Joint Neutrino Oscillation Analysis of Atmospheric and Beam Data in the Super-Kamiokande Detector

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Neutrino mixing matrix

Flavour and mass eigenstates are related by

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

where

T2K, reactors

solar neutrinos

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

atmospheric neutrinos

Oscillation parameters

Mixing angles: θ_{12}, θ_{13} & θ_{23}

CP Violation parameter: δ_{CP}

Mass terms: Δm^2_{21} & Δm^2_{32}

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

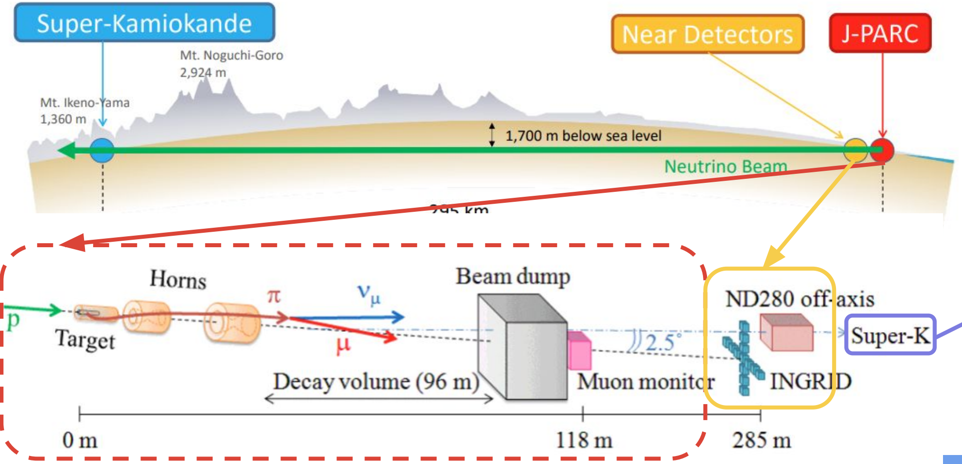
Experiments

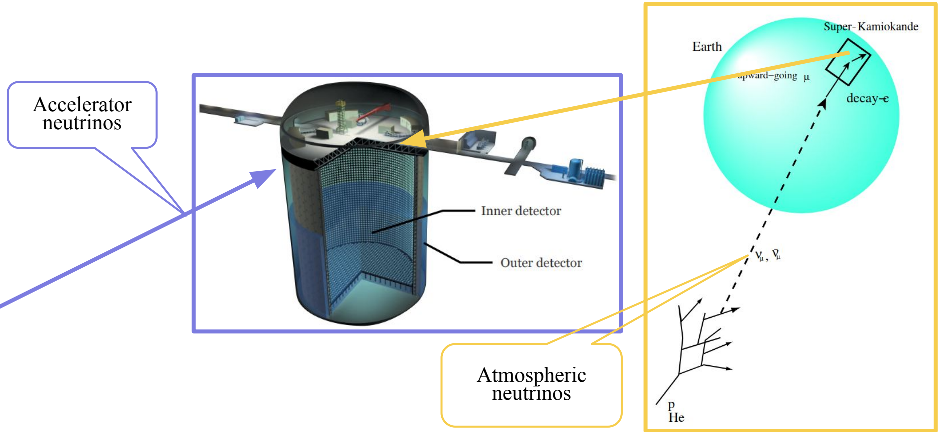
→ T2K:

- Measure neutrino oscillation parameters including CP violation in the neutrino sector
- Addressing the neutrino mass ordering
- Key Measurement:
    - $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ **appearance** (for δ_{CP} studies)
    - $\nu_\mu \rightarrow \nu_\mu$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ **disappearance** (for θ_{23}, Δm^2_{32})

→ SK:

- Detect neutrinos from T2K, the Sun, cosmic rays, and supernovae
- Major Contributions:
    - First confirmation of neutrino oscillations (1998, Nobel Prize 2015)
    - Supernova neutrino detection (SN 1987A)





Differences

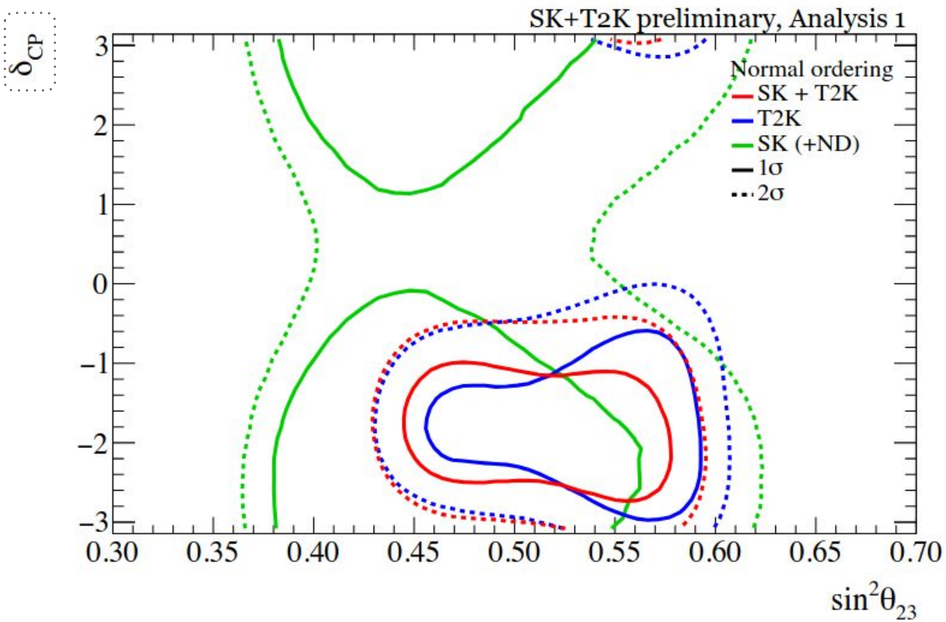
Feature	T2K Accelerator Neutrinos	SK Atmospheric Neutrinos
Source	Neutrinos from the J-PARC accelerator in Japan	Cosmic ray interactions in the atmosphere
Energy Source	0.2 – 2 GeV (narrow energy spectrum)	100 MeV to tens of GeV (wide spectrum)
Baseline (L)	~295 km (fixed distance)	Varies from ~20 km to ~12,700 km (diameter of Earth)
Neutrino Types	Mostly ν_μ and $\bar{\nu}_\mu$, with some ν_e	Mixture of ν_μ, $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$
Matter Effects	Minimal, as neutrinos travel short distance	Strong matter effects for neutrinos as they are traveling large distance through Earth

Joint Fit

Parameter	T2K Sensitivity	SK Atmospheric Sensitivity	Combined Benefit
δ_{CP} (CP violation phase)	Sensitive via $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance	Small contribution	Breaks degeneracy with mass ordering
sign(Δm^2_{32}) (Mass Ordering)	Weak sensitivity	Sensitive via matter effects	Helps resolve true hierarchy

Systematic Model	Flux: The beam and atmospheric flux models are independent	Cross-section: 1. Low energy samples (T2K & SK Sub-GeV) 2. High energy samples (SK only)	Detector: There is correlation between SK and T2K detector errors

Joint Fit Result



Comparison of the 2D posterior distribution for T2K-only and SK-only (with T2K near detector constraint) fits compared to the joint SK+T2K fit.

1. CP conservation (δ_{CP}= 0, π) is excluded < 2σ
2. Slightly prefers the normal mass ordering

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Joint Fit first Result

Comparison of the 2D posterior distri) fits compared to the joint SK+T2K fit.

1. CP conservation (δ_{CP}= 0, π) is excluded around 2σ
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FUTURE PLANS

- **Incorporating Additional Data**
  - SK Phase I-III, V
  - T2K Multi-ring samples (availability depends on cross-section model)
- **Improvement in the systematic uncertainties for the second Joint-Fit**
- **Cross-Section & Flux Model Updates**
  - After 2022 major updates have been made to Cross section and Flux Models
- **Correlated Flux Model Development**
  - The beam and atmospheric flux models were independent for first Joint-Fit analysis

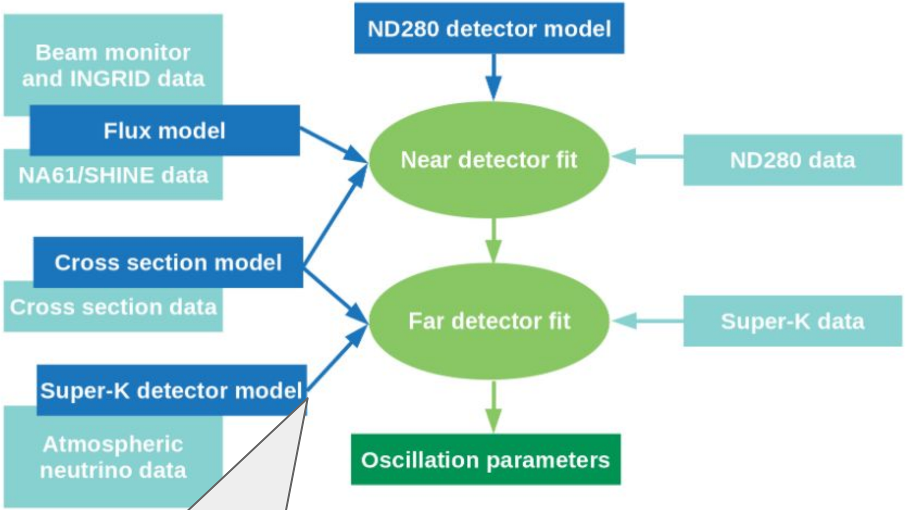
Hoping for the better results in the second Joint-Fit Analysis !!!!!!!

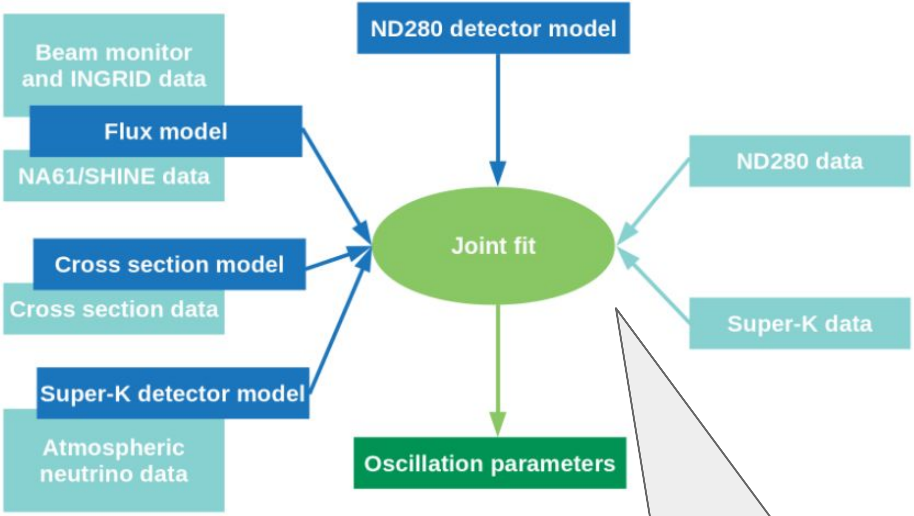
References

1. First joint oscillation analysis of Super-Kamiokande atmospheric and T2K accelerator neutrino data → Only publication as of now
2. Combined neutrino oscillation analysis between Super-Kamiokande and T2K by Aoi Eguchi
3. Joint Analysis between Super-Kamiokande atmospheric and T2K data by Zhenxiong Xie
4. T2K and T2K+SK Joint Fit by Tristan Doyle
5. T2K+SK Joint Beam and Atmospheric Fit by Dan Barrow

Backup

Oscillation analysis strategy





Sequential analysis: first fit near detector data, then fit SK data

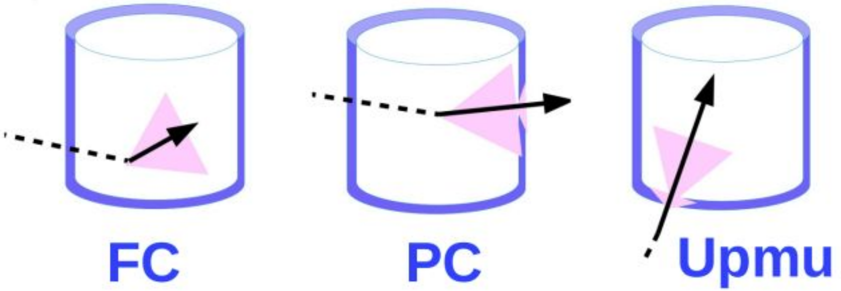
Both fitting approaches produce consistent results

Joint analysis: simultaneous fit to near and far detector data

Joint Fit (Samples)

SK-IV atmospheric (18 samples) and the T2K Run 1-10 accelerator (5 samples) neutrinos

Sample name	Category	Selection			
SubGeV elike 0de	Fully Contained (FC)	Sub-GeV	Single ring	e-like	0 decay-e
SubGeV elike 1de					1 decay-e
SubGeV mulike 0de				μ-like	0 decay-e
SubGeV mulike 1de					1 decay-e
SubGeV mulike 2de					$\geq$ 2 decay-e
SubGeV pi0like			Two rings	Two e-like rings and pass M_{inv} cut	
MultiGeV elike nue		Multi-GeV	Single ring	e-like	$\geq$ 1 decay-e
MultiGeV elike nuebar					0 decay-e
MultiGeV mulike				μ-like	
MultiRing elike nue			Multi rings	e-like	Pass MME likelihood cut and ν_e-like
MultiRing elike nuebar					Pass MME likelihood cut and $\bar{\nu}_e$-like
MultiRingOther					Fail MME likelihood cut
MultiRing mulike				μ-like	
PCStop	Partially Contained (PC)	Smaller charge deposition in outer detector			
PCThru		Larger charge deposition in outer detector			
UpStop mu	Up-going Muon (UpMu)	Stopping			
UpThruNonShower mu		Through-going non-showering			
UpThruShower mu		Through-going showering			



Cut	FHC/RHC 1Rμ	FHC/RHC 1Re	FHC 1Re1de
Min. E_{vis}	$E_{\text{vis}} > 30$ MeV		
Min. momentum	$p_\mu > 200$ MeV	$p_e > 100$ MeV	
Fiducial volume	$d_{\text{wall}} > 50$ cm $d_{\text{to-wall}} > 250$ cm	$d_{\text{wall}} > 80$ cm $d_{\text{to-wall}} > 170$ cm	$d_{\text{wall}} > 50$ cm $d_{\text{to-wall}} > 270$ cm
Decay electron	≤ 1	$= 0$	$= 1$
Max. E_{rec}	-	$E_{\text{rec}} < 1.25$ GeV	
Additional cut	π^+ rejection	π^0 rejection	

Future plans

Short-Term Goals (Attainable Soon)

- **Shift-Smear Detector Model**
  - Improves systematics treatment for joint fits
  - Step-size tuning and alignment to OA2024
- **Cross-Section & Flux Model Updates**
  - Transition to OA2024 models
  - Incorporate new ND samples
- **Incorporating Extra Samples**
  - SK Phase I-III, V
  - T2K Multi-ring samples (availability depends on cross-section model)

Long-Term Goals (Requires More Work)

- **Hybrid Pi0 Sample Generation**
- **Event Migration**
  - Migration between sub-GeV samples feasible
  - Higher GeV migration requires event selection code changes
- **Momentum/Energy Scale Shifts**
  - Requires rewriting framework
- **SK Phase VI Implementation**
- **CC1pi Interaction Model Modifications**
- **Correlated Flux Model Development**