Constraining Tau Neutrino Appearance to Improve the Measurement of the Mass Ordering with Atmospheric Neutrinos in Super-Kamiokande

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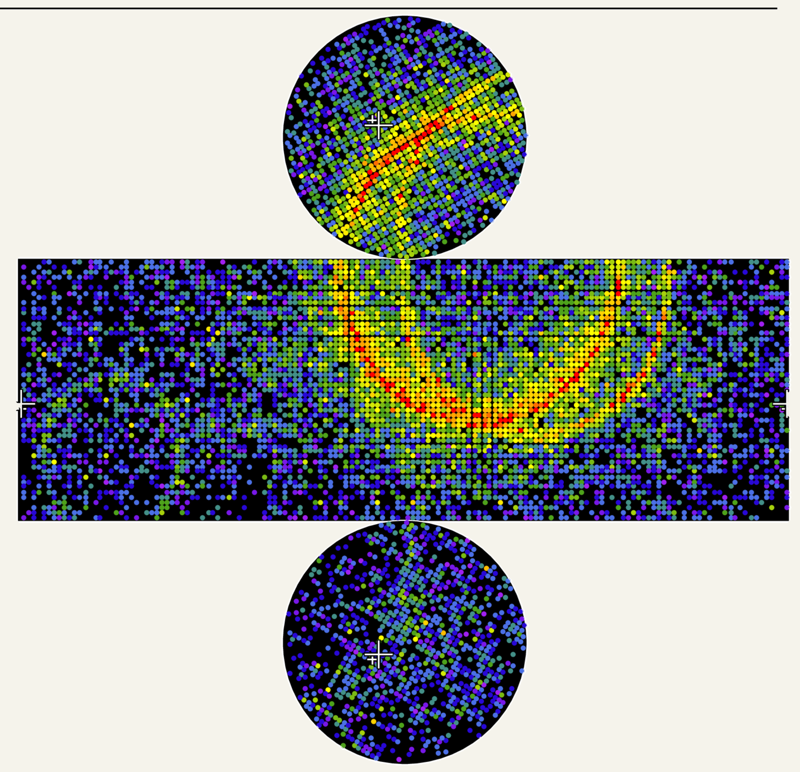
Super-Kamiokande

Super-Kamiokande (Super-K) is a large water Cherenkov detector located in Mount Ikenoyama in Japan. Super-K measures charged particles as rings read out by PMTs.

From these rings, particle ID and momentum are reconstructed.

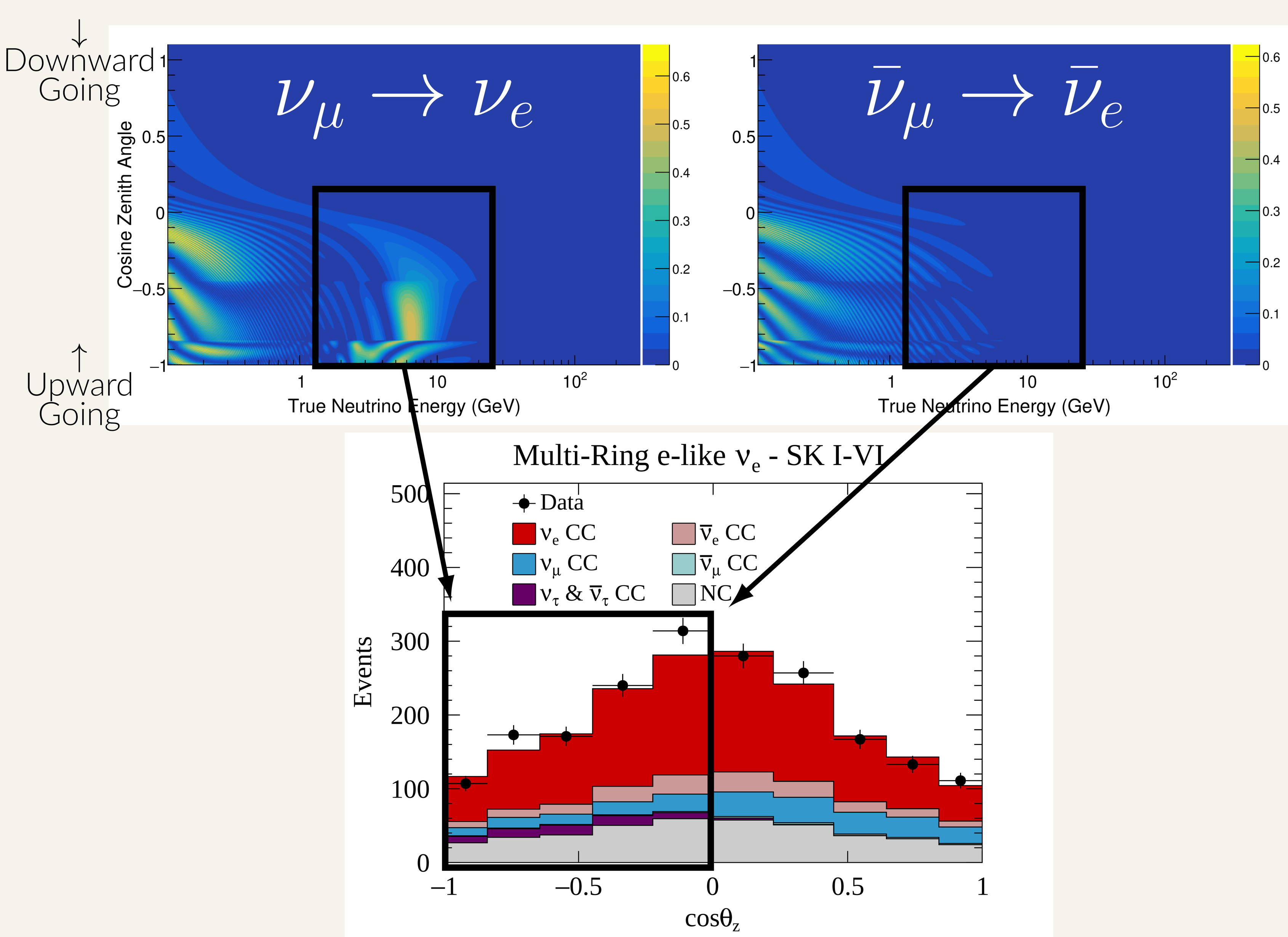
For this analysis, we use Super-K periods I-VI, corresponding to 7075.7 days of livetime.



Measuring the Mass Ordering with Atmospherics

The neutrino mass ordering can be measured with atmospheric neutrinos by detecting resonant electron neutrino appearance for normal ordering, or electron antineutrino appearance for inverted ordering.

Tau neutrinos populate the same region of upward going electron neutrinos in our MultiGeV samples, making it difficult to sort out this matter resonance from the tau neutrino content.



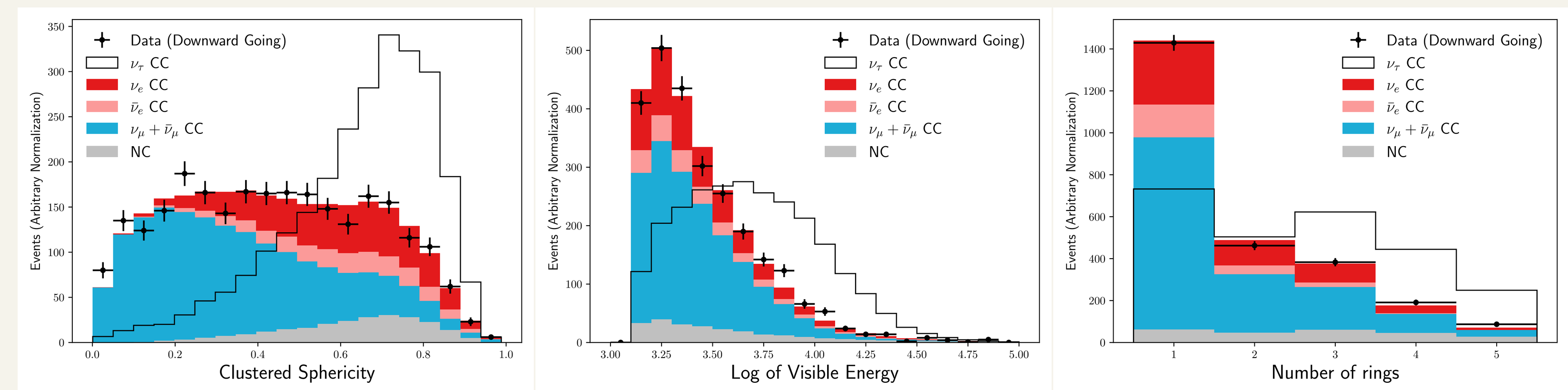
Tau neutrinos are usually easy to keep out of muon neutrino samples, but are a tricky background for electron neutrino samples.

Tau decays often include π^0s or electrons which create e-like rings, while prominent mu-like rings from muon neutrinos are easier to identify.

ν_τ Classifier

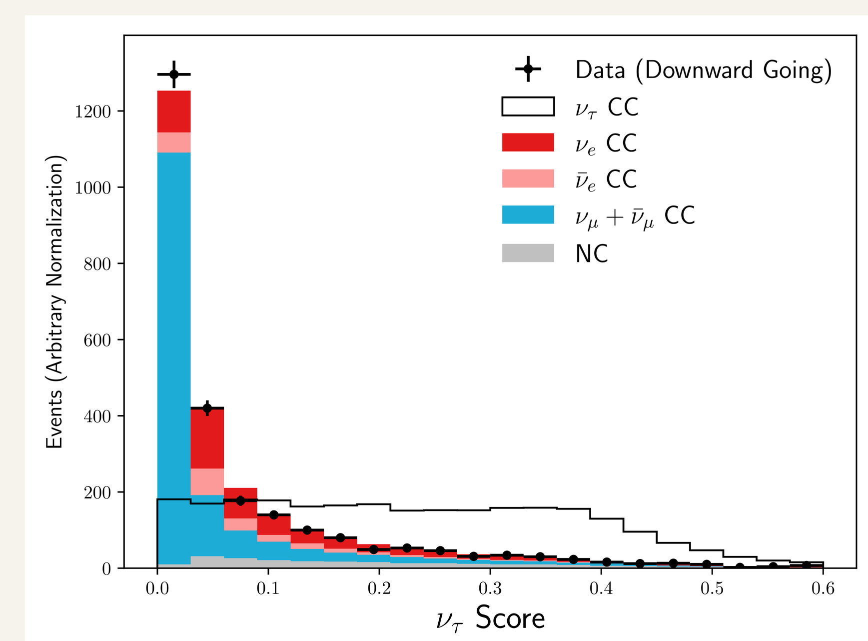
Super-K can't resolve the τ from ν_τ charged current interactions because of its short lifetime, but tau neutrinos can be resolved statistically.

To constrain tau neutrino content, a tau neutrino classifier was trained, built using a multi-layer perceptron (MLP).



This classifier takes 9 high level variables as input (3 examples shown above), outputting a score estimating the likelihood of the event being produced by a tau neutrino.

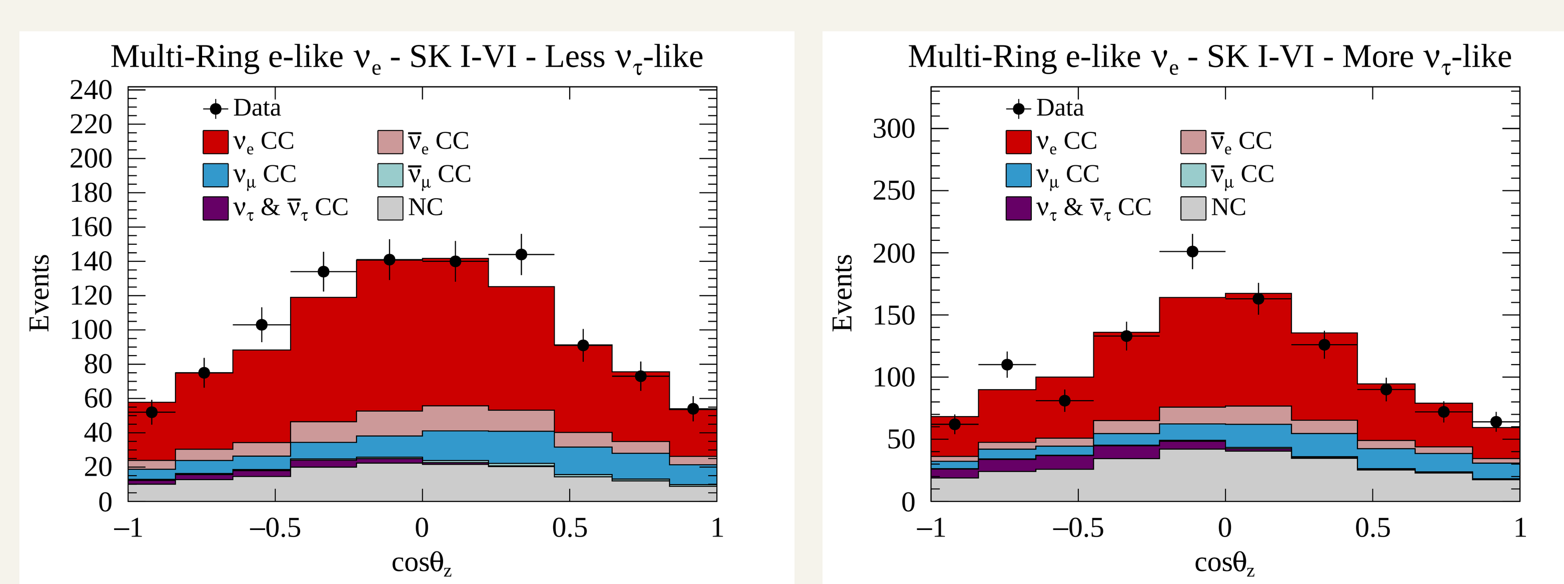
Tau neutrinos are hard to separate from NC, as the hadronic decays of the tau often look like NC.



Constraining the ν_τ Content of MultiGeV ν_e Samples

A constraint on tau neutrino content is implemented by adding a new binning dimension in terms of tau neutrino score.

Each MultiGeV electron neutrino sample is split into a more and less tau neutrino like part.



The more ν_τ-like subsample has $\sim$9% ν_τ contamination in the upward going region, while less ν_τ-like has $\sim$3%.

This scheme helps to better sort out the electron neutrino from tau neutrino content, **increasing sensitivity to mass ordering by 10%**, as well as some increase in sensitivity to the octant of θ_{23} and δ_{CP}.

It also constrains the ν_τ normalization and cross section systematic, one of the most important systematics for measuring the mass ordering.

New Analysis Results

This constraint on tau neutrinos is included in Super-K's new atmospheric neutrino analysis, along with several other improvements:

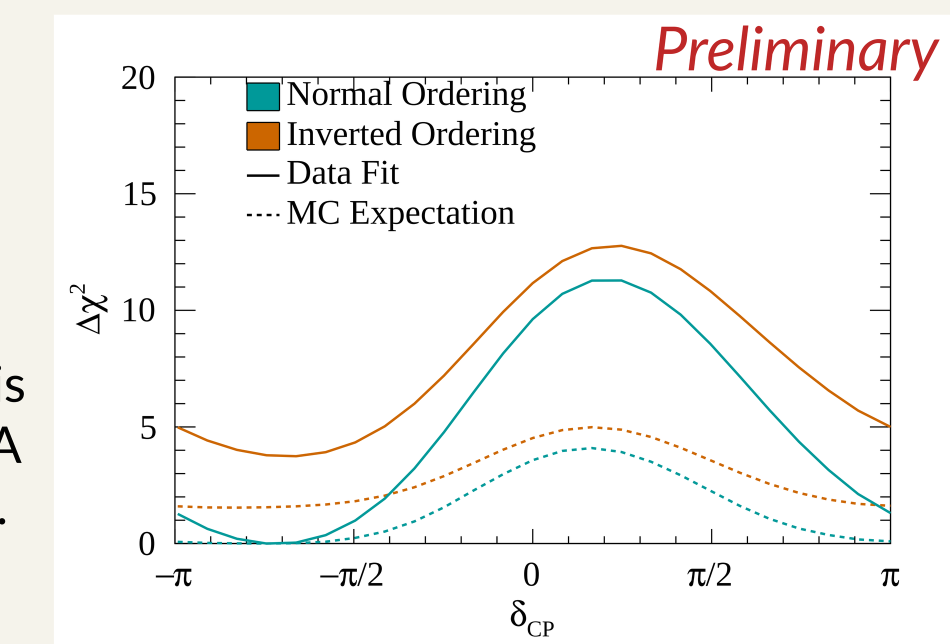
- Addition of period SK-VI (the first period including gadolinium)
- Neutron-corrected energy and direction estimators for SK-VI
- Improvements to the MultiGeV Multi-Ring Boosted Decision Tree (BDT)
- Improvements to the cross section model

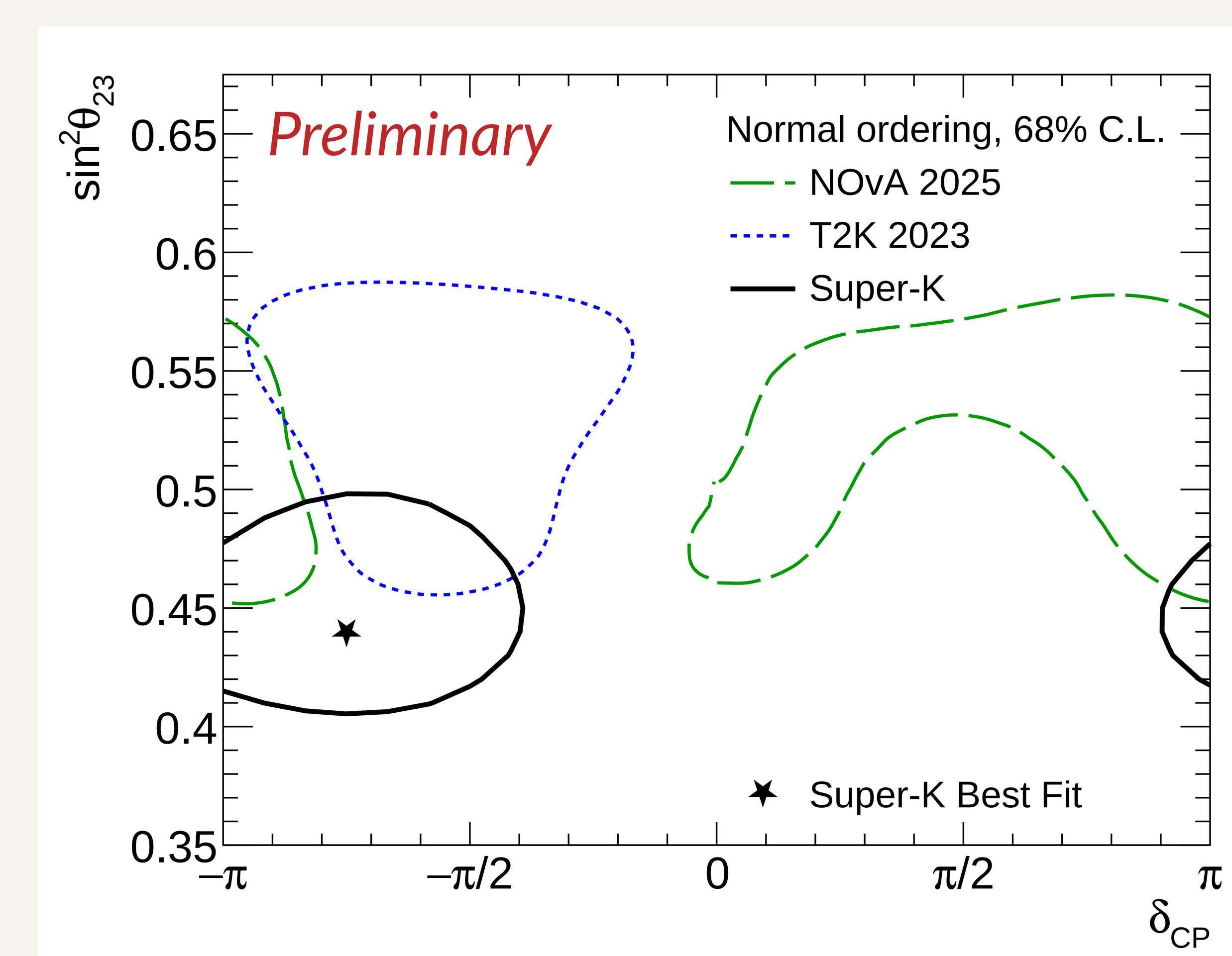
Super-K's new measurement of mass ordering is consistent with normal ordering (NO), at p_{NO} = 0.7, and disfavors inverted ordering (IO) at p_{IO} = 0.04.

This corresponds to a CL_s of 0.14 in favor of NO.

δ_{CP} rejection higher than Asimov, but within 95% of Poisson fluctuated toys.

Super-K's new measured δ_{CP} best fit is near $-\frac{3\pi}{4}$. This value lies in between NOvA and T2K's preferred values.





Super-K also still prefers the lower octant of θ_{23}, more strongly now, unlike most other experiments.

References: [1] Phys. Rev. D 109 (2024) 072014 [2] Phys. Rev. Lett. 136 (2026) 011802 [3] Eur. Phys. J. C 83 (2023) 782

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