Results of ν_e appearance from an off-axis ν_μ beam utilizing neutrino energy spectrum

Joshua Hignight

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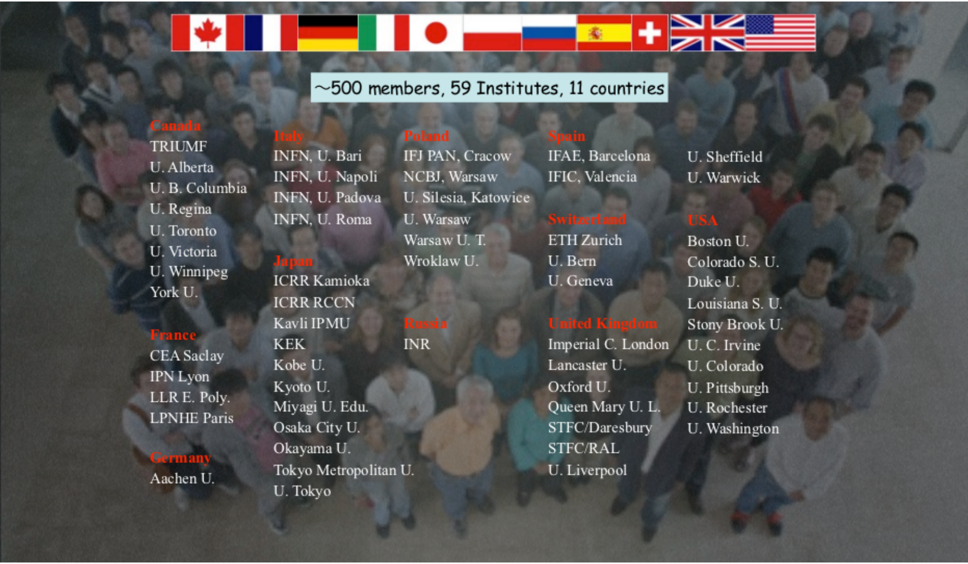
- Introduction to T2K
- Improvements to Analysis
  - Near Detector Analysis Improvement for 2013
  - New π^0 Fitter for Super-K
- Analysis Method
- New Results

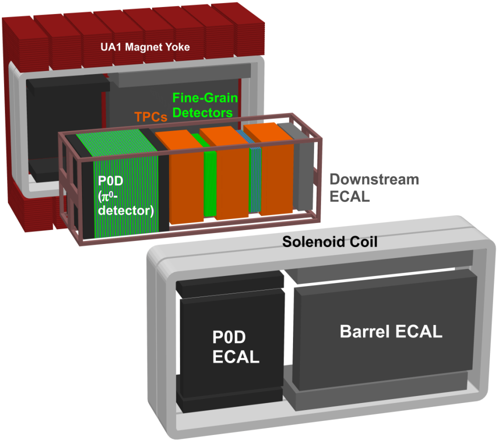
The T2K Collaboration



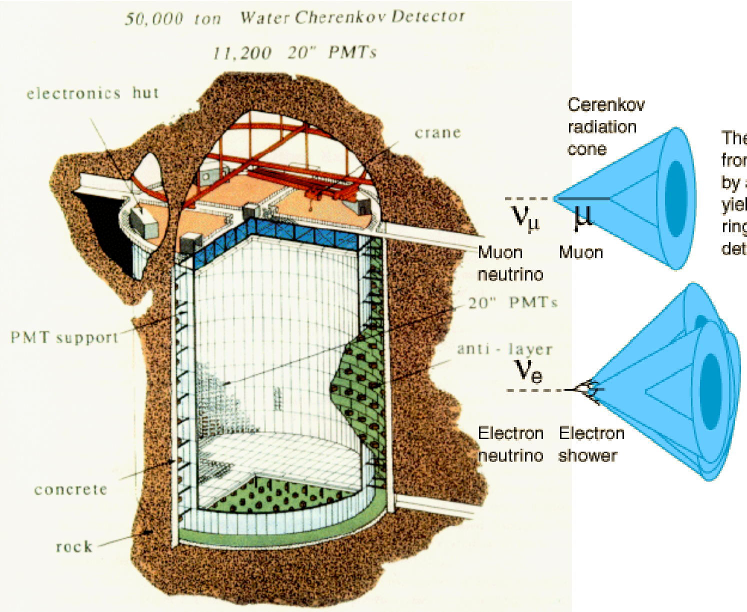
The T2K Experiment

- The T2K experiment searches for neutrino oscillations using a high purity off-axis ν_μ beam.
- A near detector is located at 280 meters (ND280) downstream of the target to measure the unoscillated neutrino spectrum.
- The neutrinos travel 295 km to Super-Kamiokande.

Near Detector: ND280



- Made up of a 0.2T magnet, π^0 detector, trackers, and calorimeters.
- Primary purpose is to measure both ν-flux and help with cross-section uncertainties.
- Combined with external constraints from NA61 and MiniBooNE, this information is used for T2K far detector MC prediction.

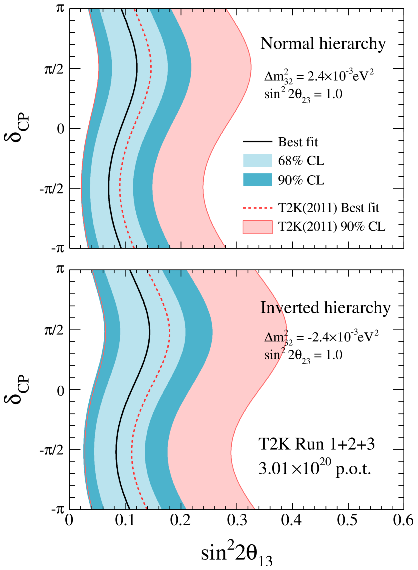


The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

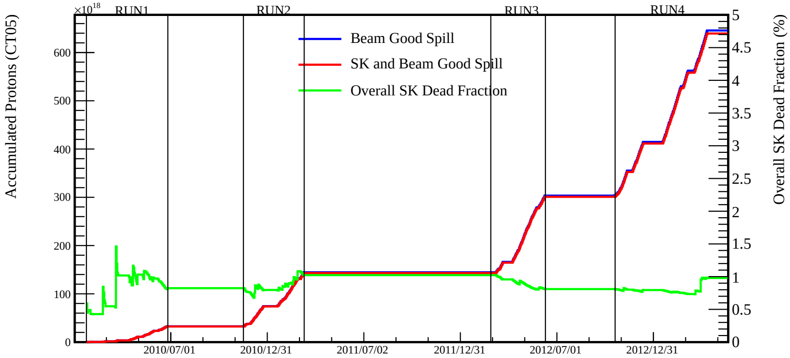
The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

Previous T2K Appearance Results

- 2011 ν_e appearance (pink)
  - Observed 6 events with an expected background of 1.5 ± 0.3 events
  - First indication of $\theta_{13} \neq 0$ at a 2.5σ significance.
  - Phys. Rev. Lett. 107, 041801 (2011)
- 2012 ν_e appearance (blue)
  - Observed 11 events with an expected background of 3.3 ± 0.4 events
  - 3.1σ exclusion of $\theta_{13} = 0$
  - arXiv:1304.0841 (accepted by PRD)



New Data



Have doubled the POT since Run3 to 6.39×10^{20} ($\approx$ 8% of total expected) while remaining a high efficiency of data taking.

Improvements to ND280 Analysis

- Significant reduction of the far detector event rate errors.
- Uncertainties on the cross-section parameters are reduced.
- Uncertainties on the flux parameters are also reduced.

Error on Far Detector ν_e Prediction (after ND280 constraint)

	Runs 1-3	Runs 1-4
$\sin^2 2\theta_{13} = 0.1$	4.7%	3.0%
$\sin^2 2\theta_{13} = 0.0$	6.1%	4.9%

Cross-Section Parameters (after ND280 constraint)

	Runs 1-3	Runs 1-4
M_A^{QE} (GeV/c^2)	1.27 ± 0.19	1.22 ± 0.07
M_A^{RES} (GeV/c^2)	1.22 ± 0.13	0.96 ± 0.06
CCQE Norm.	0.95 ± 0.09	0.96 ± 0.08
CC1π Norm.	1.37 ± 0.20	1.22 ± 0.16

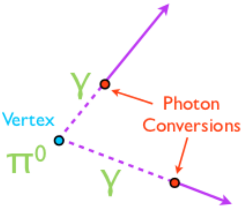
Far Detector Analysis Improvements

- For the 2012 analysis, the signal to background ratio was at 2.7 (for $\sin^2 2\theta_{13} = 0.1$)
- 2012 total background = 3.22 $\pm$ 0.43 events
  - Beam ν_e background = 1.56 $\pm$ 0.20 events (irreducible)
  - Neutral current background = 1.26 $\pm$ 0.35 events (reducible)
- By reducing the NC background (mostly π^0) we can significantly improve ν_e analysis.

- fiTQun is a new fitting algorithm at Super-K that uses the measured charge and time of every PMT hit.
- For a given event topology hypothesis, it is possible to produce a charge and time PDF for each PMT.
- Event hypotheses are distinguished by comparing best-fit likelihoods.
- Based on the algorithm used by MiniBooNE.

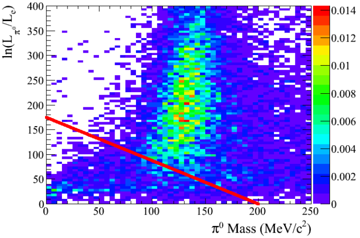
$$\mathcal{L}(x) = \prod_{unhit} P(i_{unhit}; x) \prod_{hit} P(i_{hit}; x) f_q(q_i; x) f_t(t_i; x)$$

- Assumes 2-electron rings are produced at a common vertex.
- Varies 12 parameters simultaneously for the fit.
  - Vertex (X,Y,Z,t)
  - Direction (θ_1, ϕ_1, θ_2, ϕ_2)
  - Momenta (p_1, p_2)
  - Conversion length (c_1, c_2)

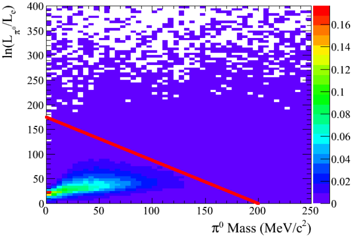


- fiTQun is now used to distinguish e^- from π^0 by using a 2D cut in the likelihood ratio along with the reconstructed π^0 mass.
- This new cut removes $\approx$ 70% of the remaining π^0 background that the old cut allowed.
- The total background is reduced by 27%
    - 6.36 events $\rightarrow$ 4.64 events for the data-set shown today.

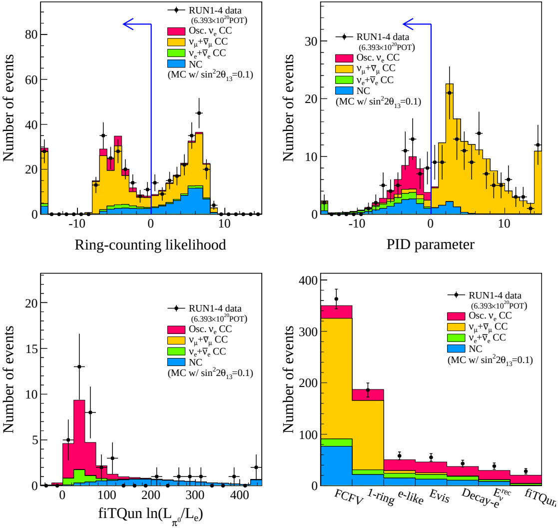
All Backgrounds



ν_e Signal



- Fully contained in the FV
- Single e-like ring
- $E_{visible} > 100$MeV
- No Michel electrons
- fiTQun π^0 cut
- $E^{rec} < 1250$



ν_e Analysis Method: E^{rec}

- There are two methods used for ν_e appearance: $p-\theta$ and E^{rec}.
- The rest of this talk will only discuss the E^{rec} analysis which I'm a part of.
- The reconstructed energy is defined as:

$$E^{rec} = \frac{m_p^2-(m_n-E_b)^2-m_e^2+2(m_n-E_b)E_e}{2(m_n-E_b-E_e+p_e\cos\theta_e)}$$

- m_p is the proton mass, m_n the neutron mass, and $E_b = 27\,\mathrm{MeV}$ is the binding energy of a nucleon inside a ^{16}O nucleus.
- E_e, p_e, and θ_e are the reconstructed electron energy, momentum, and angle with respect to the beam direction, respectively.

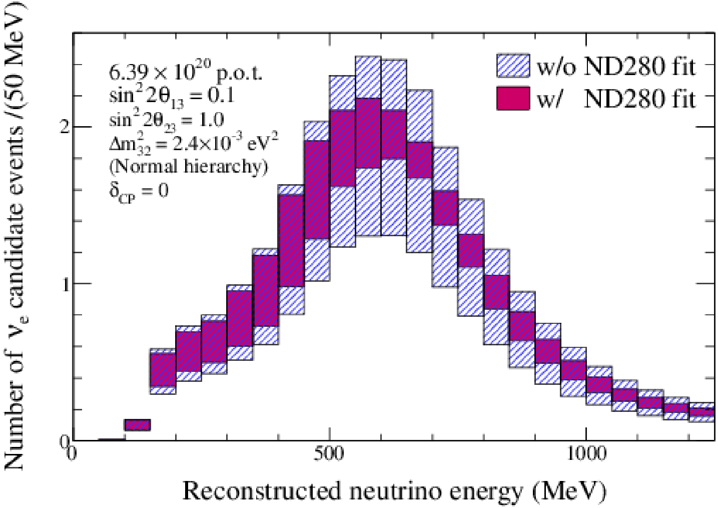
Note that due to slightly better sensitivity of $\theta_{13} \neq 0$, the $p-\theta$ analysis was chosen as the primary analysis for T2K.

- An essential part of this analysis is to improve the sensitivity by separating the ν_e signal from backgrounds using the difference of their E^{rec} spectrum shape, depending on neutrino oscillation parameters.
- ν_e candidate events are divided into 25 bins, and a PDF is constructed for ν_e appearance signal and background.
- A likelihood is defined using the number of ν_e events in each E^{rec} bin and the best-fit point of θ_{13} is obtained by searching for a maximum likelihood alongside of θ_{13} with varying systematic uncertainties.

$$\mathcal{L}(N_{obs}, \boldsymbol{E}^{rec}_{obs}; \boldsymbol{\theta}, \boldsymbol{f}) = \mathcal{L}_{norm}(N_{obs}; \boldsymbol{\theta}, \boldsymbol{f}) \times \mathcal{L}_{shape}(\boldsymbol{E}^{rec}_{obs}; \boldsymbol{\theta}, \boldsymbol{f}) \times \mathcal{L}_{syst}(\boldsymbol{f})$$

- A delta of the negative log likelihood curve is calculated as a function of θ_{13}.
- The ν_e appearance significance is evaluated by p-value based on Feldman Cousins method, where an observation of the ν_e appearance candidate is compared with many toy experiments assuming $\theta_{13} = 0$.

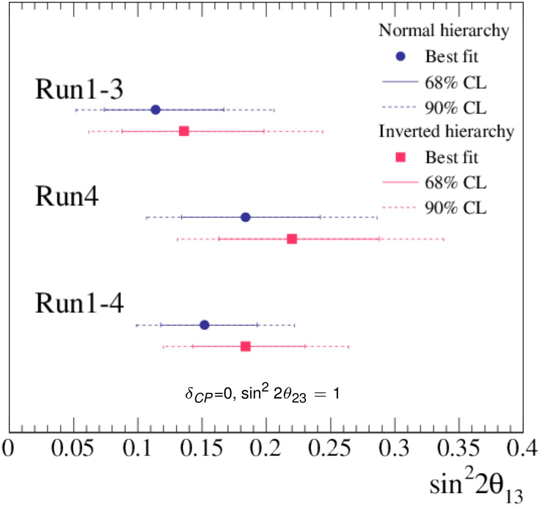
ν_e Appearance Results: Expectations



20.4±1.8 events expected w/ 4.6±0.5 background events

5.5σ sensitivity to exclude θ_{13}=0

Observed 28 ν_e events



Run1-3

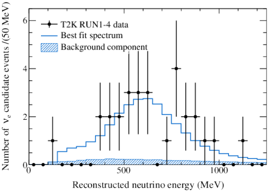
Hierarchy	(a) Normal	(b) Inverted
Best fit	0.114	0.136
68 % C.L.	0.074 - 0.167	0.088 - 0.198
90 % C.L.	0.052 - 0.206	0.062 - 0.244

Run4

Hierarchy	(a) Normal	(b) Inverted
Best fit	0.184	0.220
68 % C.L.	0.134 - 0.242	0.163 - 0.288
90 % C.L.	0.107 - 0.286	0.131 - 0.338

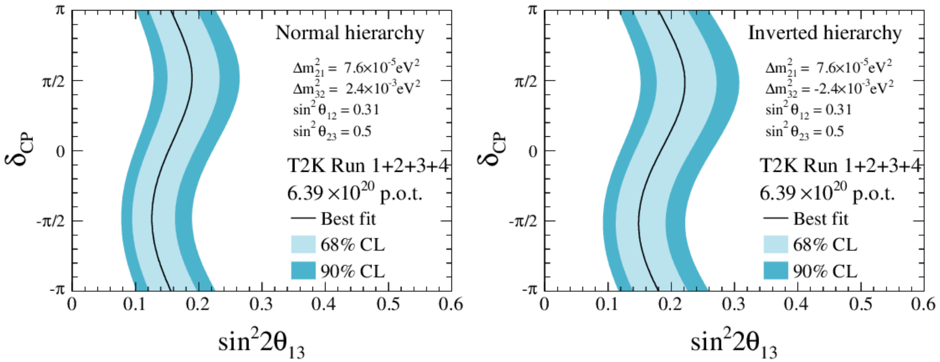
Run1-4

Hierarchy	(a) Normal	(b) Inverted
Best fit	0.152	0.184
68 % C.L.	0.118 - 0.193	0.143 - 0.230
90 % C.L.	0.099 - 0.222	0.120 - 0.264



7.4σ exclusion of $\theta_{13} = 0$

($\delta_{CP} = 0$, $\sin^2 2\theta_{23} = 1$)

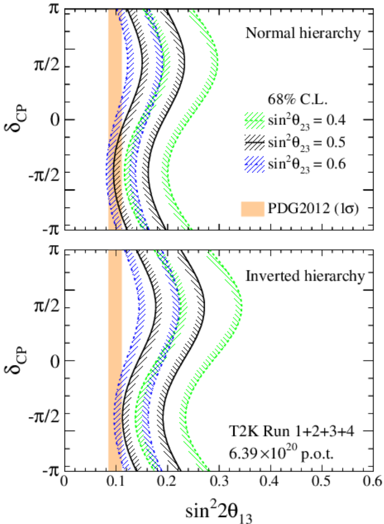


Method of evaluation	E^{rec} shape base $-2\Delta \ln \mathcal{L}$ distribution	Counting base Number of observed events
p-value	1.2×10^{-13}	4.1×10^{-12}
Significance	7.4σ	6.8σ

*Note that these are 1D contours for various values of δ_{CP}, not 2D contours

Effects of θ_{23}

- ν_e appearance probability is also dependent on θ_{23}
- Precise measurements of θ_{23} will become important to extract information about the other oscillation parameters in long baseline experiments.
- Currently there are several combined ν_e appearance + ν_μ disappearance analysis underway.



*Note that these are 1D contours for various values of δ_{CP}, not 2D contours

Summary

- T2K has made the observation of ν_e appearance from a ν_μ beam,
- $\theta_{13} = 0$ is excluded with a significance of 7.4σ ($\delta_{CP} = 0$, $\sin^2 2\theta_{23} = 1$).
- Improvements to the analysis have significantly enhanced the sensitivity to ν_e appearance.
- A new fitting algorithm, fiTQun, removes 70% of the π^0 background relative to the previous analysis.
- T2K has less than $1/10^{th}$ of its total expected data, so stay tuned for more exciting results.