

# Observation of Electron Neutrino Appearance in a Muon Neutrino Beam

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# Neutrinos in 2010 (Theory)

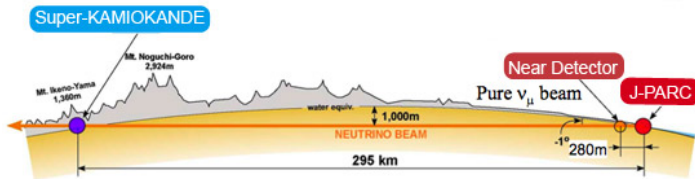
- Theoretical basis for neutrino oscillations was well established -  $U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\text{CP}})$

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) &\simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \\
 &- \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \frac{\Delta m_{21}^2 L}{4E} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \sin \delta_{\text{CP}} \\
 &+ (\text{CP even term, solar term, matter effect term}), \quad (1)
 \end{aligned}$$

# Neutrinos in 2010

- 1998 - Super Kamiokande (SK) finds evidence of oscillations in atmospheric and solar neutrinos
- Other evidence of oscillations from non-controlled sources (eg. nuclear reactors - KamLAND)
- However, no direct observation of flavor oscillations yet!

## T2K to the rescue

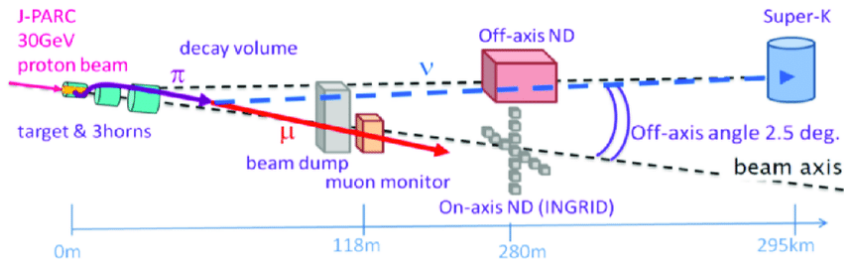


- Produce  $\nu_\mu$  at JPARC
- If you see  $\nu_e$  at SK, you've seen oscillations!

## Making the $\nu$ beam

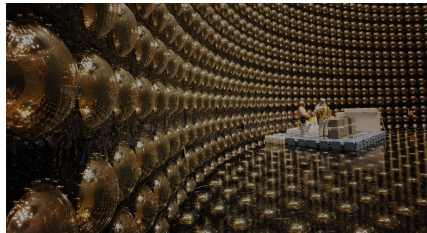
- Positive signal is an excess of  $\nu_e$  - so need original neutrino beam to be very pure  $\nu_\mu$
- Oscillation length depends on  $\nu$  energy - would be nice to tune this
- Beam intensity and direction needs to be measured to correlate signals from SK
- R&D from previous experiments helped a lot with beam characterisation (eg. MC simulations)

# JPARC



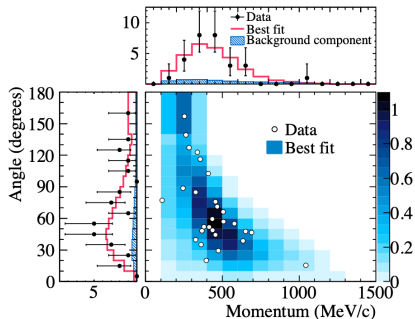
# SuperK

- Water Cherenkov detector:  
 $\nu \rightarrow \text{lepton} \rightarrow \gamma$
- Light picked up by set of PMTs on detector wall
- Made up of inner (ID) and outer detector (OD)



# Findings

- Appearance of electron neutrino in a muon neutrino beam
- 28 electron neutrino events detected with an energy distribution consistent with an appearance signal
- Further constraints on  $\delta_{CP}$
- Background:  $\approx 5$  electron neutrinos





# How can we distinguish positive events?

- Timing cut based on status of neutrino beam
- Energy cut to beam momentum (calibrated with near detectors)
- Cuts on Cherenkov ring shape and direction
- Background estimated with MC simulations

Selection	Data	$\nu_\mu \rightarrow \nu_e$ CC	$\nu_\mu + \bar{\nu}_\mu$ CC	$\nu_e + \bar{\nu}_e$ CC	NC	Total MC
Interactions in FV	-	27.1	325.7	16.0	288.1	656.8
FCFV	377	26.2	247.8	15.4	83.0	372.4
+Single-ring	193	22.7	142.4	9.8	23.5	198.4
+e-like PID	60	22.4	5.6	9.7	16.3	54.2
+ $p_e > 100 \text{ MeV}/c$	57	22.0	3.7	9.7	14.0	49.4
+No decay-e	44	19.6	0.7	7.9	11.8	40.0
+ $E_\nu^{\text{rec}} < 1250 \text{ MeV}$	39	18.8	0.2	3.7	9.0	31.7
+Non- $\pi^0$ -like	28	17.3	0.1	3.2	1.0	21.6

# Remaining uncertainty

- Errors on decay-electron rejection cut
- Uncertainty on Monte Carlo simulations
- Additional SK systematic uncertainties due to final-state interactions of pions

## After the paper

- Measure  $\nu_\mu$  disappearance, and therefore  $\theta_{23}$
- JPARC can filter beam with pion charge ( $\Pi^+ \rightarrow \nu_\mu$ ,  $\Pi^- \rightarrow \bar{\nu}_\mu$ ): can try to measure differences in oscillations related to CP violation
- Measured  $\delta_{CP} > 0$  with some confidence
- Hyper Kamiokande comes into play

# Conclusions

- Great success!
- First observation of electron neutrino appearance in a muon neutrino beam
- Step forward into constraining  $\delta_{CP}$
- Solid future effort with new experiments

## References

- *Observation of Electron Neutrino Appearance in a Muon Neutrino Beam* (K.Abe et al.)
- *Measurement of the muon beam direction and muon flux for the T2K neutrino experiment* (K.Suzuki et al.)
- *Remarks on the Unified Model of Elementary Particles* (M.Nakagawa et al.)
- *First combined analysis of neutrino and antineutrino oscillations at T2K* (K.Abe et. al.)
- *Recent results from the T2K experiment* (Marat Khabibullin)
- *t2k-experiment.org* (The T2K Collaboration)