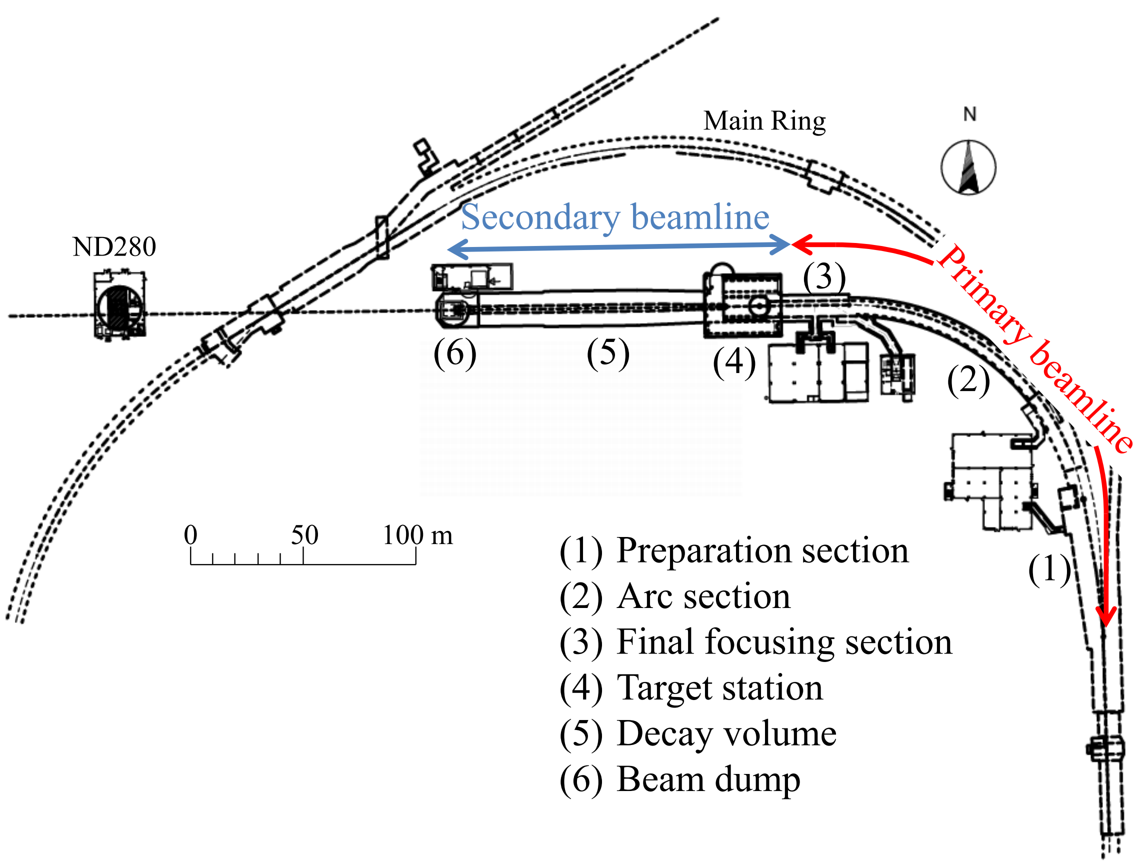
Each ESM has 4 segmented cylindrical electrodes surrounding the beam orbit. It monitors the position of the centre of the beam by measuring the top-bottom and left-right asymmetry of the beam-induced current on the electrodes.



Segmented secondary position monitor (SSEM)

Each SSEM has 2 thin titanium foils in horizontal and vertical strips with an anode HV foil between them. The strips emit secondary electrons in proportion to the number of protons that pass through them. These electrons drift in the electric field and induce a current in the strips. The proton beam profile is reconstructed from the corrected charge distribution on a bunch-by-bunch basis.

The T2K neutrino beam



The J-PARC proton accelerator consists of a linear accelerator (LINAC), a rapid-cycling synchrotron (RCS) and a Main Ring (MR) synchrotron.

8 bunches of protons are extracted from the MR into the primary beamline within a single turn by a set of 5 kicker magnets.

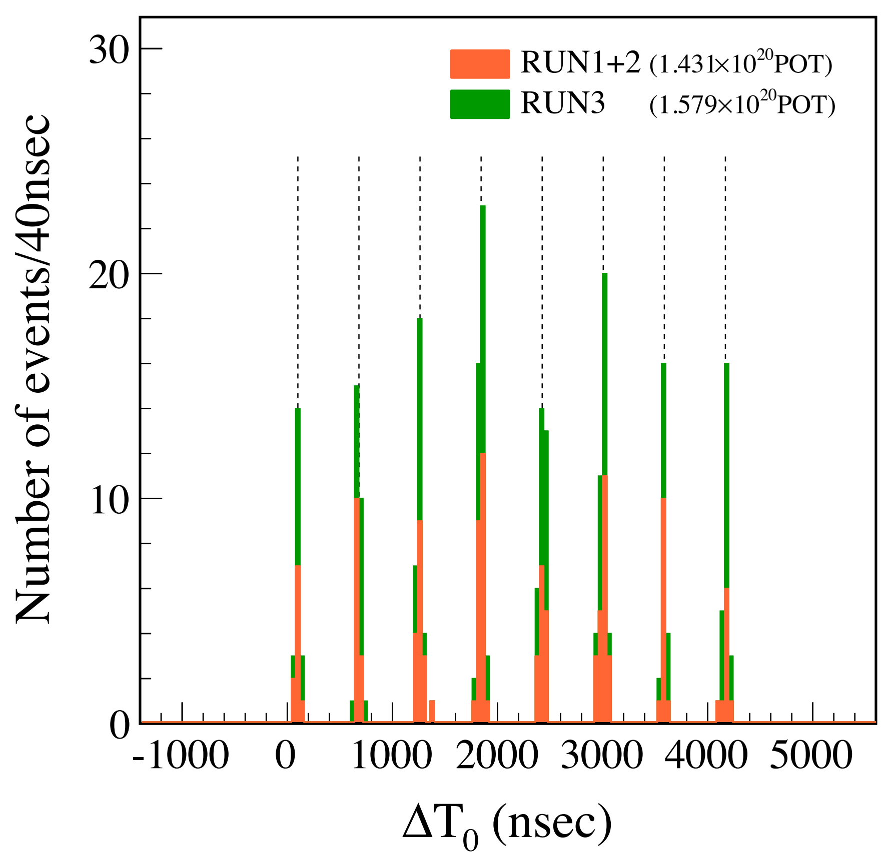
In the secondary beamline, the protons collide with a graphite target to produce charged pions and kaons.

Beam parameters

Design parameters of the J-PARC main ring for fast extraction

Circumference	1567 m
Beam power	~750 kW
Beam kinetic energy	30 GeV
Beam intensity	$\sim 3 \times 10^{14}$ p/spill
Spill cycle	~0.5 Hz
Number of bunches	8/spill
RF frequency	1.67 – 1.72 MHz
Spill width	$\sim 5\ \mu$sec

Trigger



The proton beam is delivered in spills of width 5 μs. Each spill has 8 bunches of protons of width 15 ns, and there are 3.2 sec between spills.

At Super K all PMT hits are recorded in a 1 ms window around the beam arrival time. This arrival time is calculated by adding the neutrino flight time (985 μs) from the target to Super K to the arrival time of the first proton bunch at the target. Timings at Super K are coordinated with those in the beamline using a GPS.

Flux binning

ν_μ: 0.0, 0.4, 0.5, 0.6, 0.7, 1.0, 1.5, 2.5, 3.5, 5.0, 7.0, 30.0 GeV

$\nu_\mu$bar: 0.0, 0.7, 1.0, 1.5, 2.5, 30.0 GeV (ν_μ disappearance)
0.0, 1.5, 30.0 GeV (ν_e appearance)

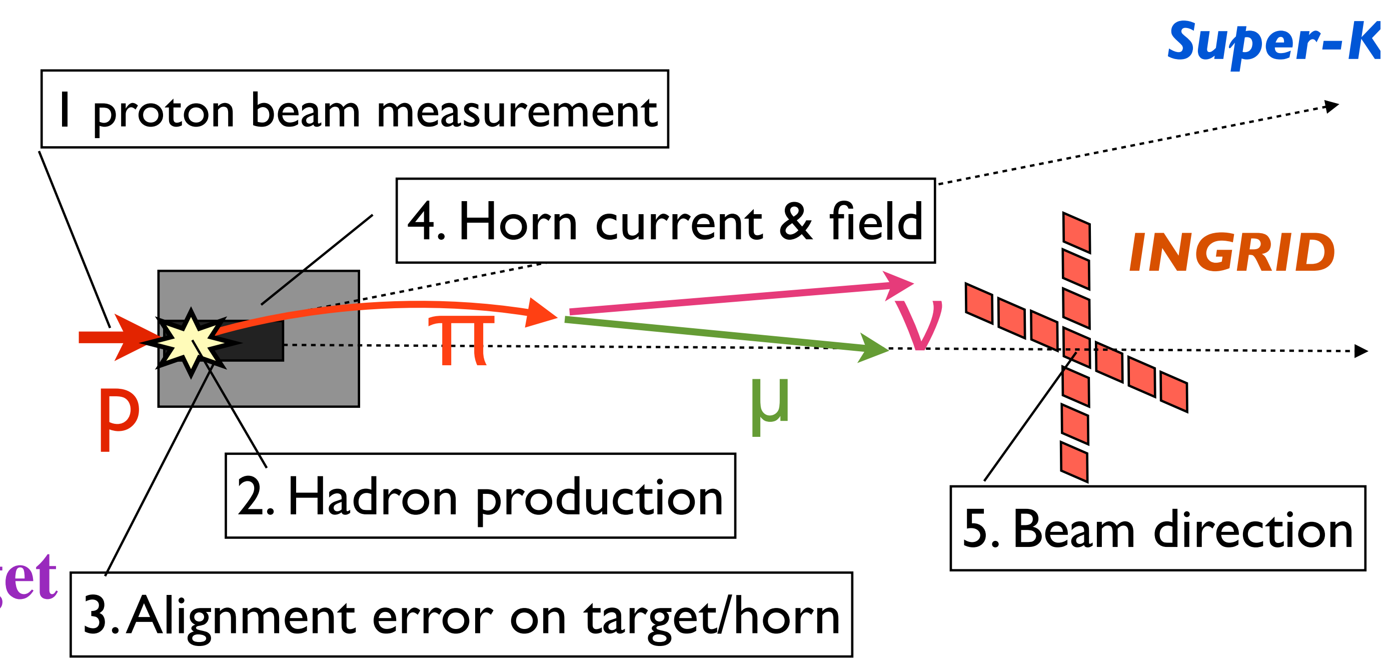
νe: 0.0, 0.5, 0.7, 0.8, 1.5, 2.5, 4.0, 30.0 GeV

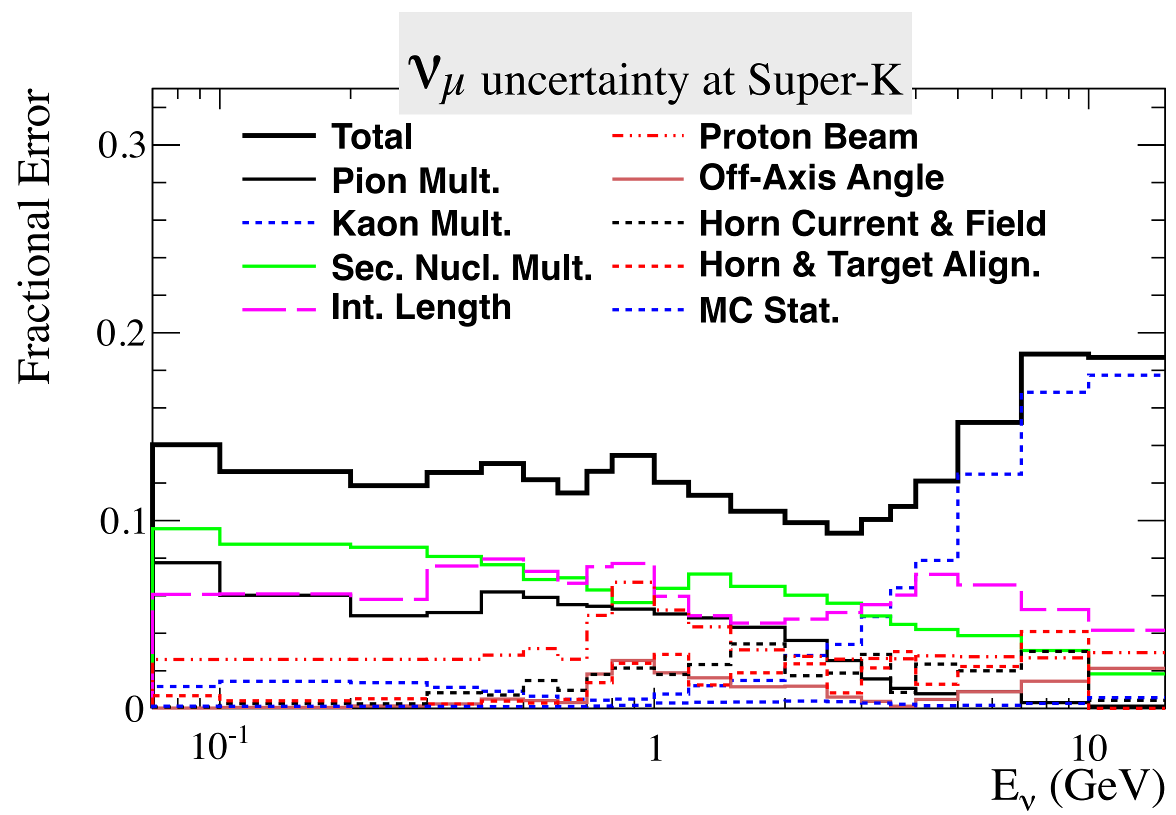
$\nu_e$bar: 0.0, 2.5, 30.0 GeV

where the bins are in true neutrino energy.

Sources of systematic error in fluxes

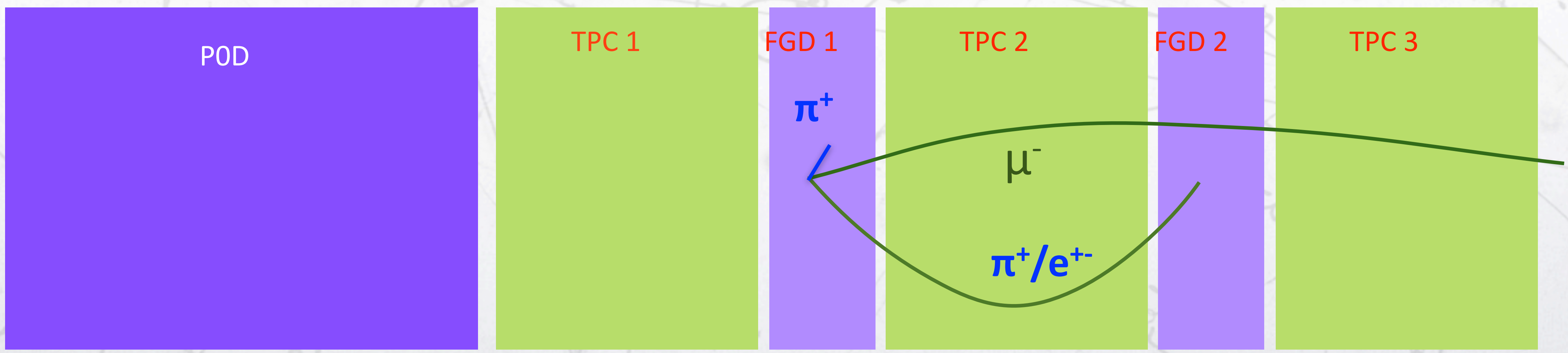
1. **Measurement error on monitoring proton beam**
2. **Hadron production**
3. **Alignment error on the target and the horn**
4. **Horn current & field**
5. **Neutrino beam direction (Off-axis angle)**



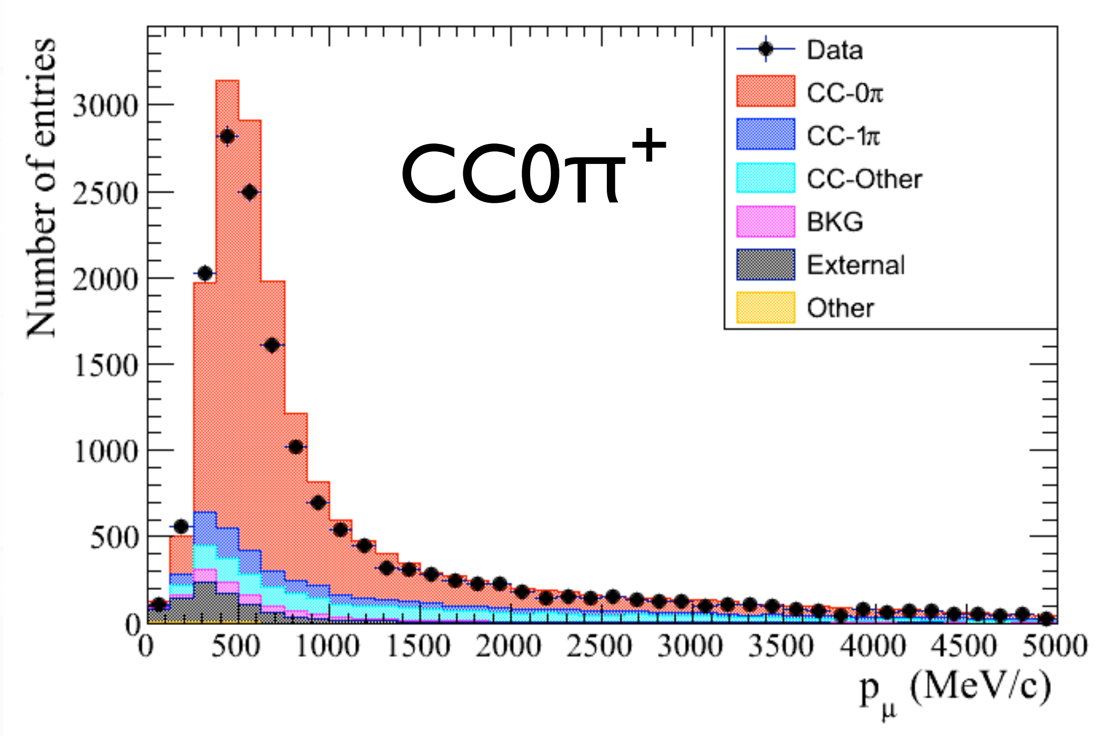


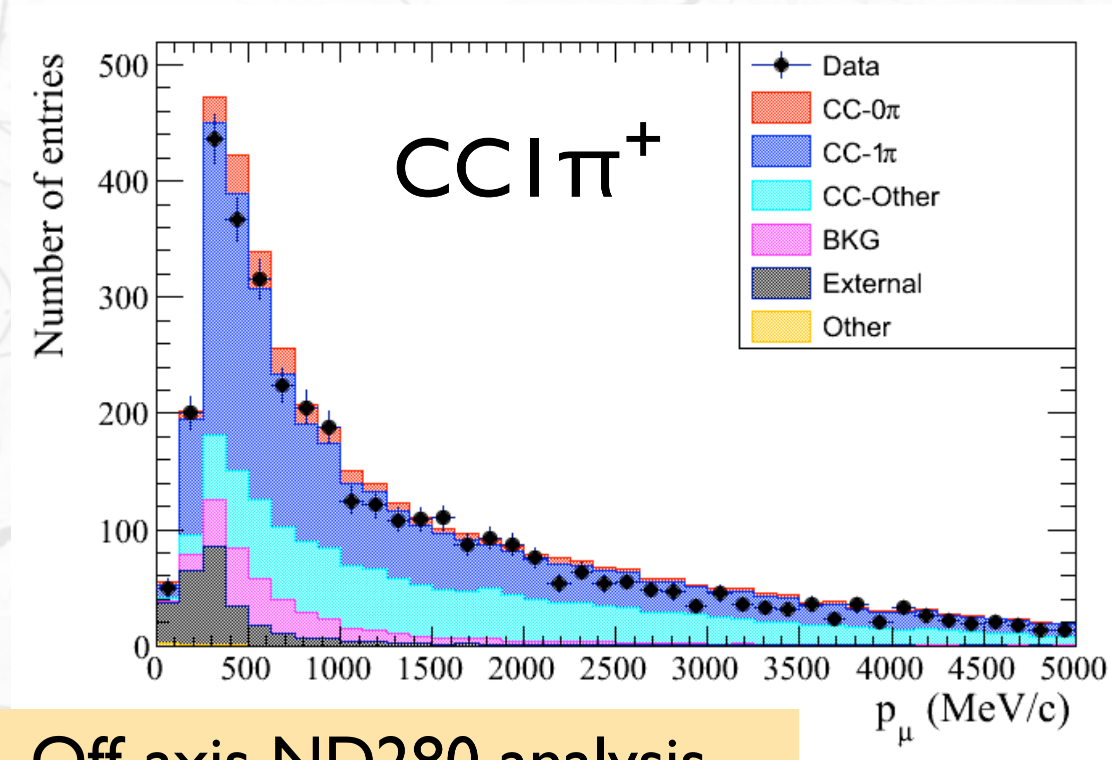
ND280 ν_μ analysis

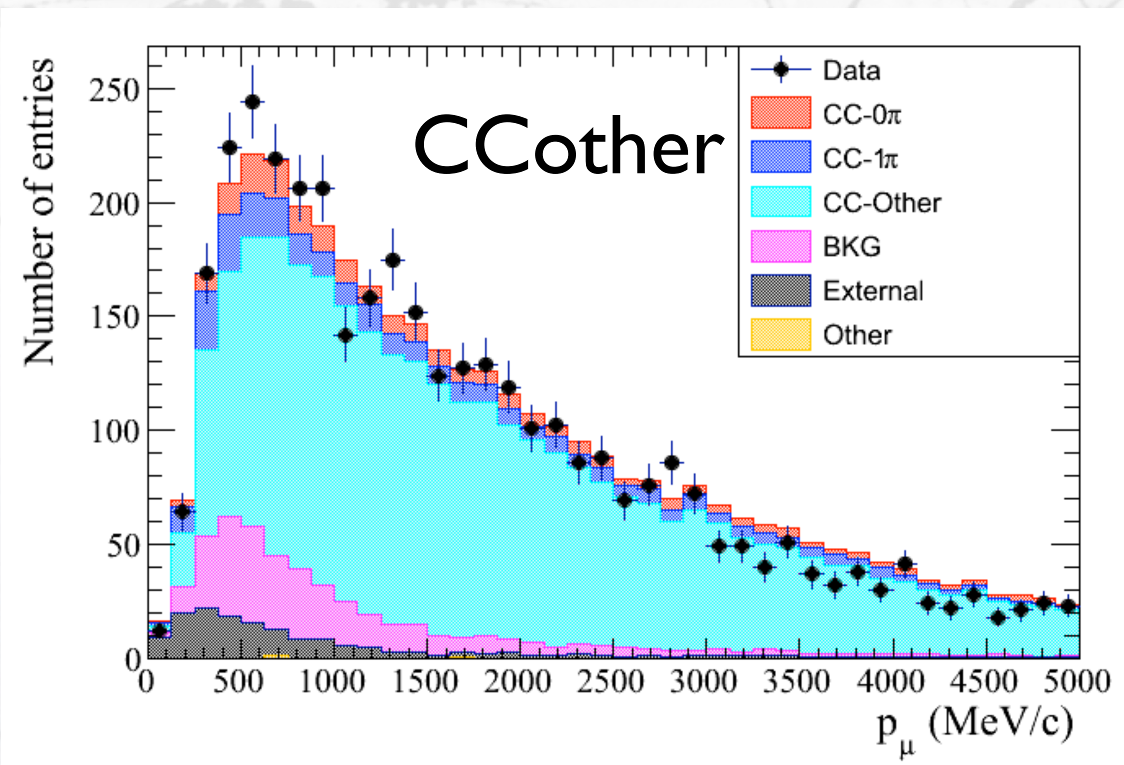
- The ND280 constrains flux and cross-section.
- Sample of CC events is selected. Muon as highest momentum negative track in the event in the target fiducial volume compatible with muon Pid in TPC.
- The sample is divided in 3 categories: $0\pi^+$, $1\pi^+$ and others (mainly Deep Inelastic Scattering) based on the detection of pions in the event.
  - Pions are detected as tracks in TPC, FGD or Michel electron signature near vertex.



ND280 ν_μ analysis



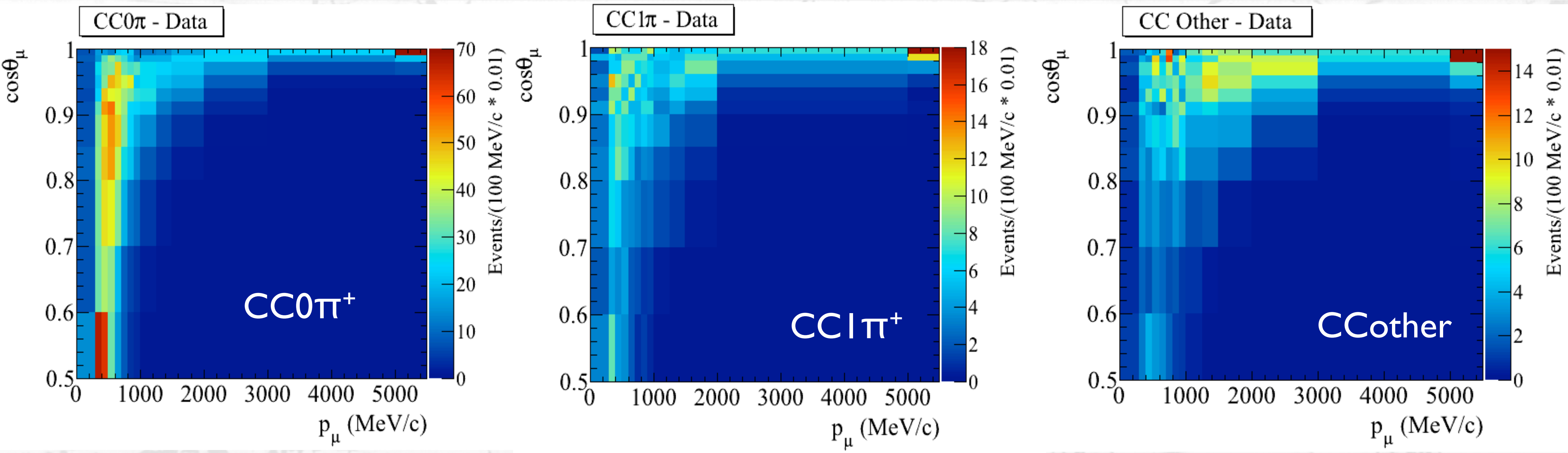




Off-axis ND280 analysis

	Purities			Efficiency
	CC0π	CC1π	CCOther	
CC0π	73.5%	6.5%	6.1%	50.1%
CC1π	8.5%	50.5%	8.3%	29.5%
CCOther	10.9%	29.8%	72.9%	35.2%
Background	2.2%	6.8%	8.7%	
Out of FV	4.9%	6.4%	4.0%	

ND280 ν_μ analysis

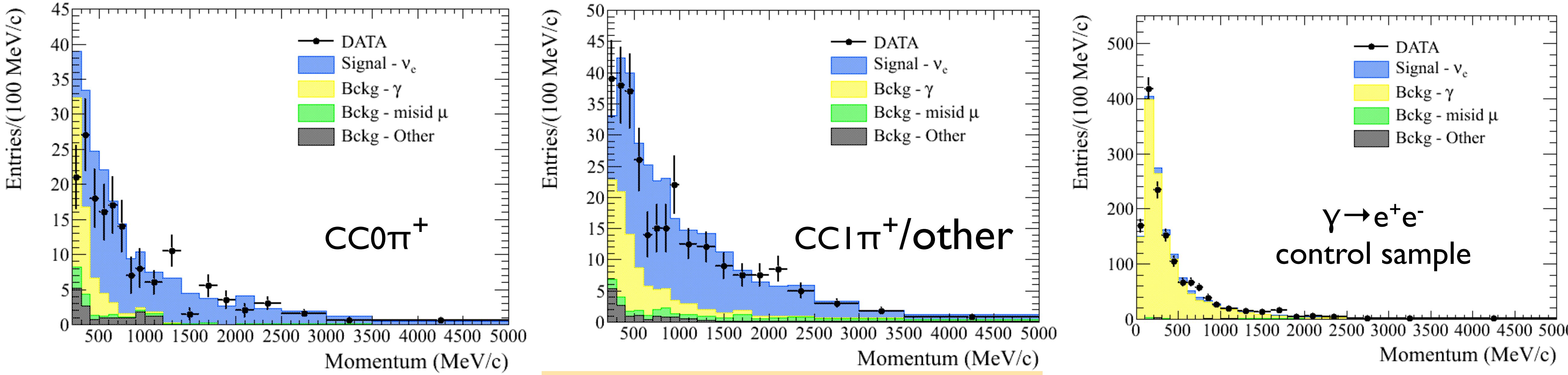


Data from T2K Runs 1-4: 5.9×10^{20} protons on target

Selection	Number of Events
CC0π	16912
CC1π	3936
CC Other	4062
CC Inclusive	24910

Data are binned in two dimensions: muon momentum (p) and angle ($\cos\theta$) preserving information on neutrino energy and interaction q^2

ND280 ν_e analysis



Off-axis ND280 analysis

- Select highest momentum negative track starting in FGD to be compatible with electron according to TPC and ECAL PID.
- Subdivide the sample according to the presence of pions in the event.
- Use the ν_e flux prediction after the ν_μ flux and cross-section fit.
- Use $\gamma \to e^+e^-$ to constrain main background from $\pi^0 \to \gamma\gamma$

$$\frac{N_e^{meas}}{N_e^{pred}} = 1.06 \pm 0.06(stat) \pm 0.08(syst)$$

$$\frac{N_\gamma^{meas}}{N_\gamma^{pred}} = 0.77 \pm 0.02(stat)$$

Cerenkov radiation

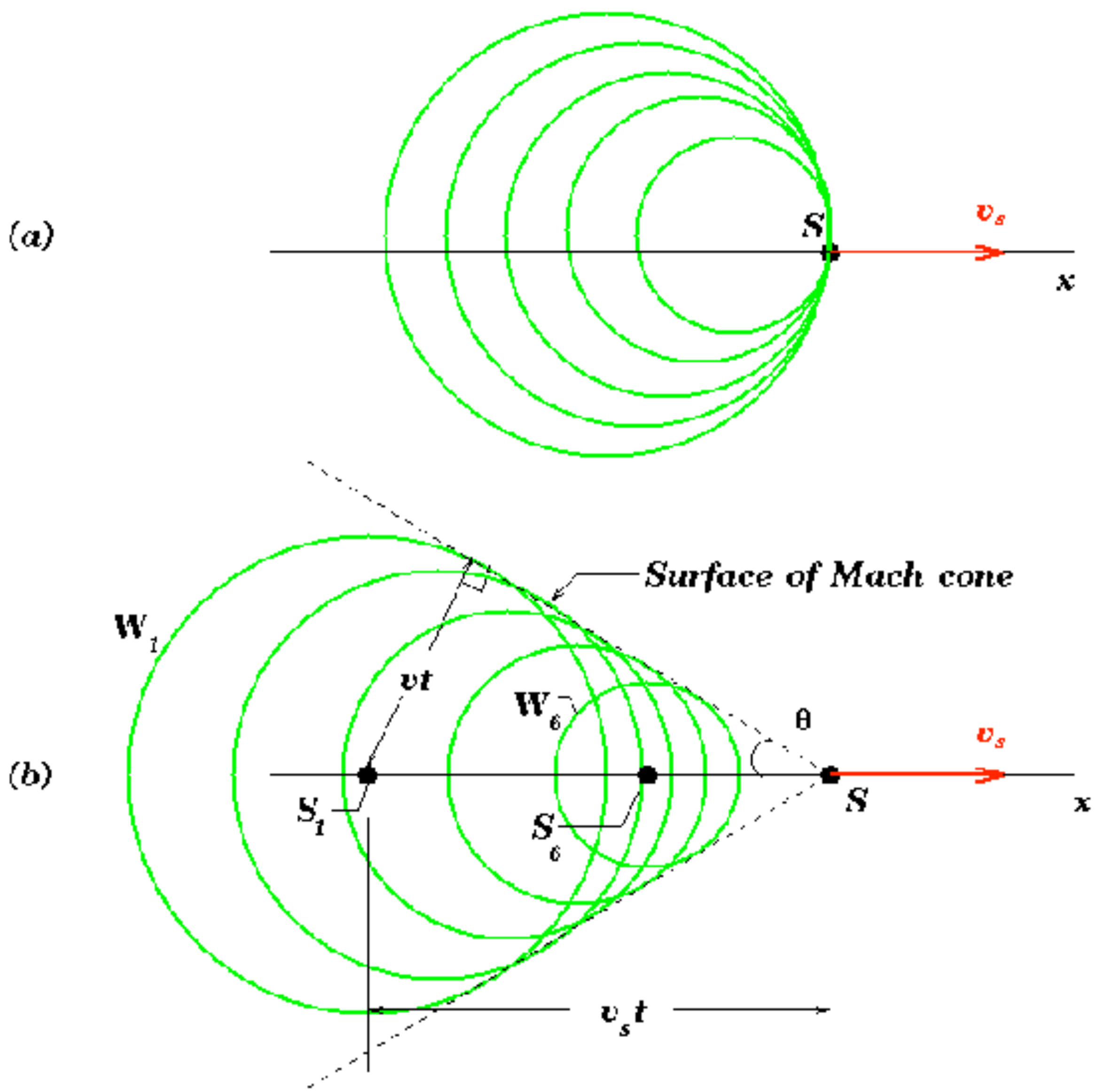


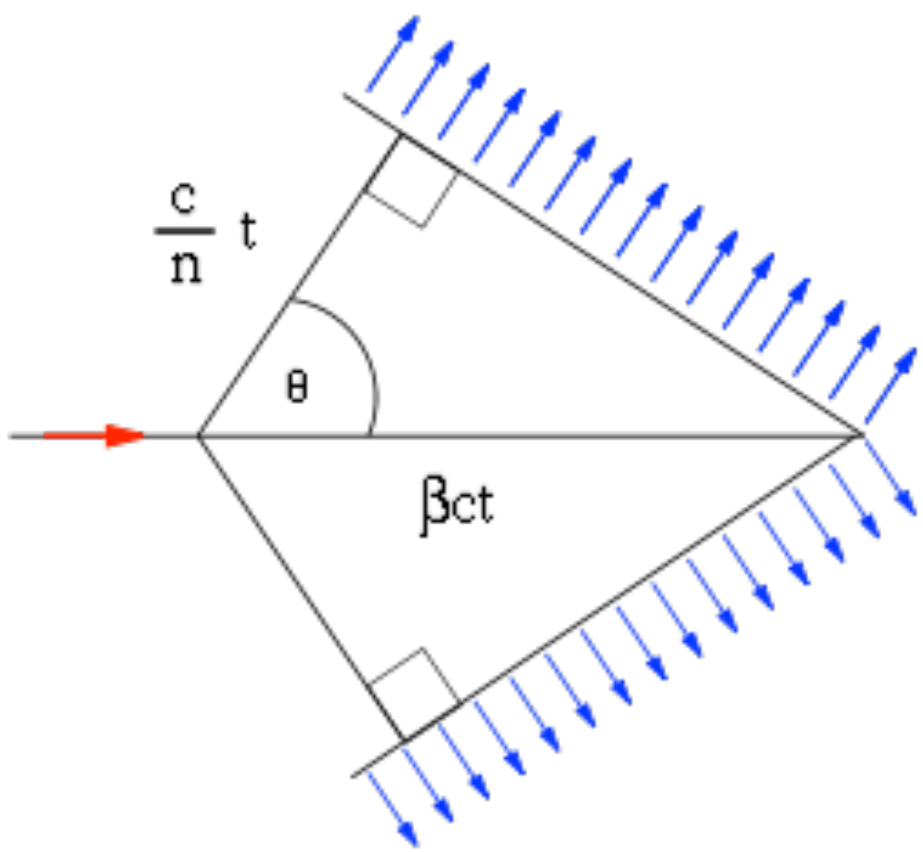
Diagram (a):

If the charged particle is moving at the velocity of light in the medium, the particle exactly keeps up with the wavefronts in its direction of travel.

Diagram (b):

If the velocity of the particle exceeds that of light in the medium, a cone of light is produced. From the diagram, it can be seen that constructive interference between the wavefronts occurs only on the surface of the cone.

Opening angle of Cerenkov cone



The charged particle moves with velocity βc, where β = v/c. Here v is the velocity of the particle and c the velocity of light in vacuum. Meanwhile the emitted wavefronts move at velocity c/n, where n is the refractive index of the medium.

In a time t, the charged particle moves a distance βct, while the emitted wavefronts move a distance (c/n)t. From the diagram, it can be seen that the opening angle θ is given by:

$\cos\theta = ct / n\beta ct = 1 / \beta n.$

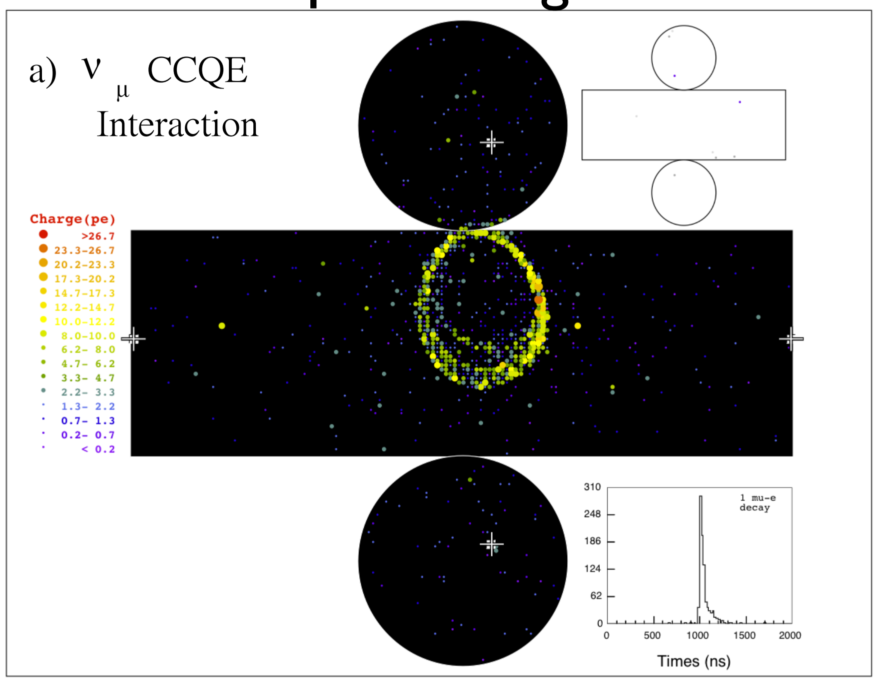
(Please note that the angle θ is different from that on the previous slide.)

Super K event selection

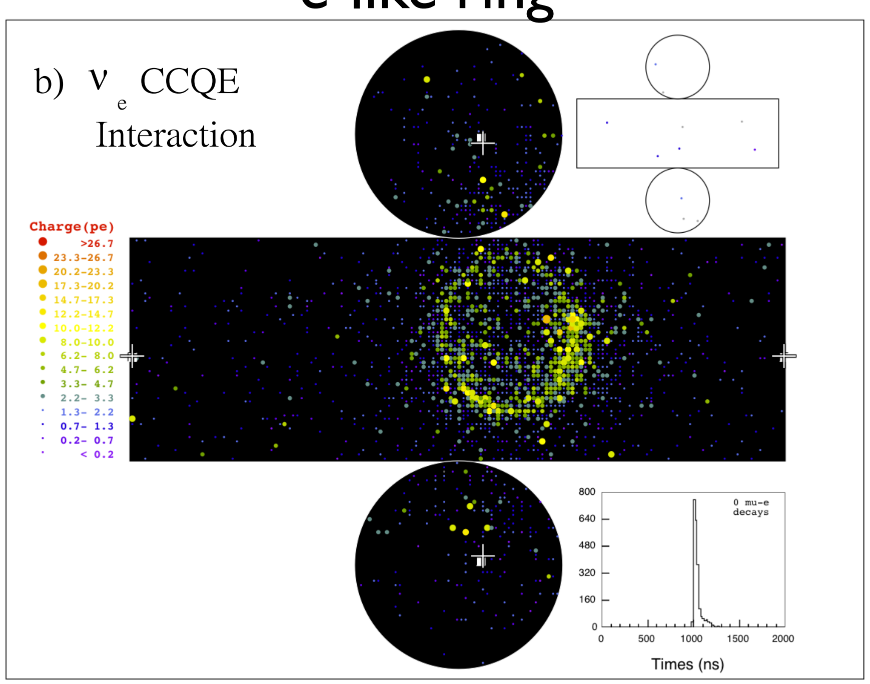
- Events are split up into four different classes: FC candidates, outer detector (OD) events, low energy (LE) events, and rejected events.
- During the first stage of classification, all events that have calibration flags are removed. Though calibration timing is generally scheduled as to not interfere with T2K beam spills, sometimes accidents happen and they are removed during this stage. These events are saved in a special rejected event file.
- The next stage looks for events that occurred in the OD. Events are tagged as OD events when more than 15 PMTs in a cluster being hit in the OD. These events are saved to a file of only OD events.
- Then LE events are separated out and saved to a different file. A LE event is defined by if the total charge inside a 300nsec window is less than 200 p.e or if the total charge in a single PMT normalized by the charge in the 300nsec window is less than 0.5.
- The final cut is made on events that are identified as Flashers, which are sudden flashing PMTs that emit light from internal corona discharges. If a flasher is identified, it is saved in the rejected event file.
- Events that pass all the cuts above are saved to a file of only FC candidates.

Distinguishing μ-like from e-like rings in Super K

μ-like ring



e-like ring



To distinguish μ-like from e-like rings in Super K, a product of two probabilities is used:

1. Probability of observed distribution of PMT hits. An electron produces an electromagnetic shower which gives a fuzzy ring. A muon produces a sharper ring.

2. Probability of the Cerenkov opening angle ($\cos\theta = 1/\beta n$). This is particularly important at low momentum when there are fewer PMT hits. At low momentum, $\beta < 1$ for muons, whereas it remains near 1 for electrons. This means that the opening angle is less for muons than for electrons at low momentum.

Event selection in far detector (Super Kamiokande)

Additional selection criteria for single μ-like ring events are:

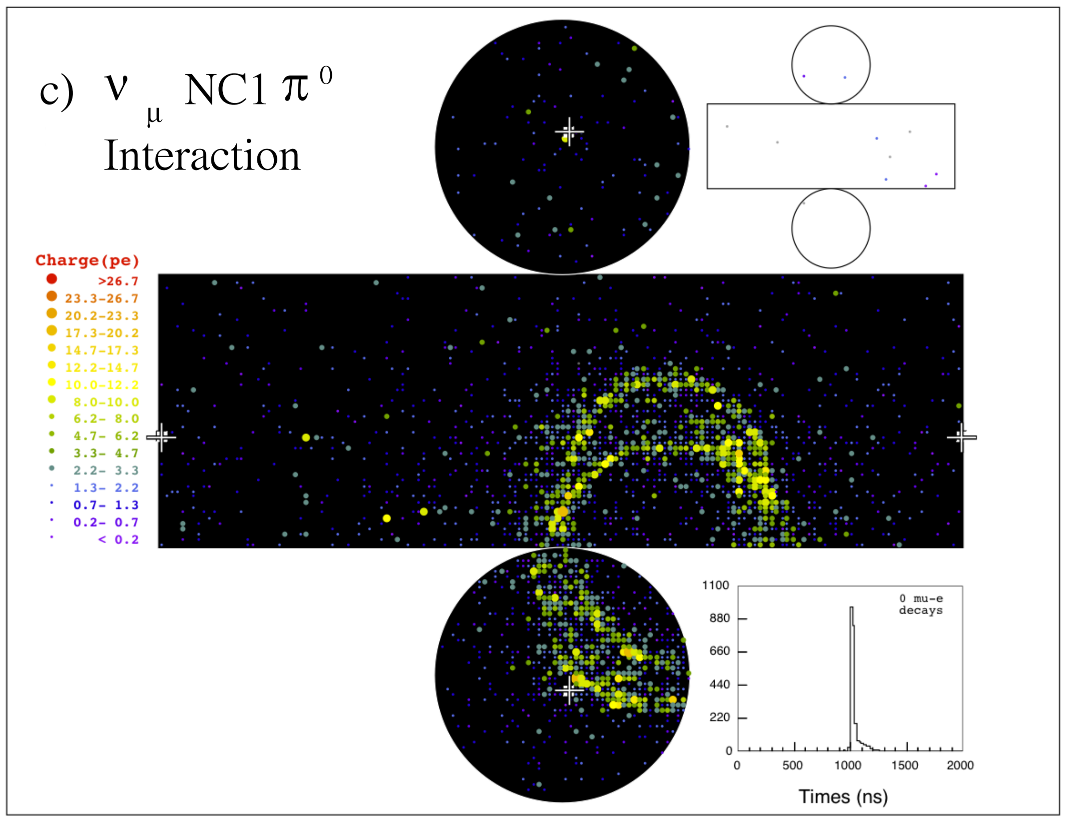
Selection	Purpose
6. Muon momentum > 200 MeV/c	Reject charged pions and misidentified electrons from decays of unseen muons or pions.
7. No more than one delayed electron	Reject events with a muon accompanied by an unseen muon or pion.

Additional selection criteria for single e-like ring events are:

Selection	Purpose
6. Visible energy > 100 MeV	Remove decay electrons from stopping CC muons and NC pions
7. No delayed electron	Remove unseen muons and pions, e.g. cosmic muons or muons below Cerenkov threshold.
8. New π^0 rejection algorithm	Reduce π^0 background
9. Reconstructed ν_e energy < 1250 MeV	Reduce events from beam ν_e - these have a high-energy tail from K decays.

Backgrounds to ν_e appearance after event selection

2 e-like rings from π^0

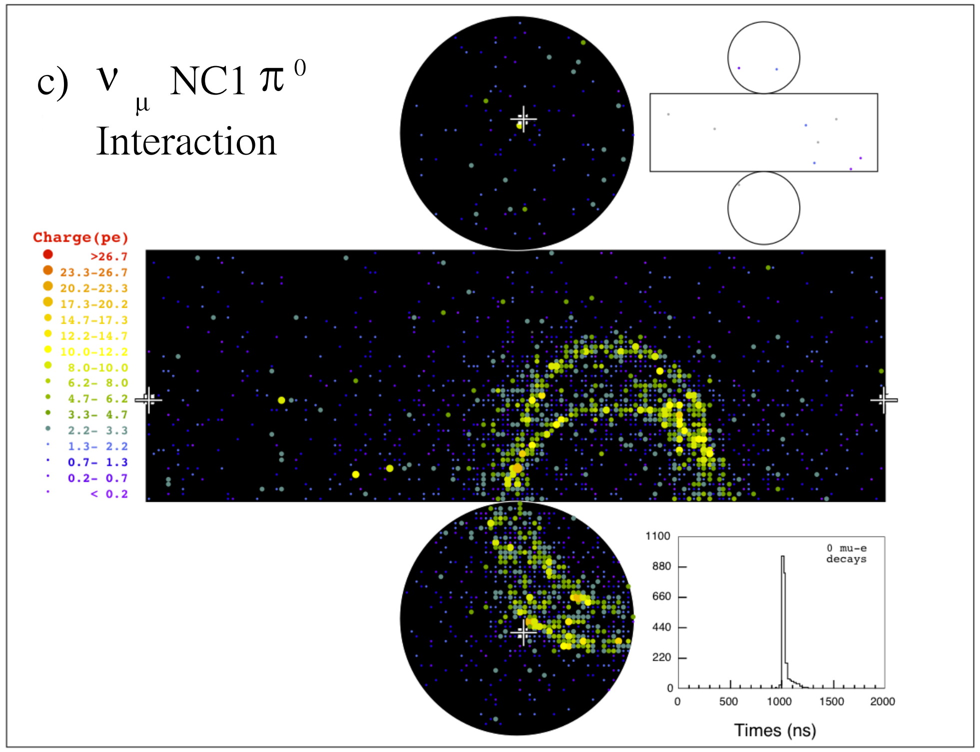


The principal backgrounds to ν_e appearance are:

1. The 1% ν_e component of the neutrino beam: this mainly comes from muon decays, while some also come from kaon decays.

2. NC π^0 production: this can mimic a ν_e if the two photon rings in Super K overlap or if one is below Cerenkov threshold.

Photonuclear interactions



A photonuclear interaction is the absorption of a photon by a nucleus. This can happen in Super K before the emission of Cerenkov light.

A π^0 decays into two photons. If one of these photons is absorbed, the π^0 gives one e-like ring, and appears to be an electron.

This has been modelled in the Super K detector simulation by removing photons according to the photonuclear cross section. Estimate a 8.7% increase in π^0 background due to photonuclear interactions

Super K detector uncertainties

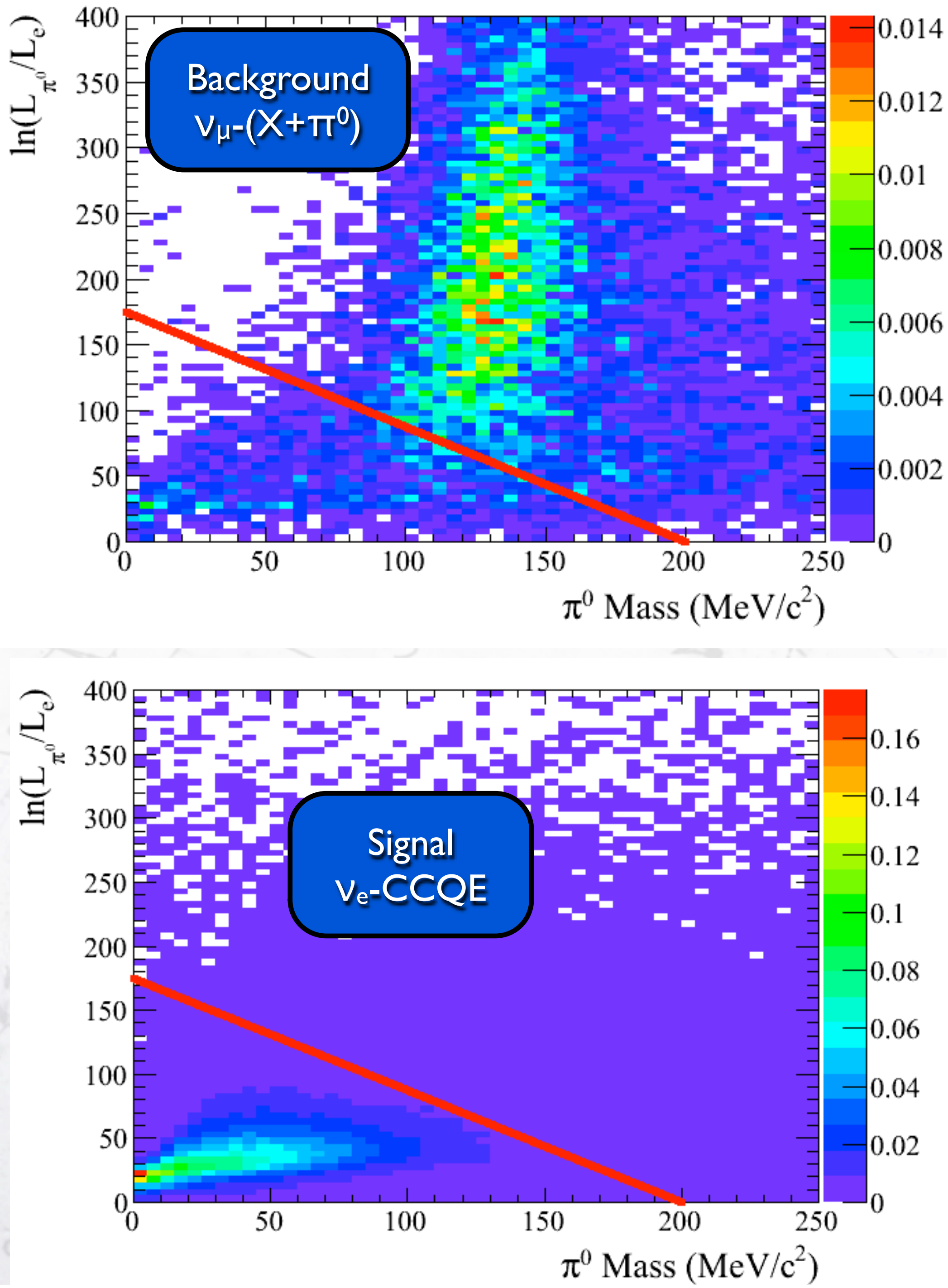
Ring-counting and particle ID efficiencies: fit Monte Carlo simulation of control samples to atmospheric neutrino data using efficiencies as fit parameters, and estimate errors in efficiencies as difference between nominal and fitted efficiencies. Define a "shift" error as the difference between the nominal and fitted efficiencies, and treat this as correlated between bins. Also define a "fit" error as the statistical uncertainty in the fitted efficiency, and this is uncorrelated between bins.

Examples of control samples

ν_μ/ν_μbar CCQE: 1 Michel electron (from μ decay), distance from muon stopping point to decay electron < 80cm.
ν_μ/ν_μbar CCnonQE: > 1 Michel electron (from μ decay), distance from muon stopping point to decay electron < 160cm.
ν_e CC: brightest ring is e-like, visible energy > 100 MeV, force reconstruction of second ring and require invariant mass of 2 rings < 105 MeV.

New π^0 rejection algorithm for single e-like ring sample

Likelihood Ratio vs π^0 Mass



Old algorithm: force reconstruction of second ring in Super K, calculate the invariant mass of the two particles, and accept events in which that invariant mass is < 105 MeV/c^2.

New algorithm: construct charge and time probability density functions for every PMT hit for each particle hypothesis. This is done using vertex position and timing, and track direction and momentum. Multiple-particle states are constructed by summing the charge contributions from each constituent particle.

Distinguish different final-state hypotheses by comparing best-fit likelihoods from fit of each particle hypothesis. To separate π^0 from ν_e events, the likelihood ratio $\ln(L_{\pi 0} / L_e)$ is used, and this is combined with invariant mass cut from old algorithm. New algorithm rejects 70% more π^0 background for same signal efficiency.

Oscillation parameter values

Oscillation probabilities are calculated in a 3-flavour framework. Matter effects are included assuming that the Earth's crust between Tokai and Kamioka has a constant density of 2.6 g/cm^3 (arXiv 1107.5857).

In the ν_μ-disappearance analysis, the non-23 oscillation parameters are fixed to their 2012 PDG values and the normal mass hierarchy is assumed:

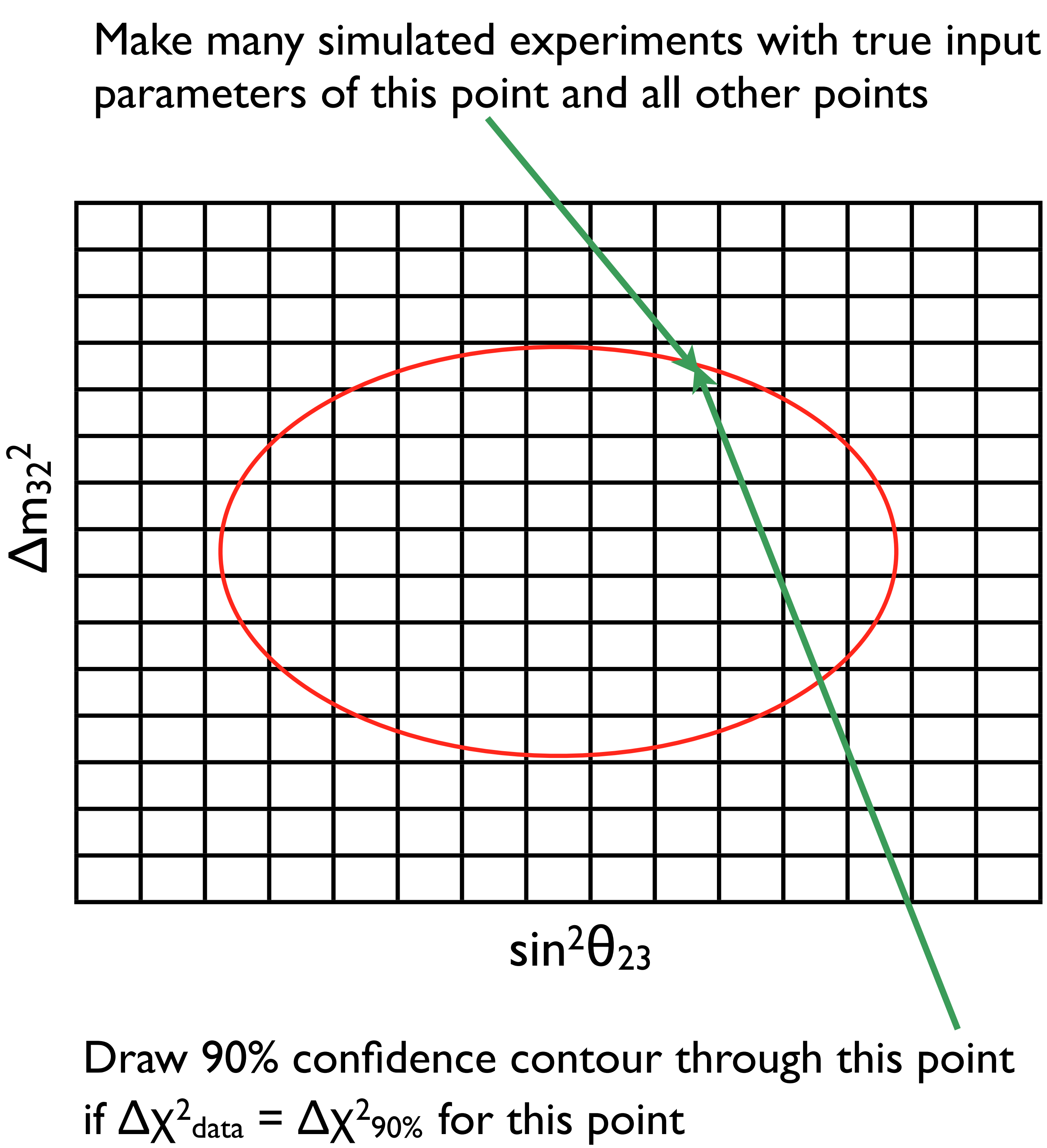
$\sin^2(2\theta_{12}) = 0.857$
$\Delta m_{21}^2 = 7.5 \times 10^{-5}\ eV^2/c^4$
$\sin^2(2\theta_{13}) = 0.098$
$\delta_{CP} = 0.$

In the ν_e-appearance analysis, the other oscillation parameters are fixed to:

$\sin^2\theta_{12} = 0.3067$
$\Delta m_{21}^2 = 7.6 \times 10^{-5}\ eV^2/c^4$
$\sin^2\theta_{23} = 0.5$
$|\Delta m_{32}^2| = 2.4 \times 10^{-3}\ eV^2/c^4$

Note: $P(\nu_\mu \rightarrow \nu_e)$ depends on $\sin^2(\theta_{23})$ as well as $\sin^2(2\theta_{13})$ since the leading-order term is $2 \sin^2(\theta_{23}) \sin^2(2\theta_{13})$.

Confidence regions



Divide $\sin^2\theta_{23}$ - Δm_{32}^2 plane into rectangular grid with a grid point at centre of each rectangle.

Make a few thousand simulated experiments using true input parameters of each point, and find $\Delta\chi^2 = \chi^2$ (true) - χ^2 (best fit) for each experiment. At each point, order values of $\Delta\chi^2$ and find their 90th percentile $\Delta\chi^2_{90\%}$.

Using real data, find value of $\Delta\chi^2_{data}$ at each grid point. Draw 90% confidence contour through points for which $\Delta\chi^2_{data} = \Delta\chi^2_{90\%}$.

If experiment repeated many times and a 90% contour is drawn for each experiment, true unknown values will be in 90% of those contours.

Calculating neutrino oscillation probablities

Oscillation probabilities are calculated using $UMU^\dagger$

where $$M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{12} & 0 \\ 0 & 0 & \Delta m^2_{13} \end{pmatrix}$$

The neutrinos pass through the Earth's crust, and there is coherent forward scattering of ν_e in CC interactions with electrons in the crust. For neutrinos, these "matter effects" are taken into account by adding the potential $2E\sqrt{2}G_F N_e$ to the real part of the first diagonal element of $UMU^\dagger$ (for antineutrinos it is subtracted from the real part of the first diagonal element of the complex conjugate of $UMU^\dagger$).

The resulting matrix is diagonalised. The differences between the eigenvalues are the effective Δm^2 in matter. The normalised eigenvectors are the columns of the effective mixing matrix in matter (UMatter).

Diagonalising UMU

Calculate the eigenvalues by solving the (cubic) characteristic equation using Cardano's method (arXiv:physics 0610206). The differences between them are the effective Δm^2 in matter. Calculate the (complex) eigenvectors algebraically: set one component equal to 1.0 (real) and calculate the other 2 components using 2 of the 3 simultaneous equations $UMU^\dagger - \lambda I = 0$. Then normalise the eigenvectors, and they become the columns of the effective mixing matrix in matter (UMatter).

Calculating neutrino oscillation probablities

Then carry out the following steps:

1. Define a complex 1x3 column vector to represent a ν_μ flavour eigenstate.

2. Multiply by UMatter† to convert to mass eigenstates.

3. Propagate to Super K by multiplying the jth component by $\exp(-i\ \Delta m_{1j}^2\ L / 2E)$.

4. Convert back to flavour eigenstates by multiplying by UMatter.

5. The probabilities of each flavour are given by the moduli squared of the components of the resulting 1x3 complex vector.

Reconstructing neutrino energy

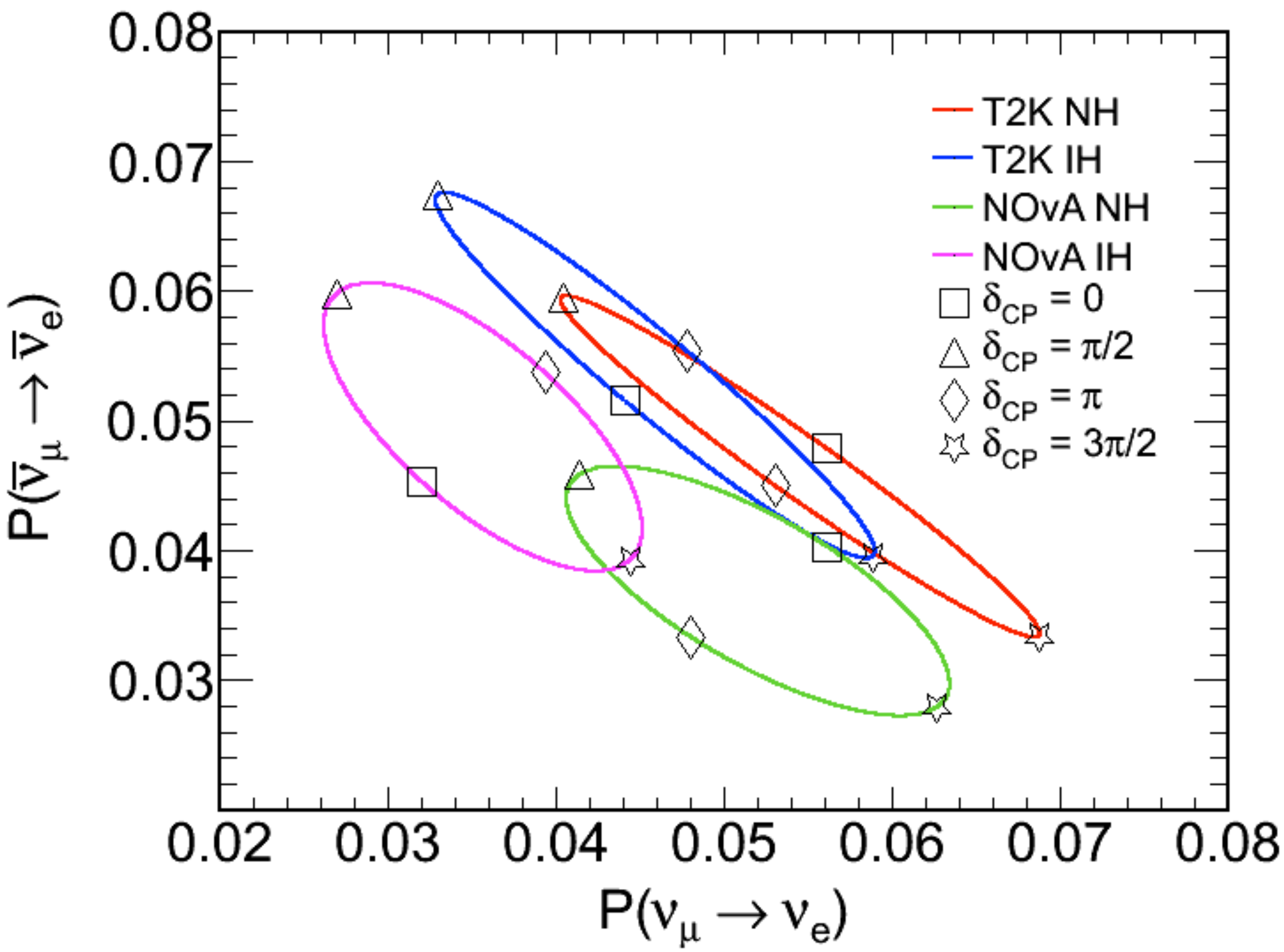
The energy of a neutrino in the T2K beam is unknown and must be reconstructed. This is done using CCQE events.

Neglecting the Fermi motion of the nucleon with which the neutrino interacts, the neutrino energy is reconstructed as

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

where m_p is the proton mass
m_n is the neutron mass
E_b = 27 MeV is the binding energy of a nucleon in a ^{16}O nucleus
E_μ is the reconstructed energy of the muon
p_μ is the reconstructed momentum of the muon
$\cos\theta_\mu$ is the reconstructed angle between the incoming neutrino and the muon

$P(\nu_\mu \rightarrow \nu_e)$ and $P(\nu_\mu bar \rightarrow \nu_e bar)$ (with matter effects)



$\sin^2(2\theta_{12}) = 0.87$
$\sin^2(2\theta_{13}) = 0.1$
$\sin^2(2\theta_{23}) = 1.0$
$\Delta m_{12}^2 = 7.6 \times 10^{-5}\ eV^2$
$|\Delta m_{32}^2| = 2.32 \times 10^{-3}\ eV^2$

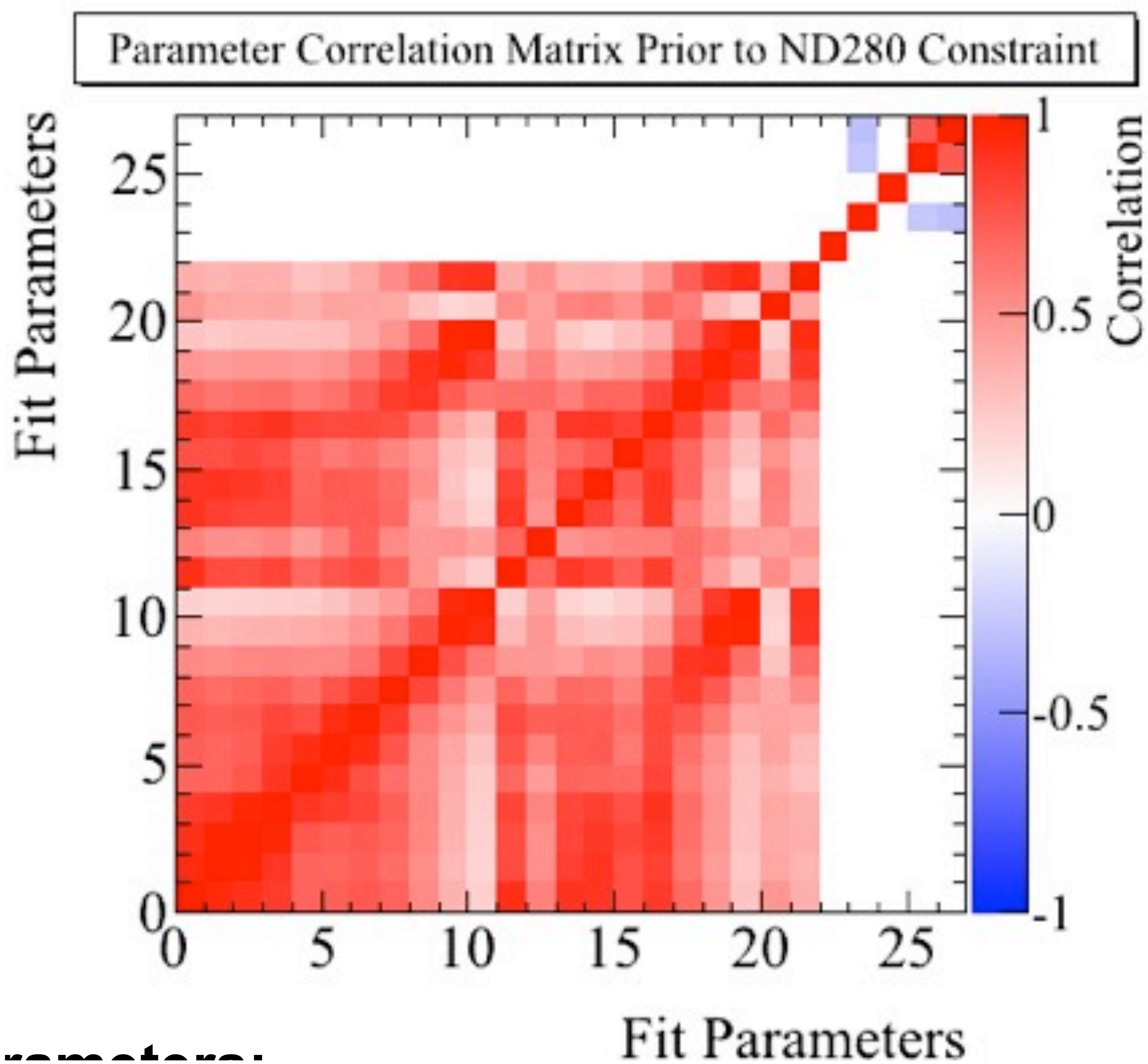
Earth crust density = 2.6 g/cm^3
NH = normal mass hierarchy
IH = inverted mass hierarchy
T2K energy = 0.6 GeV
NOvA energy = 2.0 GeV

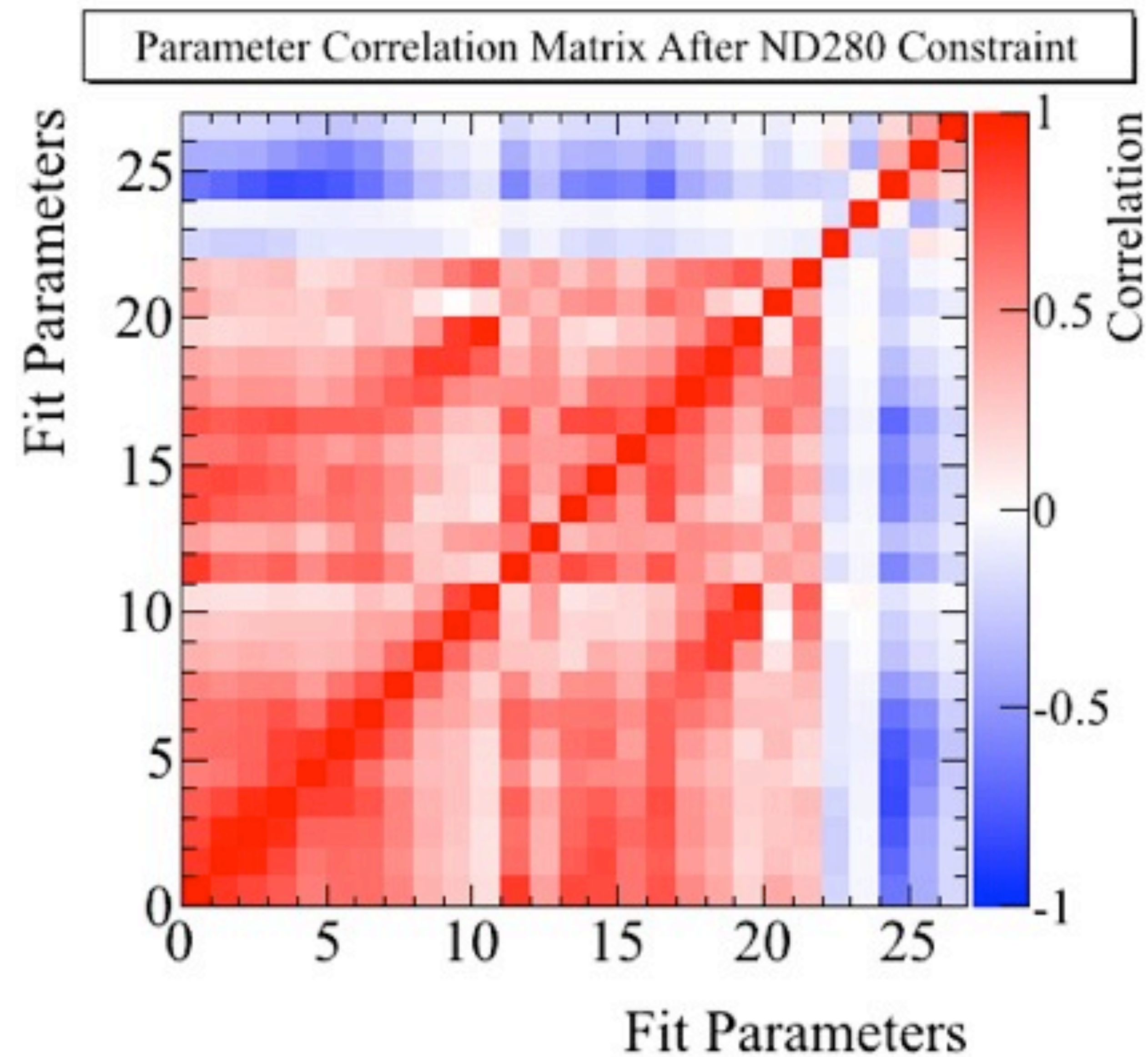
T2K might be able to measure δ_{CP} if it is close to $3\pi/2$ (normal hierarchy) or $\pi/2$ (inverted hierarchy). However for most values of δ_{CP}, its effects are entangled with those of the mass hierarchy.

NOvA might be able to measure δ_{CP} if it is between π-2π (normal hierarchy) or 0-π (inverted hierarchy).

Note that, for $\delta_{CP} = 0$, $P(\nu_\mu \rightarrow \nu_e) \neq P(\nu_\mu bar \rightarrow \nu_e bar)$. This is due to matter effects.

Correlations between flux and cancelling xsec parameters





Cross-section fractional uncertainties

Correlated with flux parameters

MaQE	7.2% (external and ND280 data)
MaRES	6.8% (external and ND280 data)

Uncorrelated

Fermi momentum	13.3% (external data)
Binding energy	33.3% (external data)
Spectral function	On/off (external data)
W shape	52% (external data)
Pionless delta decay	20% (external data)
CC other shape	40% (external data)
CC coherent cross section	100%
NC1π± cross section	30% (external data)
NC other cross section	30% (external data)
ν_e / ν_μ cross section	3% (external data)
$\nu_\mu$bar / ν_μ cross section	40% (external data)

T2K GPS system

At both J-PARC and Super Kamiokande there are:

1. Two independent single-frequency common-view GPS receivers and antennae. Each receiver gives one signal per second whose leading edge is synchronous with the start of a new second in Coordinated Universal Time (UTC).

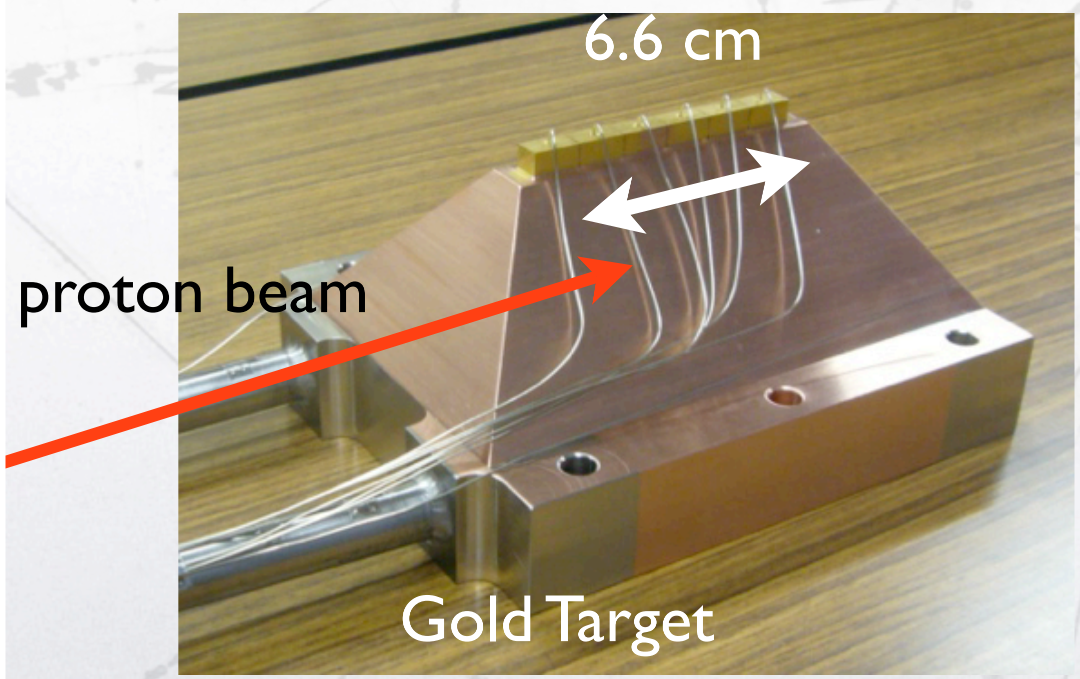
2. A rubidium atomic clock (Research Systems FS-725) that is synchronised with the GPS pulses.

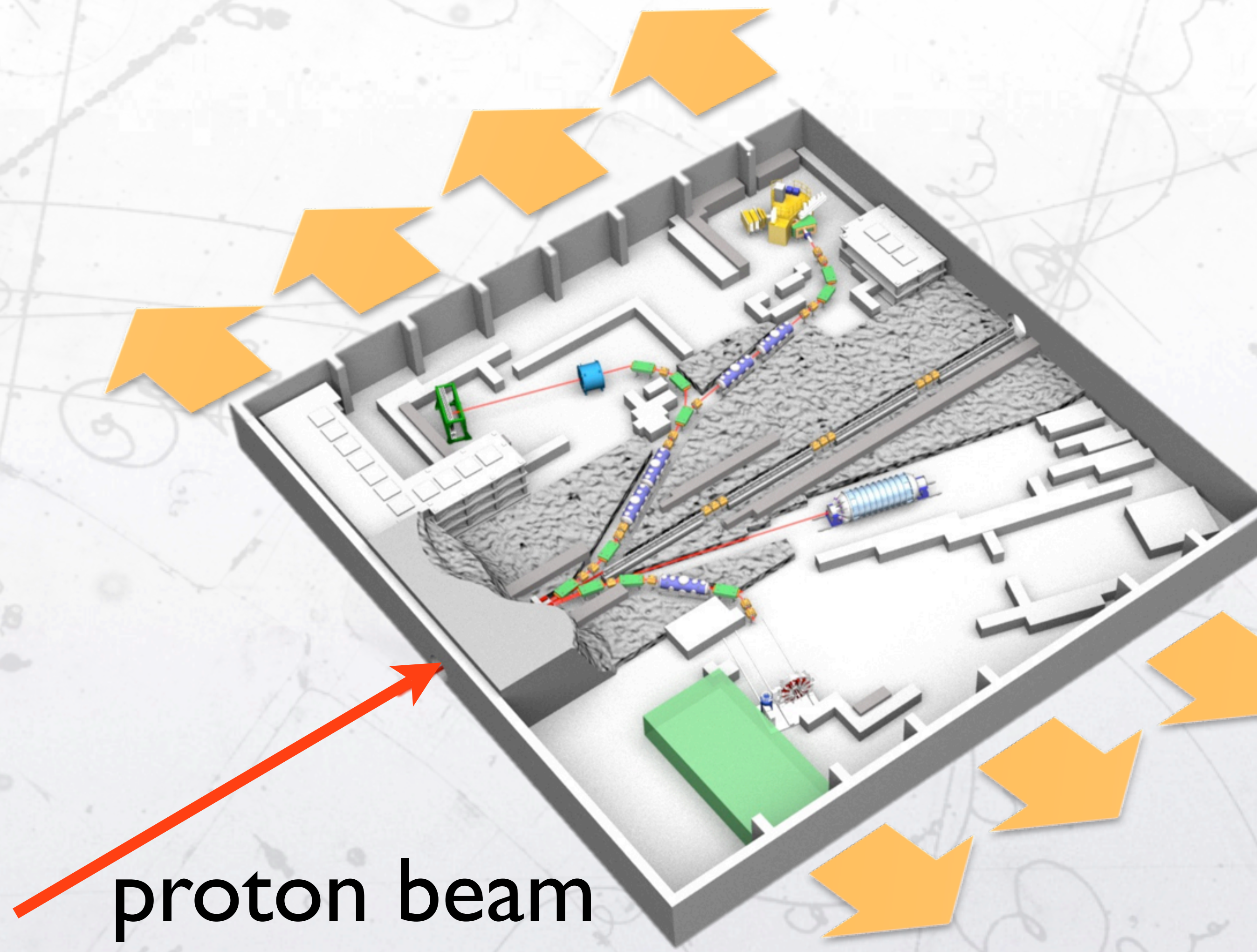
3. A custom electronics board called the local time clock. This uses the time base from the rubidium clock, and produces timestamps every 10 ns.

J-PARC accident

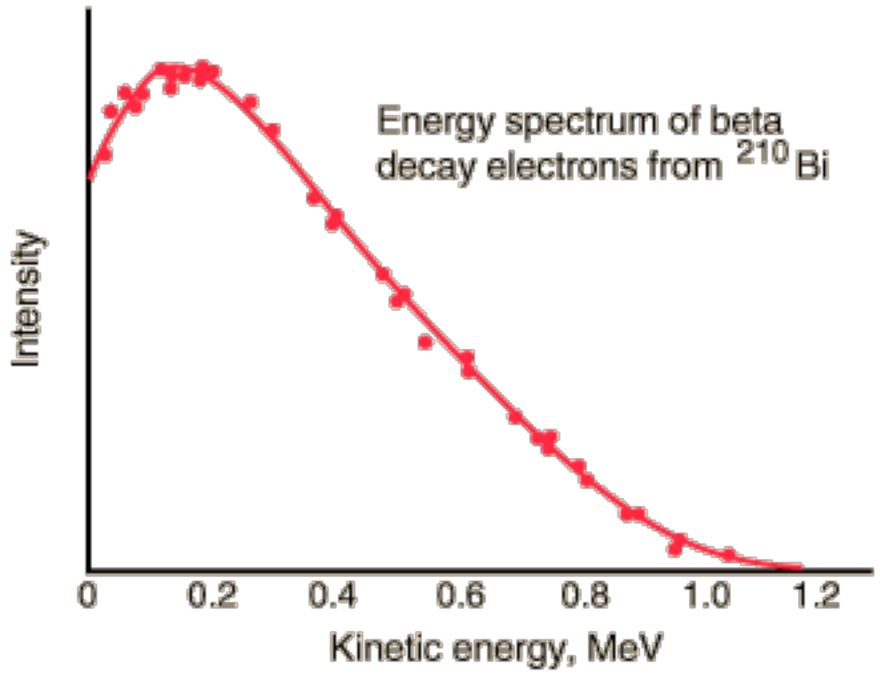
11:55 on May 23

- An abnormal proton beam was injected to the gold target.
- The target heated up to a extraordinarily high temperature.
- Radioactive material was released from the target.
- The radioactive material was leaked into the HD hall: xWorkers were exposed to radiation.
- The radioactive material was released to the outside of the radiation controlled area and to the environment outside of the HD hall.





Pauli proposes the neutrino



Wolfgang Pauli

In 1930, it was thought that β^- decay was

$n \rightarrow p + e^-$

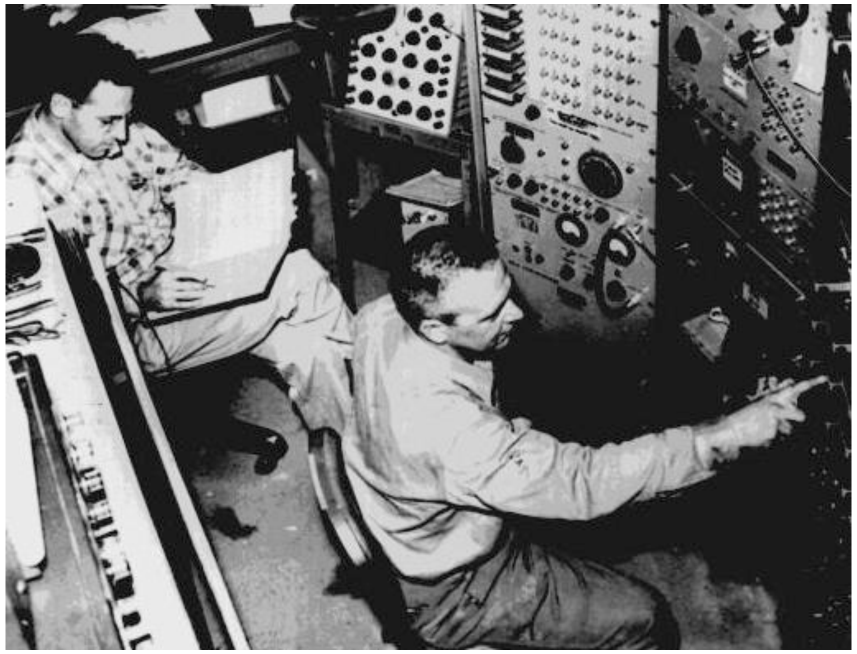
In this decay all the electrons should have the same kinetic energy. But experimentally it was found that they have a range of energies.

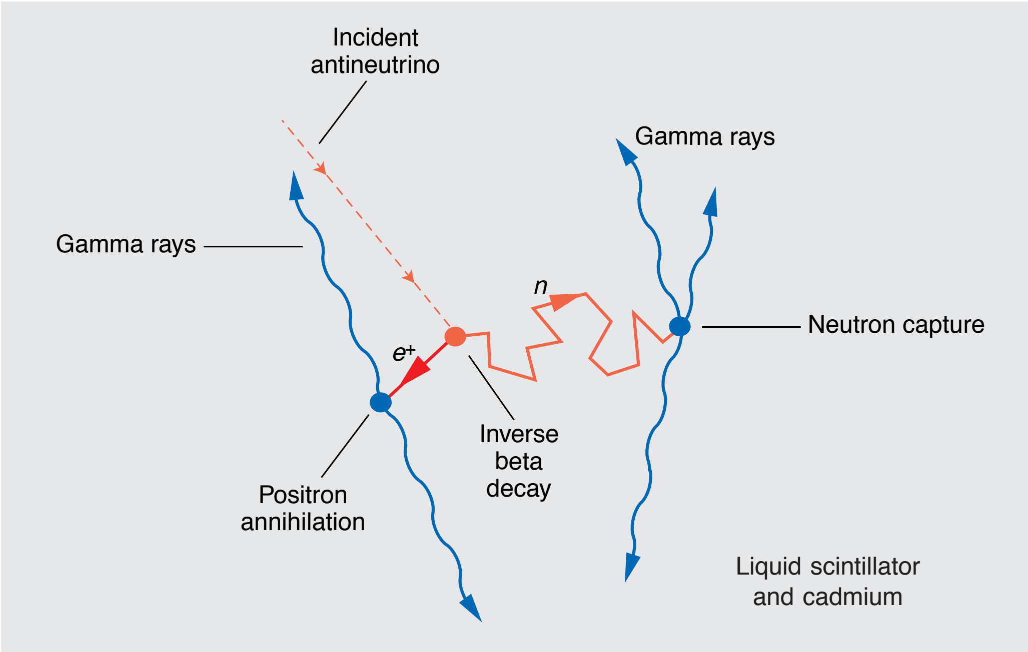
To save conservation of energy, Wolfgang Pauli proposed a "desperate" solution that a light, electrically neutral particle carried away the missing energy.

Pauli said "I have done a terrible thing. I have postulated a particle that cannot be detected."

Discovery of electron antineutrino

Frederick Reines and Clyde Cowan at Hanford Site (1953)





Interactions in water which is surrounded by photomultipliers to detect photons

In 1956, Reines and Cowan detected electron antineutrinos from a reactor at Savannah River (Nobel Prize for Reines in 1995). This was done using inverse β decay:

$\nu_e\mathrm{bar} + p \rightarrow n + e^+$

where the proton is in the water target. The positron annihilates with an electron to give two photons of 0.5 MeV. The neutron is captured by cadmium which is added to the water:

$n + {}^{108}\mathrm{Cd} \rightarrow {}^{109m}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd} + \gamma$

This photon appears 5 msec later than those from the positron/electron annihilation.