Muon neutrino and antineutrino disappearance analysis from T2K

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Neutrino oscillation physics with T2K

- T2K (Tokai-to-Kamioka): long-baseline accelerator neutrino experiment [1].
- ν_μ and $\bar{\nu}_\mu$ beam is measured with a set of near detectors [1] and then Super-Kamiokande [2] (SK) water-Cherenkov far detector 295 km apart.

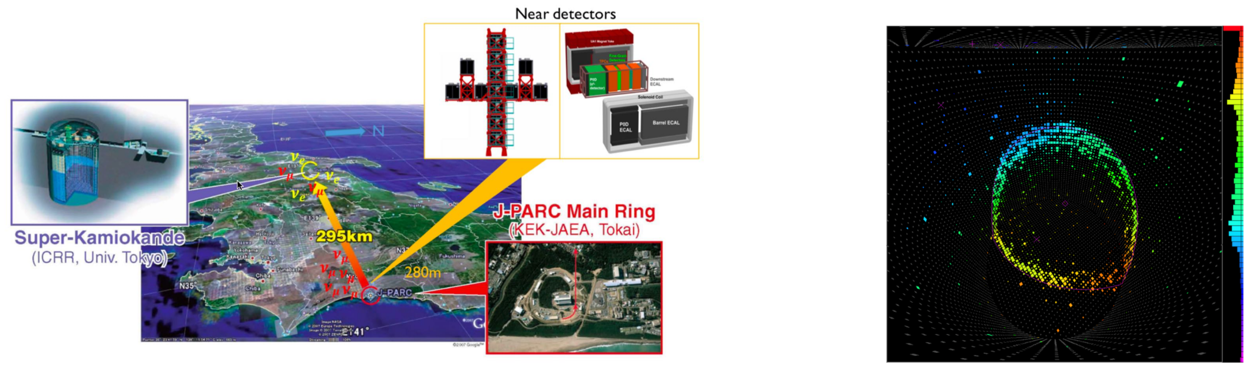

Figure 1: Left: The T2K detector complex, and the beamline from Tokai to Kamioka. Right: A Cherenov ring from a muon event inside Super-K.

- Recently, T2K excluded values of δ_{CP} at 3σ confidence for the first time [3].
- This analysis: $\mathbf{1.49 \times 10^{21}}$ protons on target (POT) in ν mode and $\mathbf{1.64 \times 10^{21}}$ in $\bar{\nu}$ mode (Run 1–9).

Muon neutrino and antineutrino disappearance

- **GOALS**: Test compatibility between ν_μ and $\bar{\nu}_\mu$ disappearance
- **CONTEXT**: Latest results from T2K oscillation fit [4]:

Sample	Prediction	Data
ν_μ	272.34	243
$\bar{\nu}_\mu$	139.47	140

$$\sin^2 2\theta_{13} = 0.0830,\ \delta_{CP} = -1.601$$
$$\Delta m^2_{32} = \Delta \bar{m}^2_{32} = 2.509 \times 10^{-3}\ \mathrm{eV}^2/\mathrm{c}^4$$
$$\sin^2 2\theta_{23} = \sin^2 2\bar{\theta}_{23} = 0.528$$

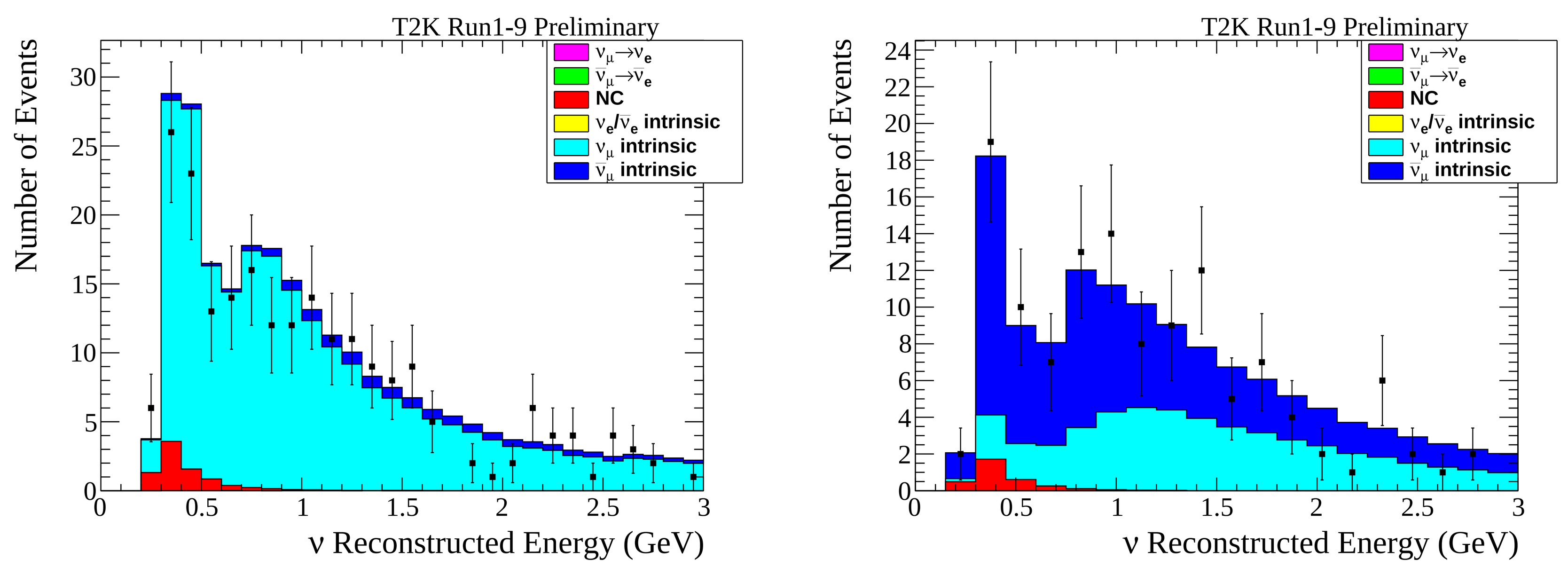

Figure 2: μ-like (left) and $\bar{\mu}$-like (right) signal events reconstructed inside Super-K (points) superposed with simulation (histograms).

- 2 methods to test if more ν_μ than expected hints at BSM
  - 3-flavour fit with $\Delta m^2_{32}, \sin^2 2\theta_{23}$ for ν_μ and $\Delta \bar{m}^2_{32}, \sin^2 2\bar{\theta}_{23}$ for $\bar{\nu}_\mu$.
    $\Rightarrow$ Allows ν_ν and $\bar{\nu}_\mu$ to take different values for PMNS.
  - 2-flavour fit, not assuming the underlying PMNS model, and allow the mixing parameter to go to unphysical region.
    $\Rightarrow$ Allows ν_ν and $\bar{\nu}_\mu$ to take values **not** allowed by PMNS.

Analysis Strategy

- Follows the general T2K oscillation strategy, described in detail in [3].
- Super-K can not distinguish between $\nu_\mu/\bar{\nu}_\mu$.
  $\Rightarrow$ Use all samples from the beam operation mode $(\nu/\bar{\nu})$
- Sytematic uncertainties constrained from the unoscillated flux data fit.

Error source	ν-mode	$\bar{\nu}$-mode
Flux	4.3%	4.1%
Xsec (constr. by ND280)	4.7%	4.0%
Xsec (all)	5.6%	4.4%
Flux + Xsec (constr. by ND280)	3.3%	3.3%
Flux + Xsec (all)	5.4%	3.2%
SK detector effects+FSI+SI	3.3%	2.9%
Total	5.5%	4.4%

Table 1: Systematic uncertainty on the number of events in each of the $(\nu/\bar{\nu})$ muon-like samples broken down by uncertainty source.

- $\nu_\mu/\bar{\nu}_\mu$ parameters extracted from joint marginal maximum-likelihood fit.
- Frequentist C.L using the $\Delta\chi^2$ values for gaussian likelihood functions .

3-flavour fit

	ν_μ	$\bar{\nu}_\mu$
$\Delta \overset{(-)}{m}{}^2_{32}$	$2.47^{+0.08}_{-0.09} \times 10^{-3}\ \mathrm{eV}^2$	$2.50^{+0.18}_{-0.13} \times 10^{-3}\ \mathrm{eV}^2$
$\sin^2 \overset{(-)}{\theta}_{23}$	$0.51^{+0.06}_{-0.07}$	$0.43^{+0.21}_{-0.05}$

Table 2: Best fit values for ν_μ and $\bar{\nu}_\mu$ oscillation parameters assuming Normal Hierarchy.

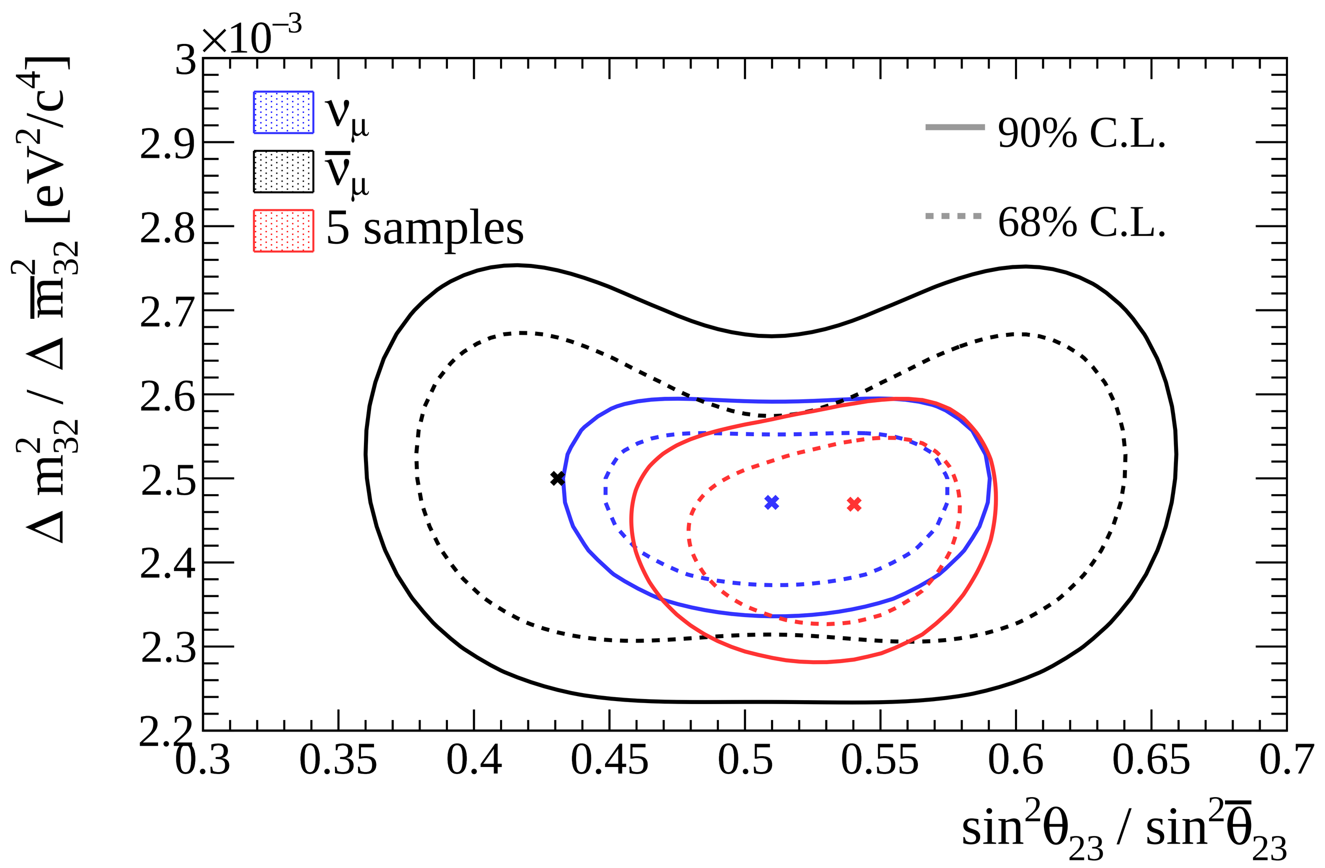

Figure 3: 68% and 90% confidence interval on the atmospheric parameters, for ν_μ, $\bar{\nu}_\mu$, and compared to the full T2K fit including the electron samples [4].

2- flavour fit

- Use modified version of the canonical two-flavor oscillation formula [5]:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \alpha \sin^2 1.267 \frac{\Delta m^2 L[\mathrm{km}]}{E[\mathrm{GeV}]}$$

- α emulates the mixing angle, but it is allowed to take values > 1.
- Effective mass can be related to the 3-flavour parameters:

$$\Delta m^2 = \Delta m^2_{32} + \sin^2\theta_{12}\Delta m^2_{21} + \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}.$$

	ν_μ	$\bar{\nu}_\mu$
$\Delta m^2/\Delta\bar{m}^2$	$2.49^{+0.08}_{-0.08} \times 10^{-3}\ \mathrm{eV}^2$	$2.51^{+0.15}_{-0.14} \times 10^{-3}\ \mathrm{eV}^2$
$\alpha/\bar{\alpha}$	$1.008^{+0.017}_{-0.016}$	$0.976^{+0.029}_{-0.029}$

Table 3: Best fit values for ν_μ and $\bar{\nu}_\mu$ oscillation parameters assuming Normal Hierarchy.

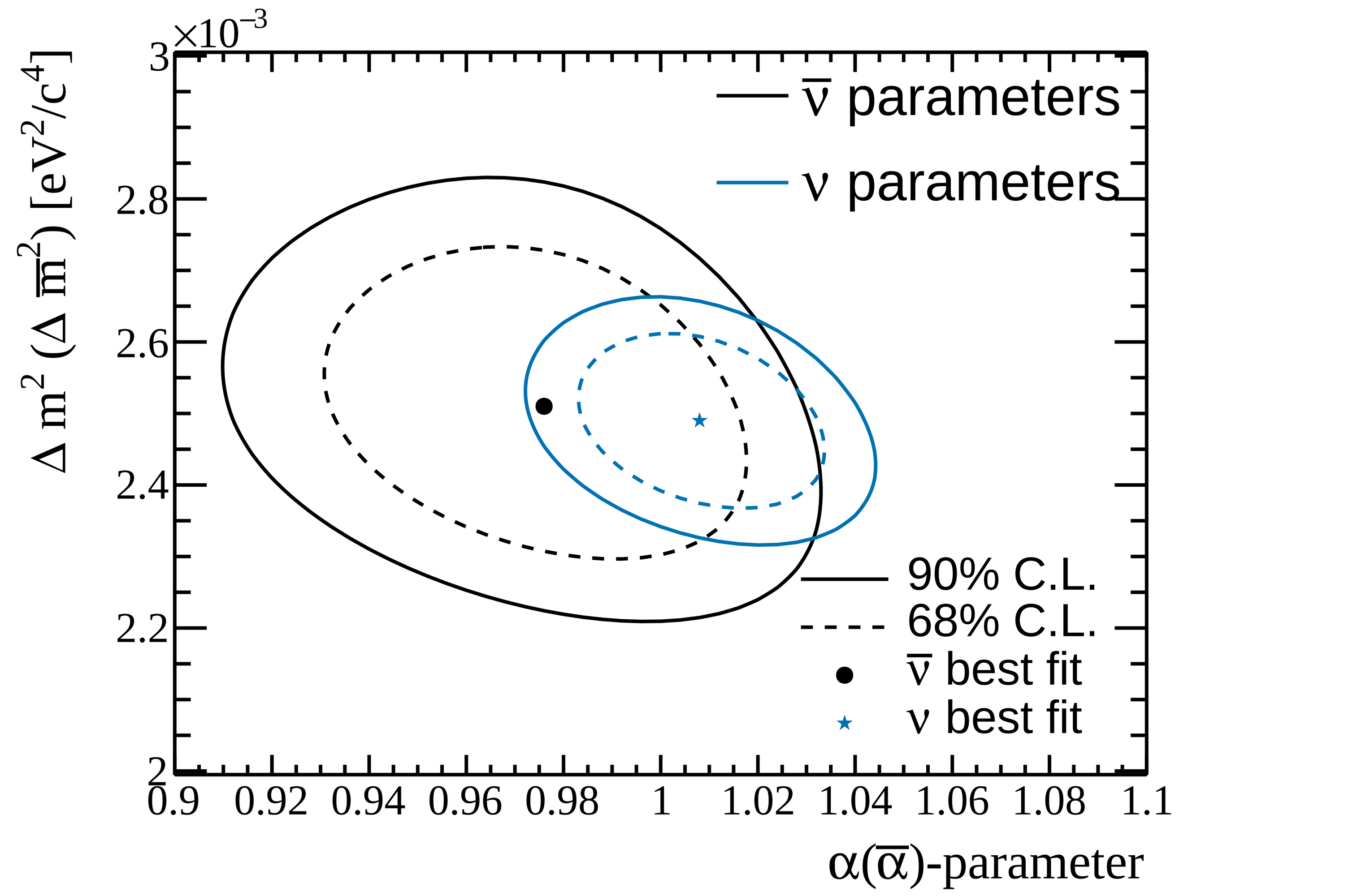

Figure 4: 68% and 90% confidence interval on the $\Delta m^2/\Delta\bar{m}^2$ with respect to $\alpha/\bar{\alpha}$.

Conclusions

NO significant incompatibility between ν_μ / $\bar{\nu}_\mu$ oscillation parameters, and **NO** significant deviation from PMNS.

References

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[3] K. Abe et al. Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations. *Nature*, 580(7803):339–344, 2020.
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[5] Hiroshi Nunokawa, Stephen J. Parke, and Renata Zukanovich Funchal. Another possible way to determine the neutrino mass hierarchy. *Phys. Rev. D*, 72:013009, 2005.

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