The T2K Experiment

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Neutrinos in 2010 (Theory)

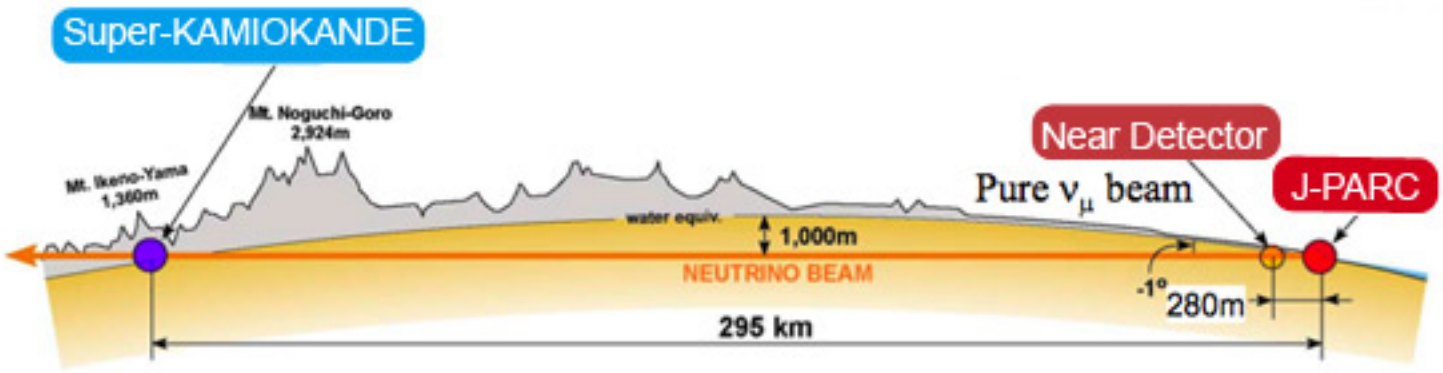
- Theoretical basis for neutrino oscillations was well established - $U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{cp})$

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

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

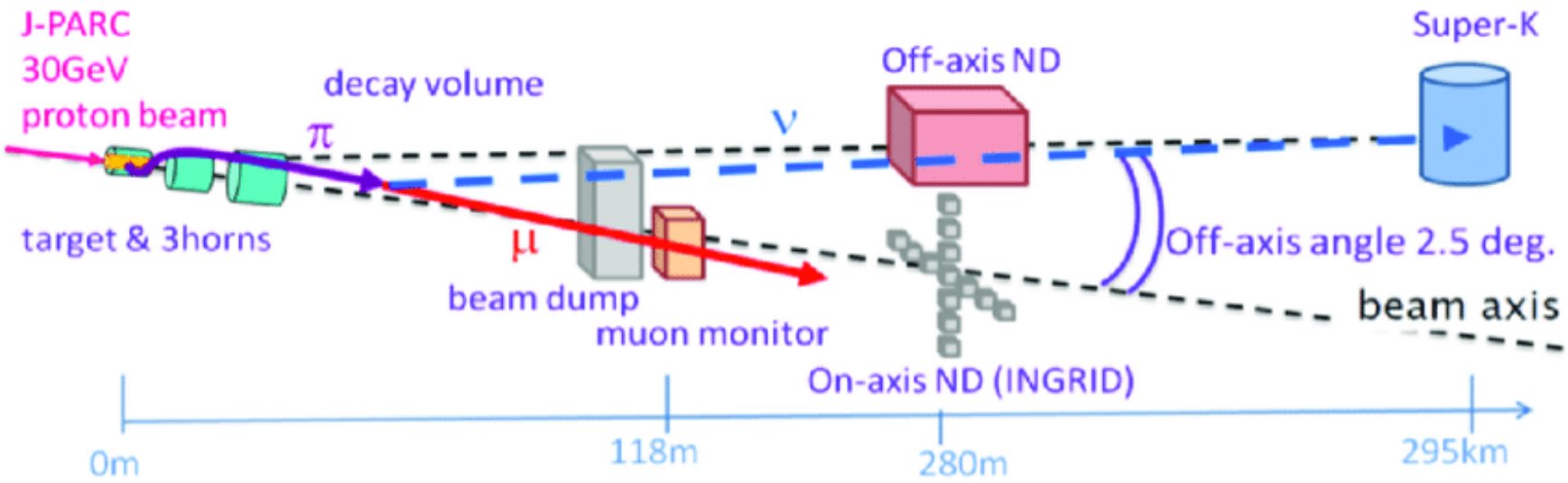


- Produce ν_μ at JPARC
- If you see ν_e at SK, you've seen oscillations!

Making the ν beam

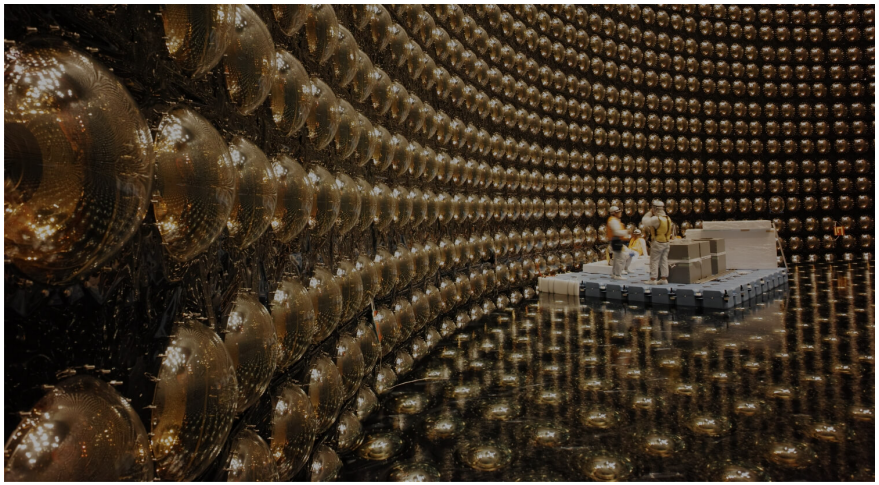
- Positive signal is an excess of ν_e - so need original neutrino beam to be very pure ν_μ
- Oscillation length depends on ν energy - would be nice to tune this
- Beam intensity and direction needs to be measured to correlate signals from SK
- R&D from previous experiments helped a lot with beam characterisation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

JPARC


J-PARC
30GeV
proton beam
target & 3horns
decay volume
π
μ
ν
beam dump
muon monitor
Off-axis ND
On-axis ND (INGRID)
Super-K
Off-axis angle 2.5 deg.
beam axis
0m
118m
280m
295km

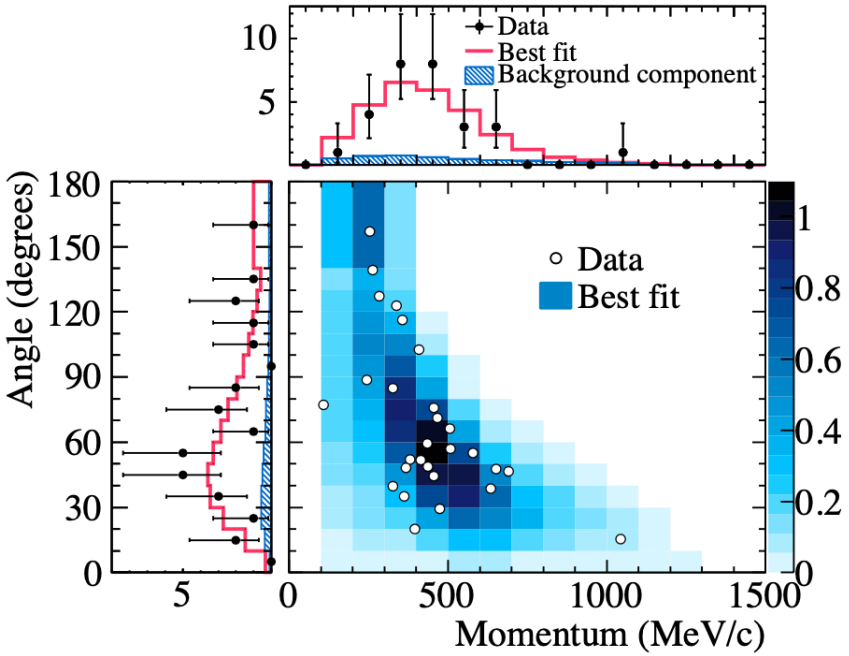
SuperK

- Water Cherenkov detector: $\nu \rightarrow$ 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 δ_{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	$\nu_\mu \to \nu_e$ CC	$\nu_\mu + \overline{\nu}_\mu$ CC	$\nu_e + \overline{\nu}_e$ 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>100MeV/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_ν^{rec}<1250MeV	39	18.8	0.2	3.7	9.0	31.7
+Non-π^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 ν_μ disappearance, and therefore θ_{23}
- JPARC can filter beam with pion charge ($\Pi^+ \to \nu_\mu$, $\Pi^- \to \bar{\nu}_\mu$): 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 costraining δ_{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)