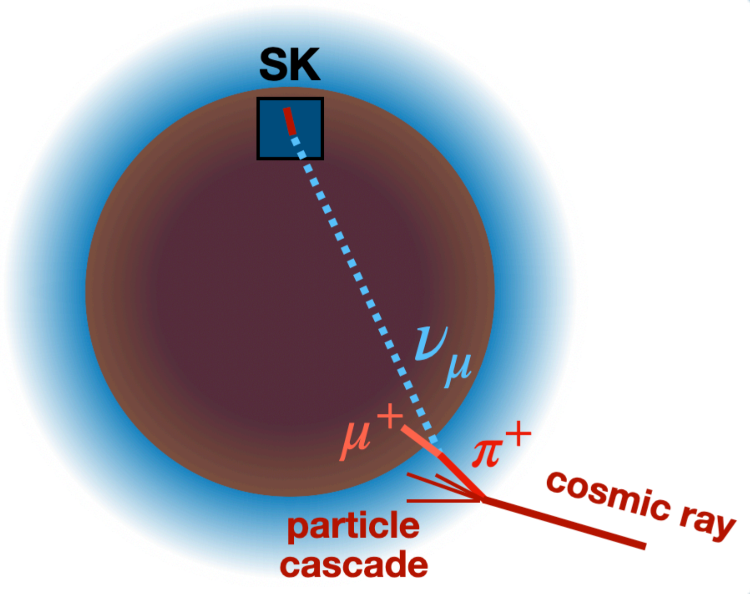
Oscillatory pattern of atmospheric muon neutrino disappearance in Super-Kamiokande

Mariusz Girguś (University of Warsaw) for the Super-Kamiokande Collaboration, mariusz.girgus@fuw.edu.pl

NEUTRINO 2026 at University of California, Irvine

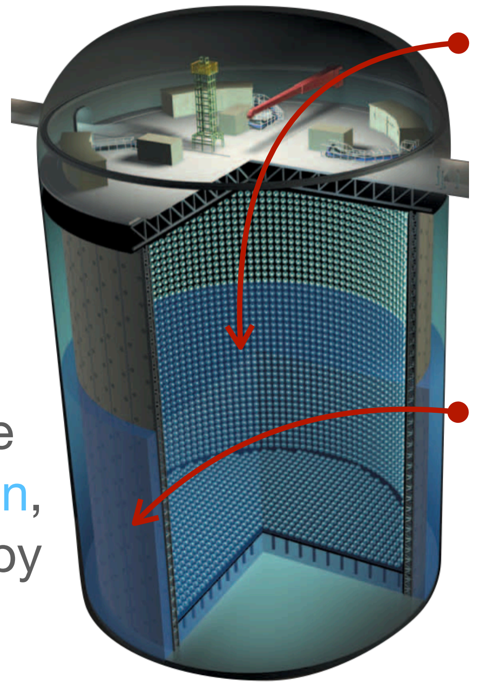
1. Atmospheric neutrinos

- Produced when cosmic ray particles collide with atomic nuclei in our atmosphere.
- Disappearance of atmospheric $\nu_\mu/\bar{\nu}_\mu$ is sensitive to $|\Delta m^2_{32}|$ and θ_{23}.
- Broad range of L/E containing multiple oscillation minima and maxima of survival probability.



2. Super-Kamiokande (SK) detector

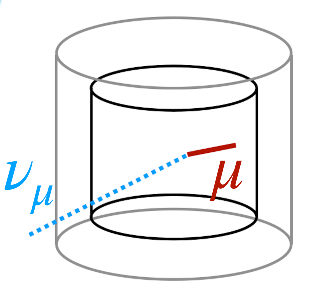
- SK is a 50-kton water-Cherenkov detector located in Japan.
- Charged particles created in neutrino interaction produce Cherenkov radiation, which is detected by the photomultiplier tubes (PMTs).



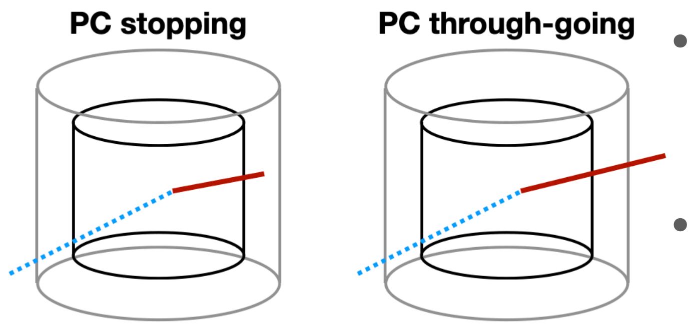
Inner detector (ID)
$\sim$ 11000 PMTs used to reconstruct important properties of neutrino (energy, direction, flavor).

Outer detector (OD)
$\sim$ 2000 PMTs used mainly to identify cosmic muons entering the detector. They also tell us if charged particles leave the ID.

3. μ-like events and improved reconstruction



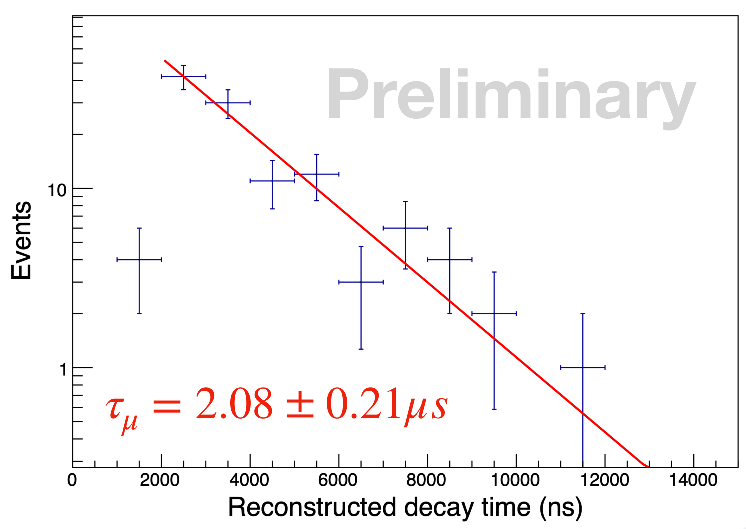
- Fully Contained events: majority of our dataset.
- μ-like Cherenkov ring (sharp edges).



- Partially Contained events: less frequent, but have better pointing accuracy.
- Poor energy resolution for through-going events.

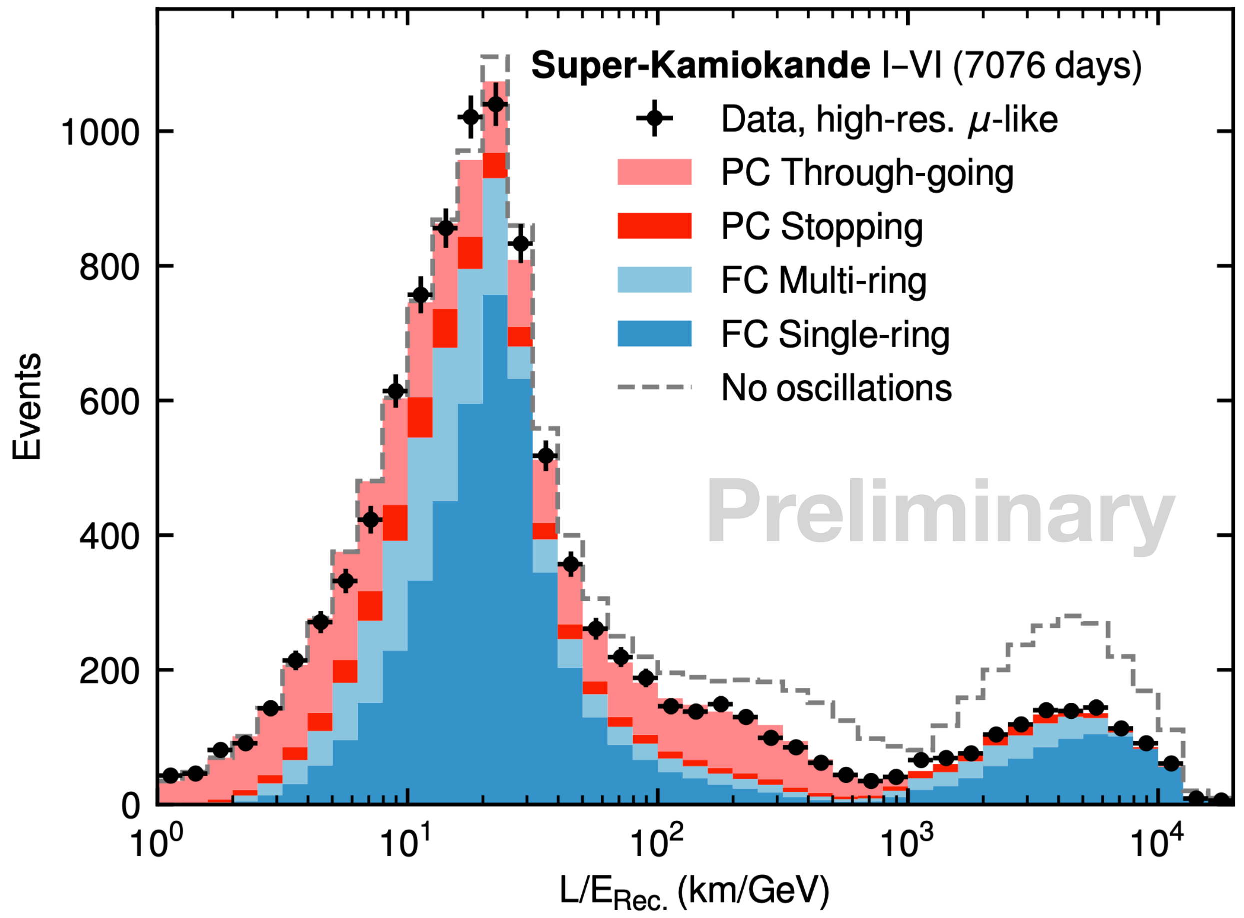
- In order to improve energy estimation for PC events, a new PC stopping/through-going classifier was developed.
- Classification is performed by a Boosted Decision Tree with four input variables:
  - ✱ OD charge ratio: charge is correlated with the muon track length inside of the OD
  - ✱ Concentration of OD hits
  - ✱ OD decay electron flag (used for the first time)
  - ✱ Number of tracks

Tagged OD decay electrons

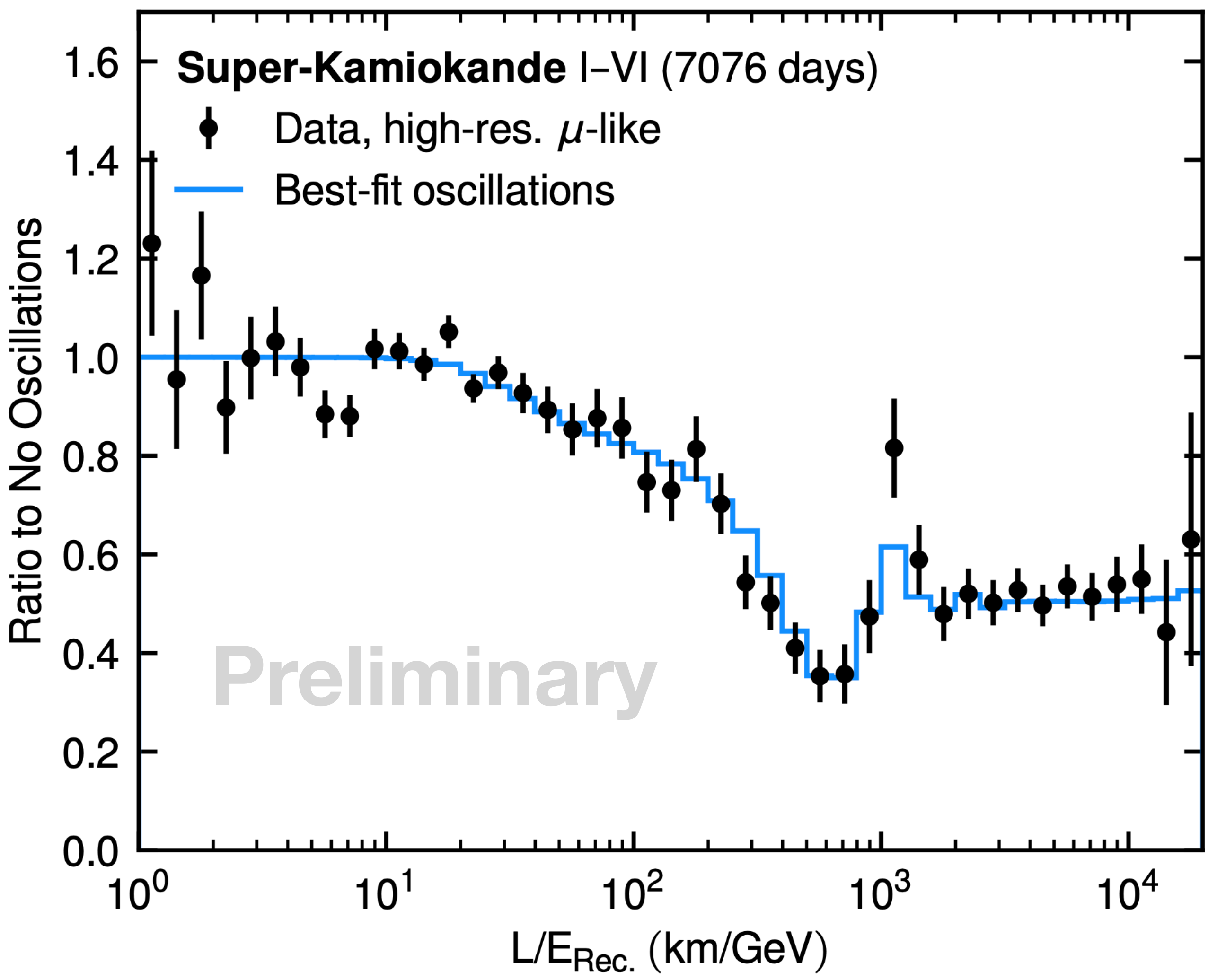


4. High resolution samples

- Resolution of L/E corresponds to the spread of true L/E for fixed reconstructed zenith angle and neutrino energy. Worst resolution - horizontal and low energy events.
- Only high resolution events are binned in L/E, other events are binned according to the zenith scheme [1].
- Resolution threshold depends on L/E [1] - high precision for high values of L/E without removing all horizontal events from the intermediate region of L/E.



5. Improved resolution cut

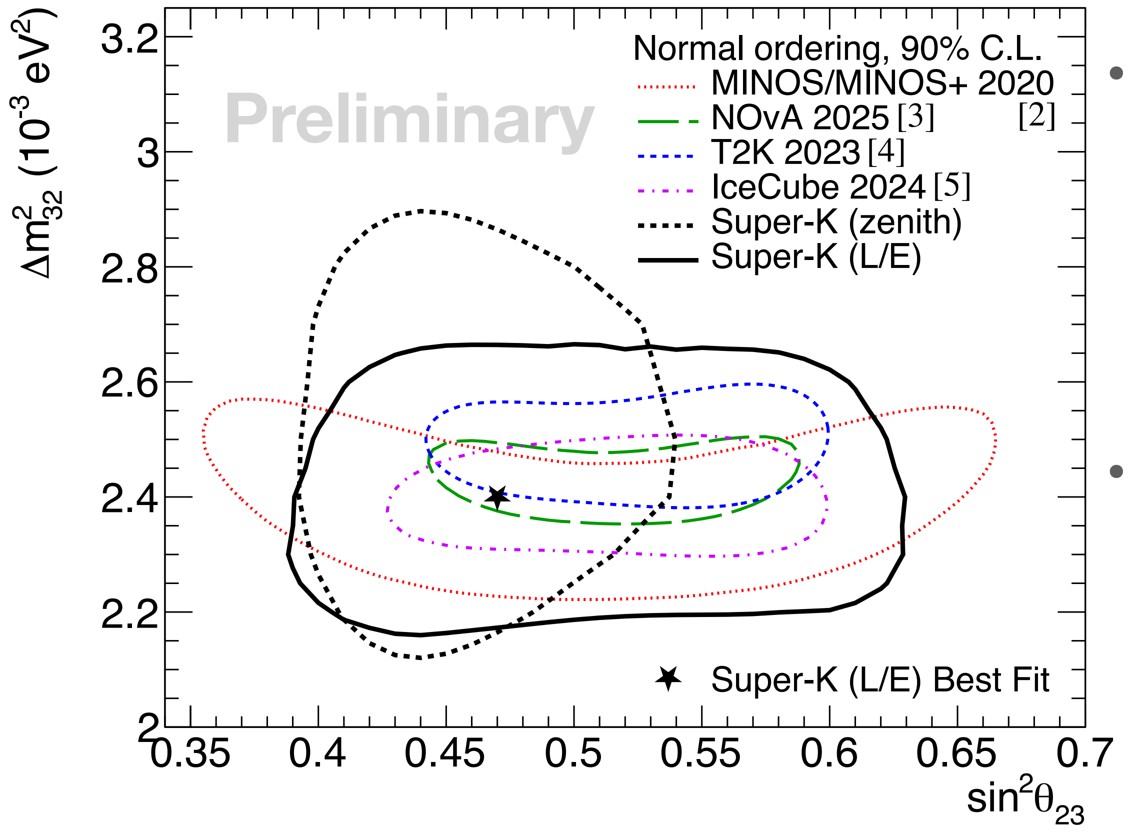


- Resolution cut balances precision and statistics in each bin, using figure of merit:

$$\sum |L/E_{\mathrm{Rec.}} - L/E_{\mathrm{True}}|/\sqrt{N}$$

- Resolution cut was tuned on Monte Carlo to maximize the significance of the first oscillation minimum and second oscillation maximum.

6. Results and prospects



- Even though this analysis studies only μ-like samples, as opposed to the SK's zenith analysis, it is more sensitive to $|\Delta m^2_{32}|$.
- However, since the e-like samples are not included, there is no sensitivity to the octant of θ_{23}.

In the future:
Introduce L/E scheme for μ-like samples to the full oscillation analysis and take advantage of the improved sensitivity to $|\Delta m^2_{32}|$ to provide stronger constraint on other oscillation parameters.

References

[1] T. Wester (NEUTRINO 2024 poster)
https://doi.org/10.5281/zenodo.13234652

[2] Phys. Rev. Lett. 125, 131802 (MINOS+)

[3] Phys. Rev. Lett. 136, 011802 (NOvA)

[4] Eur.Phys.J.C 83 (2023) 9, 782 (T2K)

[5] Phys. Rev. D 108, 012014 (IceCube)

Author would like to acknowledge the support of the National Science Centre (UMO-2022/46/E/ST2/00336), the Ministry of Science and Higher Education (2023/WK/04), in Poland; the European Union's Horizon 2020 Research and Innovation Programme H2020-MSCA-RISE-2019 SK2HK grant agreement no. 872549.