Improved Event Selection of ν_e Charged-Current Single-Pion Production Interactions at T2K Far Detector

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

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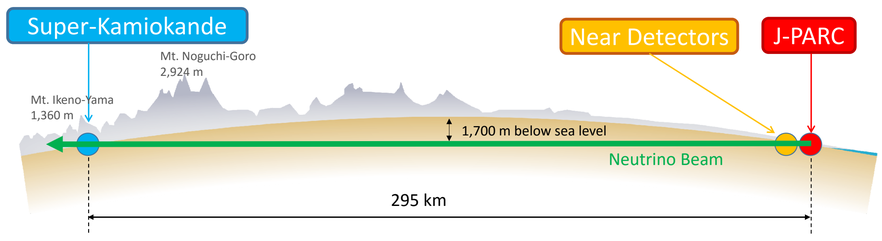
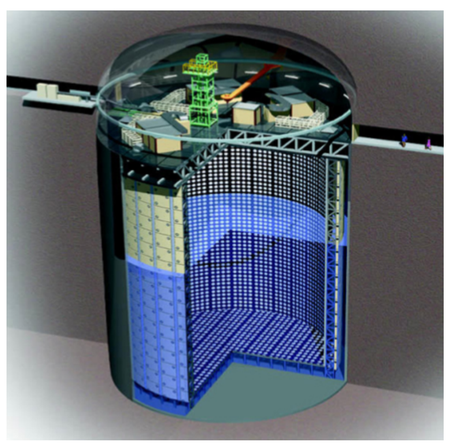
T2K

1. The T2K Experiment

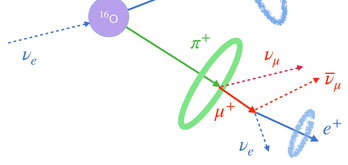


- **Long baseline** neutrino experiment that studies neutrino oscillations with a $\nu_\mu(\overline{\nu}_\mu)$ beam produced at J-PARC and a suite of near detectors and a far detector.
- The far detector, **Super-Kamiokande** (SK) captures **Cherenkov rings** produced by charged particles moving through water with excellent PID capability based on the ring shape.
- T2K's main goals are **precision measurements of atmospheric mixing parameters** and the **leptonic CP violating phase δ_{CP}**, key to explaining the matter-antimatter asymmetry in the universe.
- ν_e **appearance** from the T2K beam at SK gives sensitivity to δ_{CP}.

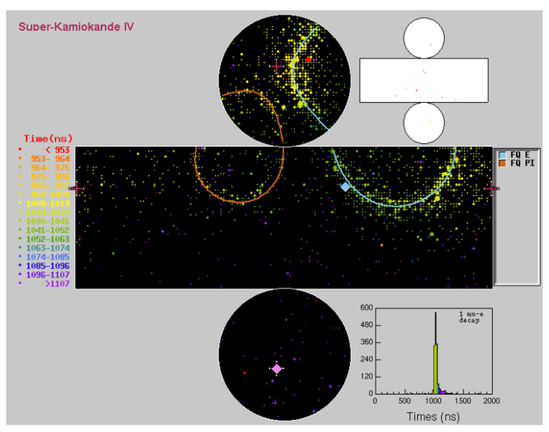


2. The multi-ring ν_e CC$1\pi^+$ sample

- Charged Current single pion production (**CC**$1\pi^+$) interactions are the **second-most dominant** interactions at T2K's beam energy after CC quasi-elastic interactions.



- T2K's past oscillation analyses already used a **single-ring ν_e CC$1\pi^+$ sample**, whose π^+ momentum is below its Cherenkov threshold.
- This sample had a **data excess** at **low momentum**[1], but was not statistically significant. The same sample with much higher statistics at SK also showed a similar trend, barring statistical fluctuations.
- Adding the multi-ring ν_e CC$1\pi^+$ sample with the π^+ momentum above its Cherenkov threshold **removes** the **threshold dependence** separating the two samples, and hence any biases coming from **pion kinematic modelling**.
- This also **increases the total ν_e CC$1\pi^+$ statistics by ~60%**, predicting ~6 more events to the ν_e appearance analysis for T2K's Run1-11 data taking period.



The multi-ring ν_eCC$1\pi^+$ sample has an $e^-+\pi^+$ topology† at SK

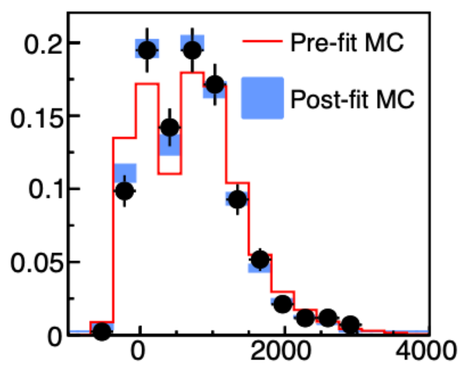
Fid. Volume + SK inner det.
↓
2 Reco. Rings
↓
One Michel electron
↓
Passes $e\pi/\pi\pi$ PID
↓
Passes $e\pi/\pi^0$ PID
↓
Reco. E_ν < 1.25 GeV

† Topology here is defined as the number and particle type of Cherenkov rings observed at SK.

Cut	ν_e CCQE	ν_e CC1π^+	$\nu_e/\overline{\nu}_e$ CC	ν_μ CCQE	ν_μ CC1π^+	$\nu_\mu/\overline{\nu}_\mu$ CC	NC	MC Total
FC	99.89	51.33	54.78	319.10	227.76	510.90	459.70	1723.46
FC, FV, E_{vis}	22.40	24.79	34.61	22.06	68.65	333.43	302.06	807.98
No. of Rings	5.41	10.77	7.62	11.36	24.16	46.17	159.67	265.17
No. of Decay e	0.14	6.25	1.87	4.31	10.33	20.89	17.08	60.86
$e\pi/\pi\pi$ PID	0.14	5.84	1.83	0.26	1.64	10.70	10.94	31.35
$e\pi/\pi^0$ PID	0.06	3.90	0.40	0.18	0.65	2.39	1.62	9.19
E_{rec} < 1.25 GeV	0.01	3.28	0.18	0.12	0.53	0.92	1.01	6.05

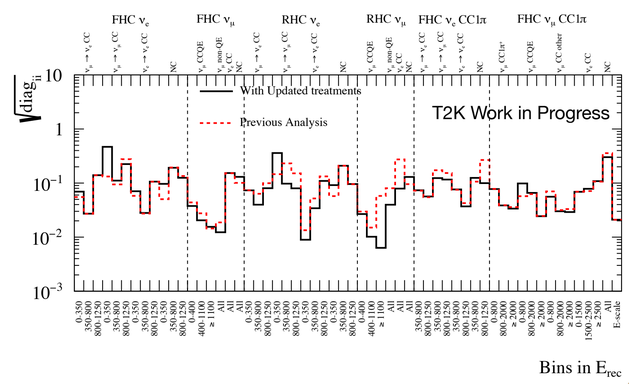
3. Improved SK detector systematics

- SK detector modelling errors, which manifest as **biases in PID variables** are estimated through **shifting and smearing** of PID variables using an **Markov Chain Monte Carlo approach**.
- A fit using **SK atmospheric data and MC** is performed on a total of **540 parameters** (one shift and smear parameter for each of the 10 PID variables x 9 topologies x 3 visible energy bins)
- The errors on T2K beam samples are then obtained through a **toy MC procedure** by sampling from these MCMC posteriors and reweighting the beam MC to obtain event rate variations.



Data-MC comparisons of a multi-ring PID parameter

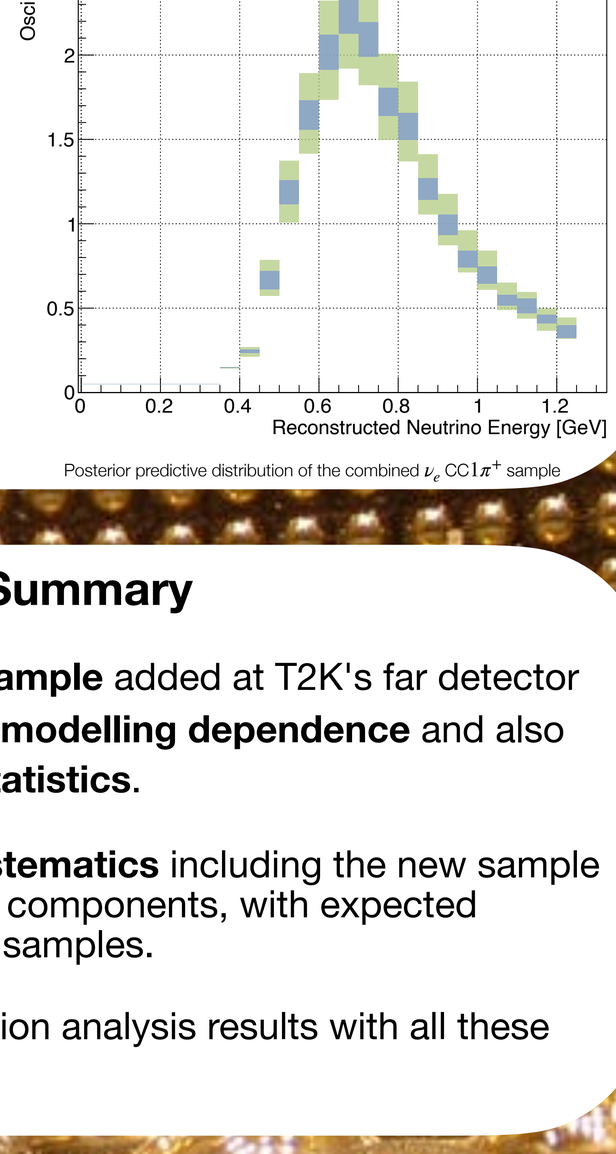
- For the next fit: Systematics on the **new sample's PID** and targets its associated $1e^- + 1\pi^+$ **topology** at SK.
- **Updated treatment** of **Michel electron tagging**, **improved implementation** of single-ring and multi-ring **event migrations**.
- Re-evaluation of **secondary interactions** and **photonuclear** uncertainties.
- Preliminary studies show finite reductions in errors for samples.



Comparison of diagonal elements from the SK detector covariance matrix

4. T2K's upcoming Oscillation Analysis

- The sample is now implemented in T2K's **oscillation analysis fitters**.
- The upcoming analysis includes **multiple improvements** in the **near detector**, and also in the **cross-section model**.
- Checked the **impact of near detector constraints** on the far detector predictions from an **Asimov fit**[2].
- **Data fits** are on their way!



Posterior predictive distribution of the combined ν_e CC$1\pi^+$ sample

5. Summary

- **New multi-ring ν_e CC$1\pi^+$ sample** added at T2K's far detector that **removes π^+ kinematic modelling dependence** and also **increases ν_e appearance statistics**.
- **Revamped SK detector systematics** including the new sample and other updates in various components, with expected reduction in errors across all samples.
- **Stay tuned** for T2K's oscillation analysis results with all these additions coming soon!

[1] Eur.Phys.J.C 83 (2023) 9, 782
[2] E. Miller, *Fitting T2K Near Detector Data using Markov Chain Monte Carlo, Neutrino 2024*

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