NuFact 2023

(Seoul, South Korea)

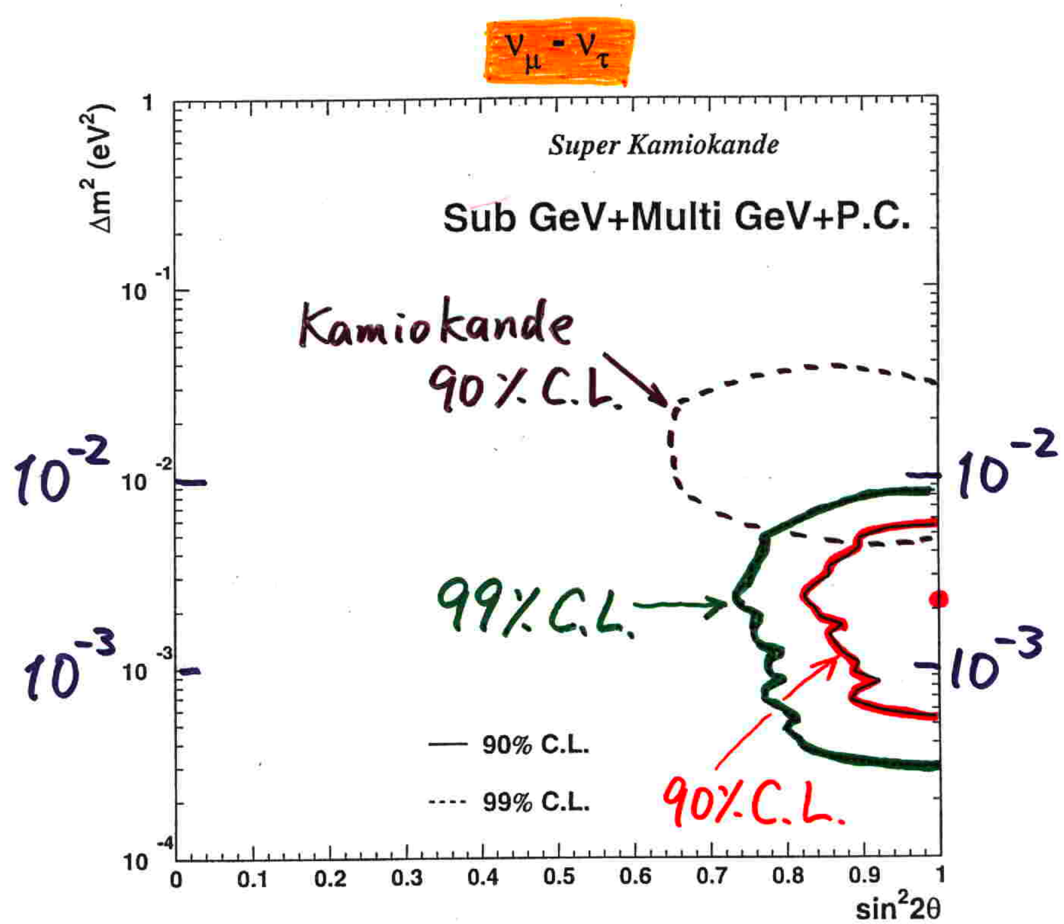
Overview of Atmospheric neutrinos

Alfonso Garcia

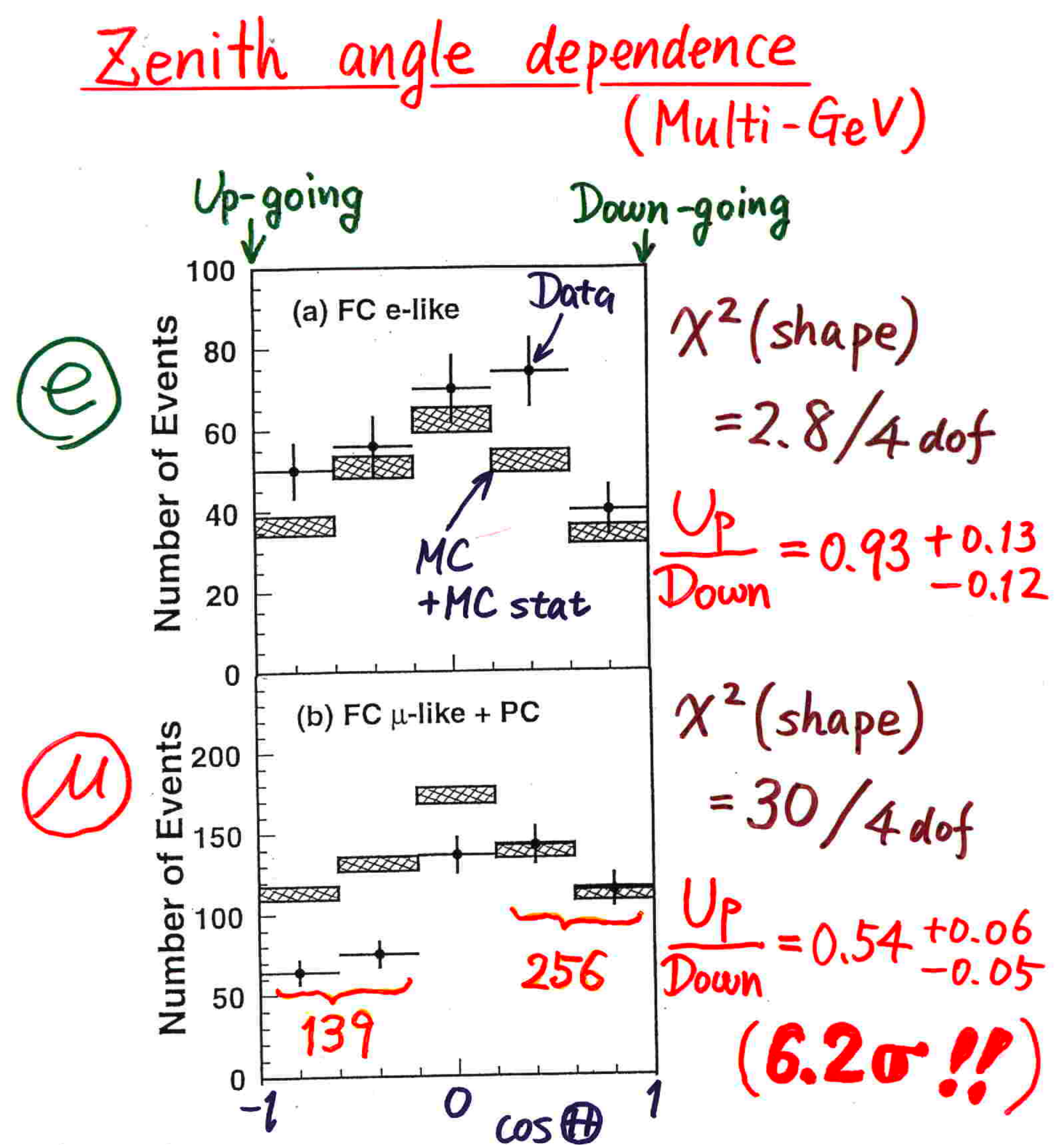
alfonsogarciasoto@fas.harvard.edu

Recap

- Atmospheric neutrinos -> first strong evidence of oscillations

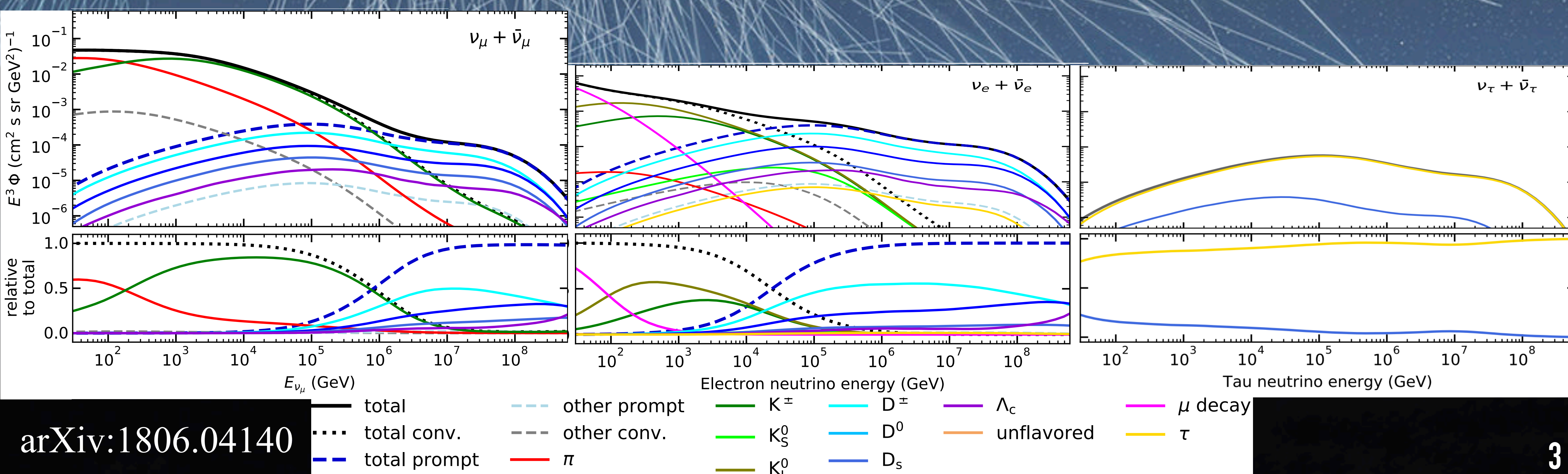


T.Kajita (Neutrino 98)



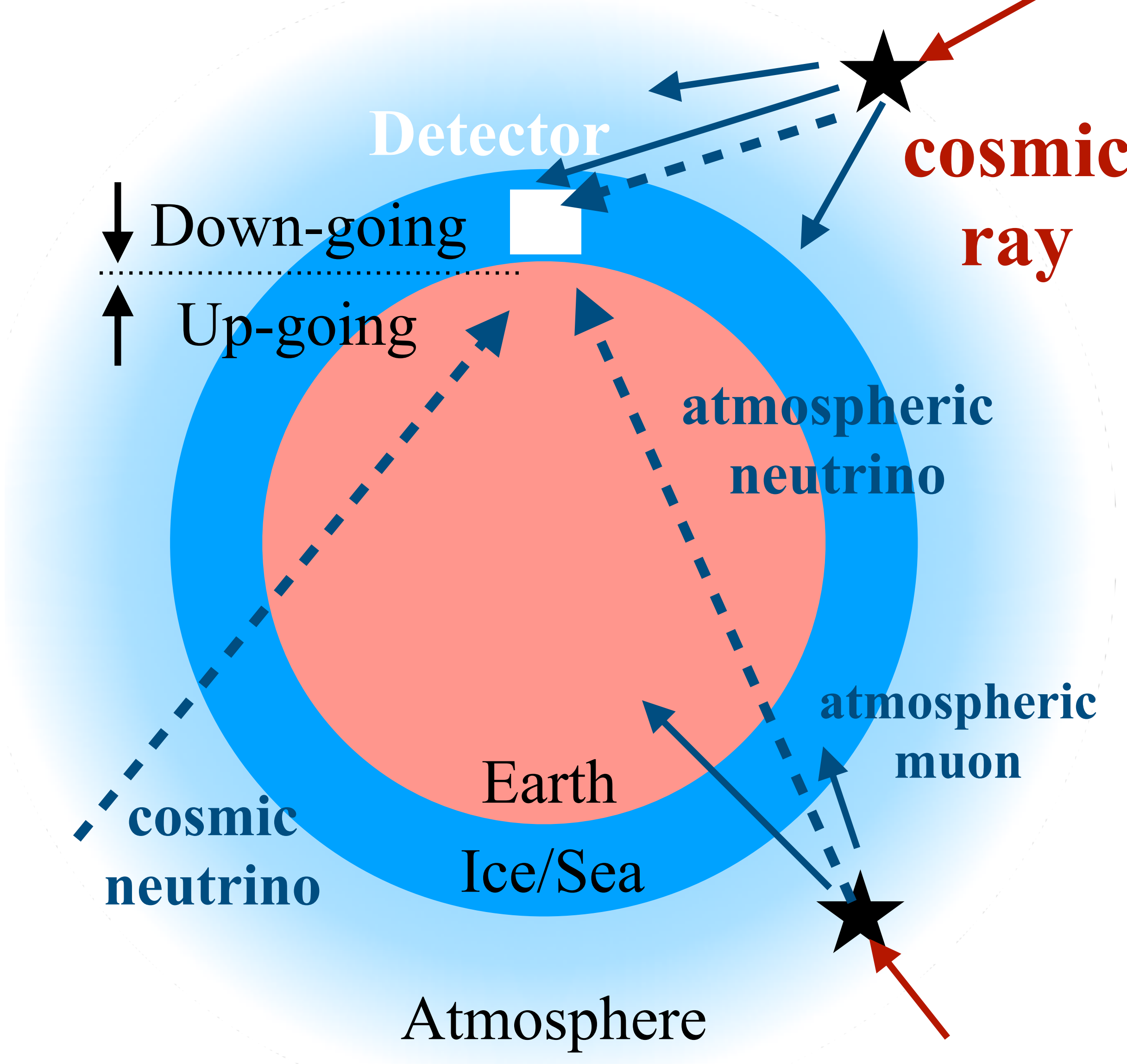
Atmospheric neutrino flux

- Cosmic ray interactions with air molecules:
  - -Muon neutrinos leading contribution.
  - -Electron neutrinos from muon decay.
  - -No tau neutrino.



arXiv:1806.04140

Oscillations



- Multiple baselines and flavours:
  - Reconstructed topology, energy and zenith.
- Downgoing vs upgoing asymmetry:
  - Constrain systematic.

Vacuum

$$P(\nu_e \to \nu_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P(\nu_\mu \leftrightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P(\nu_\mu \leftrightarrow \nu_\tau) \simeq \sin^2 2\theta_{23}\cos^4\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P(\nu_e \leftrightarrow \nu_\tau) \simeq \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Matter

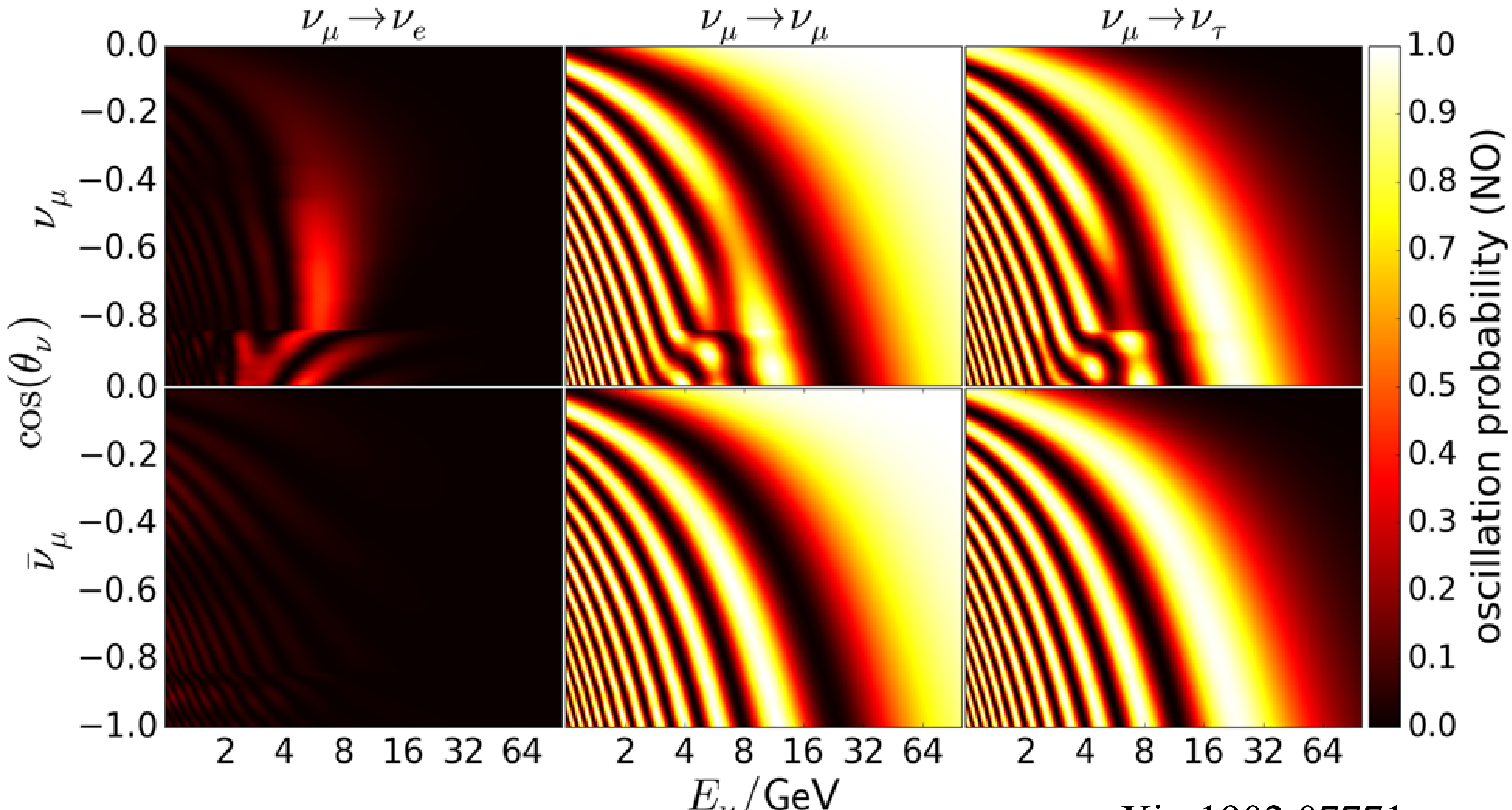
$$V_e = \pm\sqrt{2}G_F N_e$$

$$\Delta m^2_{31,M} = \Delta m^2_{31}\sqrt{\sin^2 2\theta_{13} + (2EV_e/\Delta m^2_{31} - \cos 2\theta_{13})^2}$$

$$\sin^2 2\theta_{13,M} = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (2EV_e/\Delta m^2_{31} - \cos 2\theta_{13})^2}$$

Oscillations

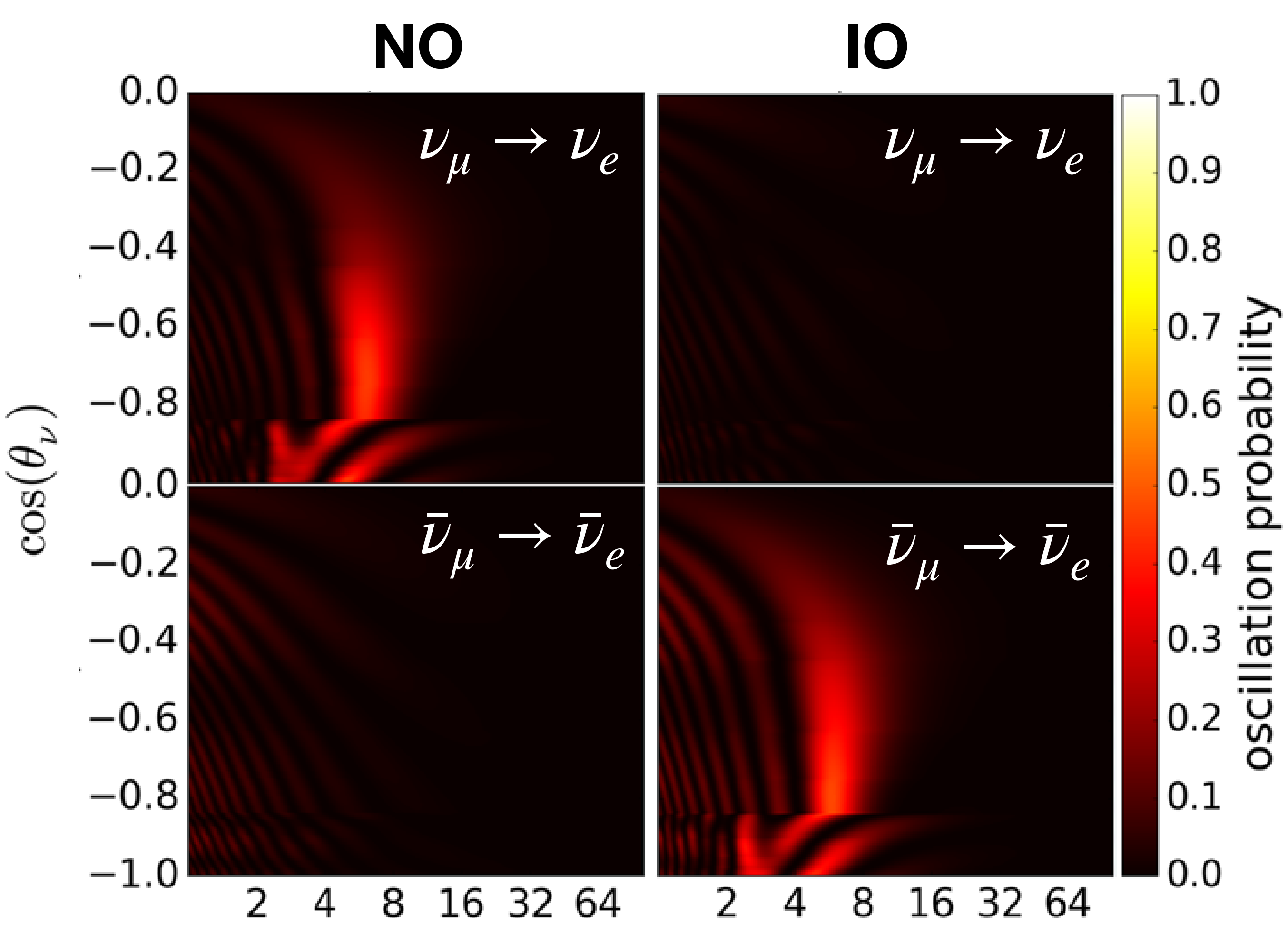
- E>100 GeV:
  - Too high energies to observe oscillations.
- Multi-GeV:
  - First oscillation $\nu_\mu \rightarrow \nu_\tau$ very sensitive to θ_{23} and Δm_{31}.



arXiv:1902.07771

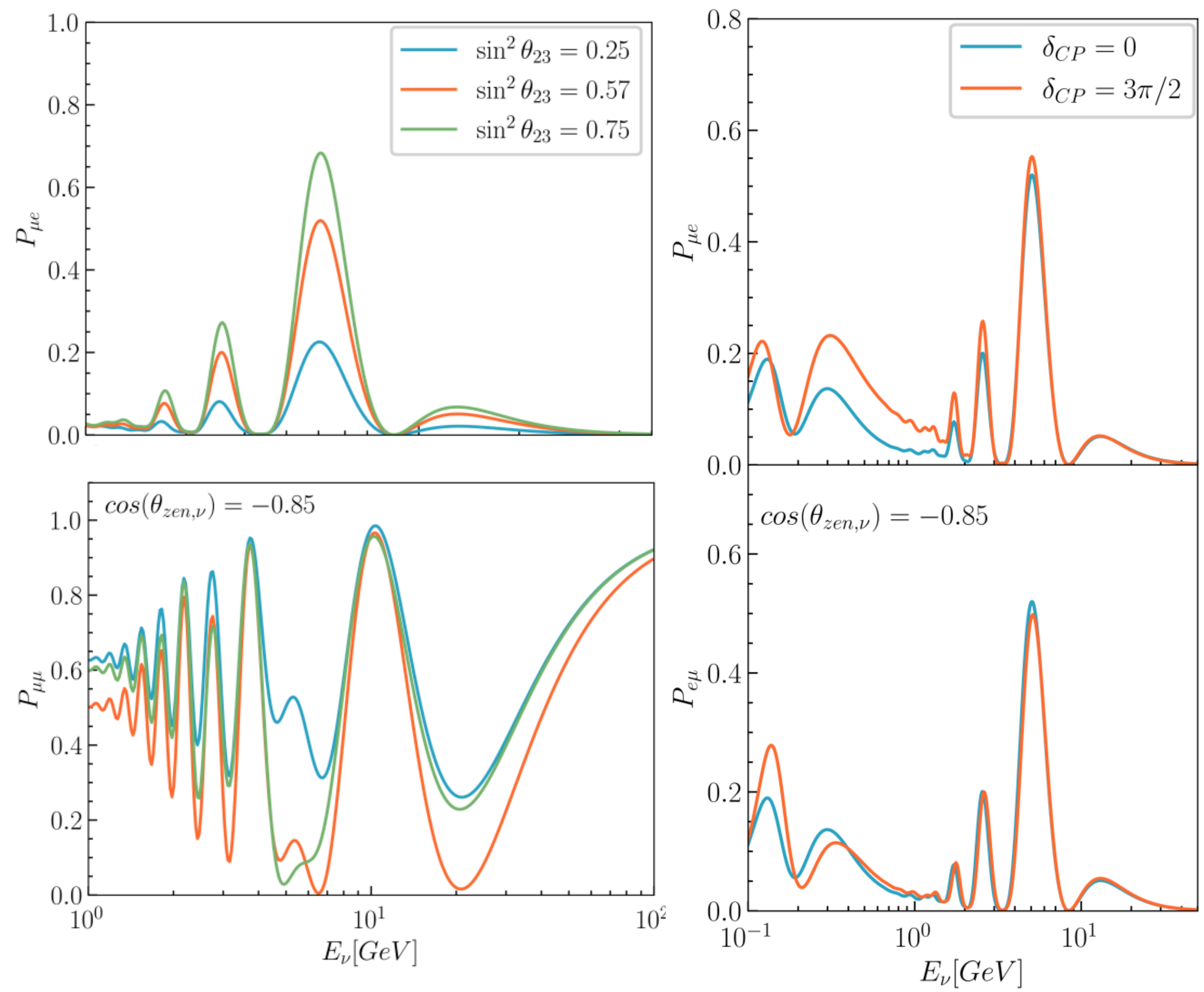
Oscillations

- Few-GeV:
  - Mass ordering -> matter effects difference between $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.
  - Octant θ_{23} can also be extracted.
- Sub-GeV:
  - Electro appearance sensitive to CP term.



arXiv:1902.07771

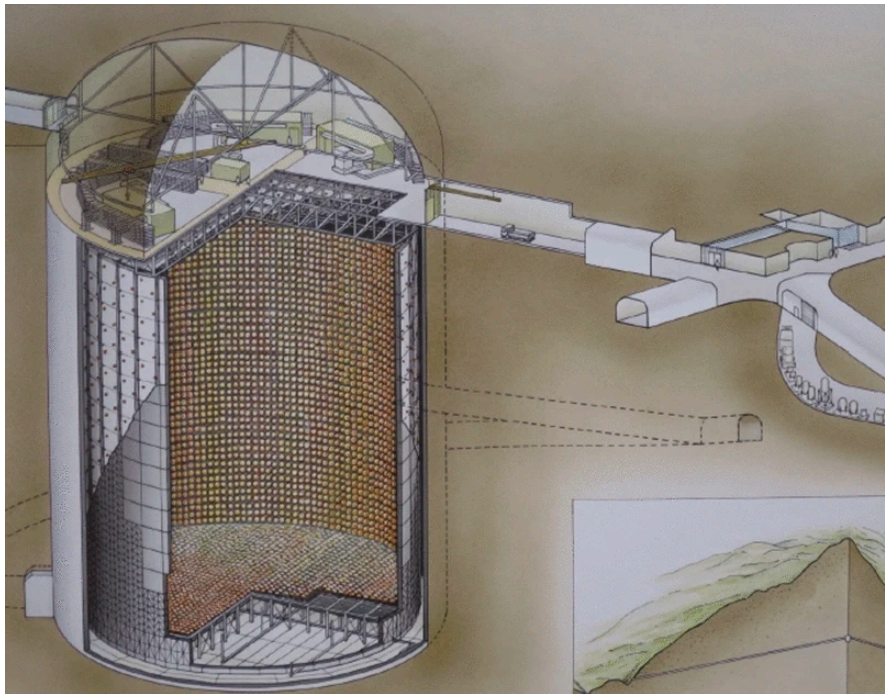
arXiv:2211.02666



Running detectors

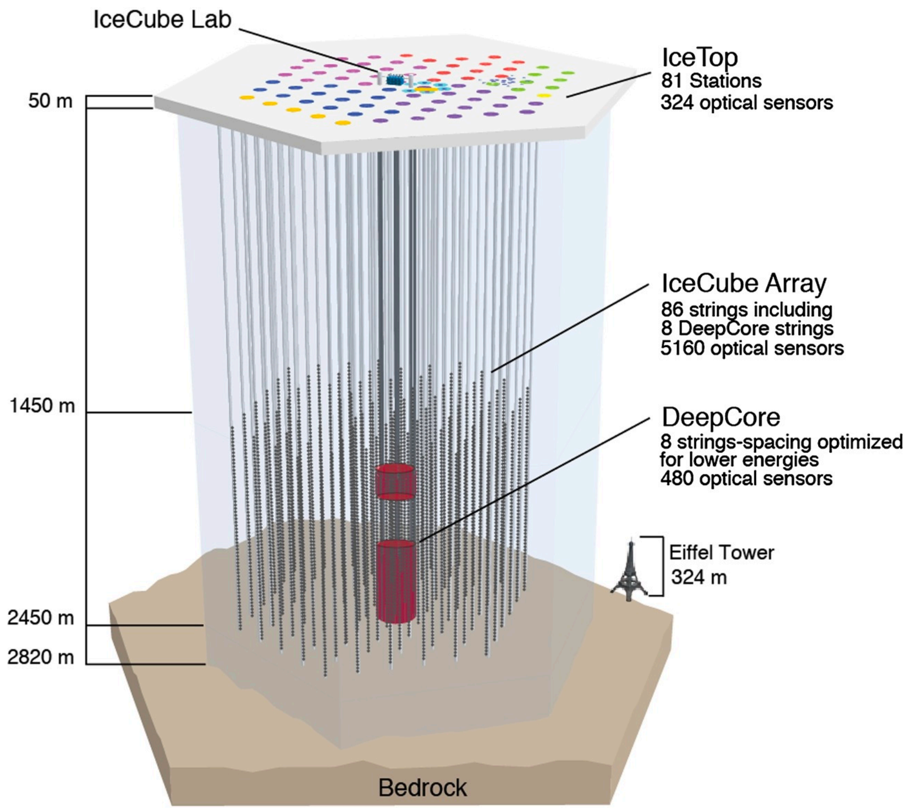
- Three detectors are currently operational:

SuperK



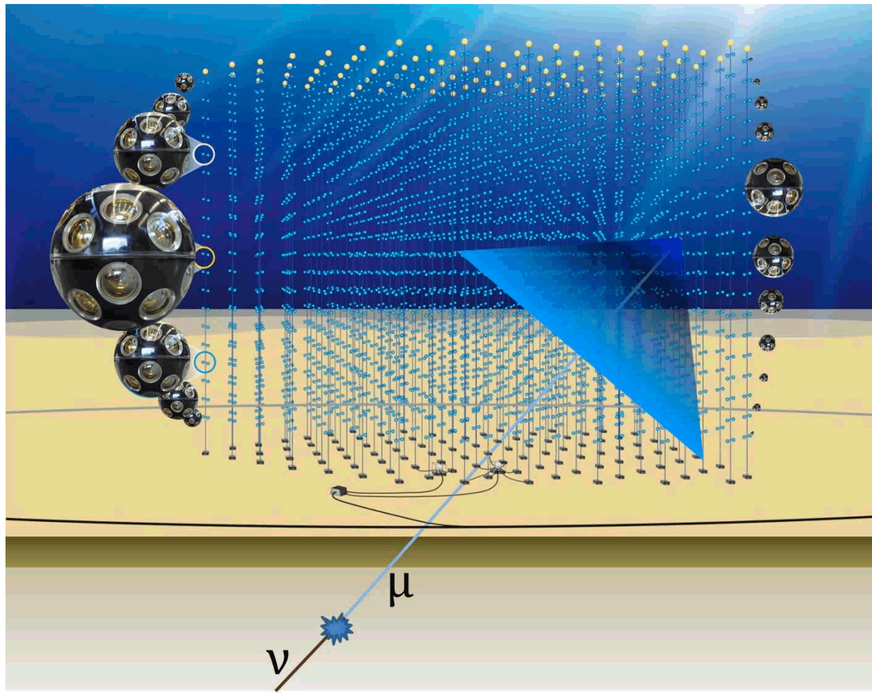
1k under rock
50 kton
11k PMTS
>25y data

IceCube-DeepCore



2.5 km under ice
10 Mton
>500 OMs
~50m horizontal
~7m vertical
>9y data

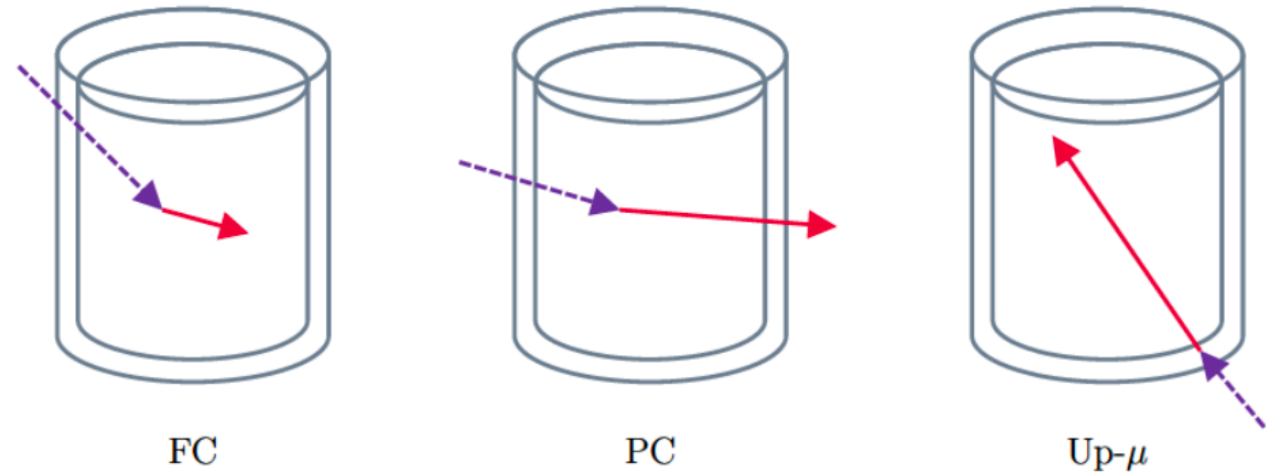
KM3NeT-ORCA



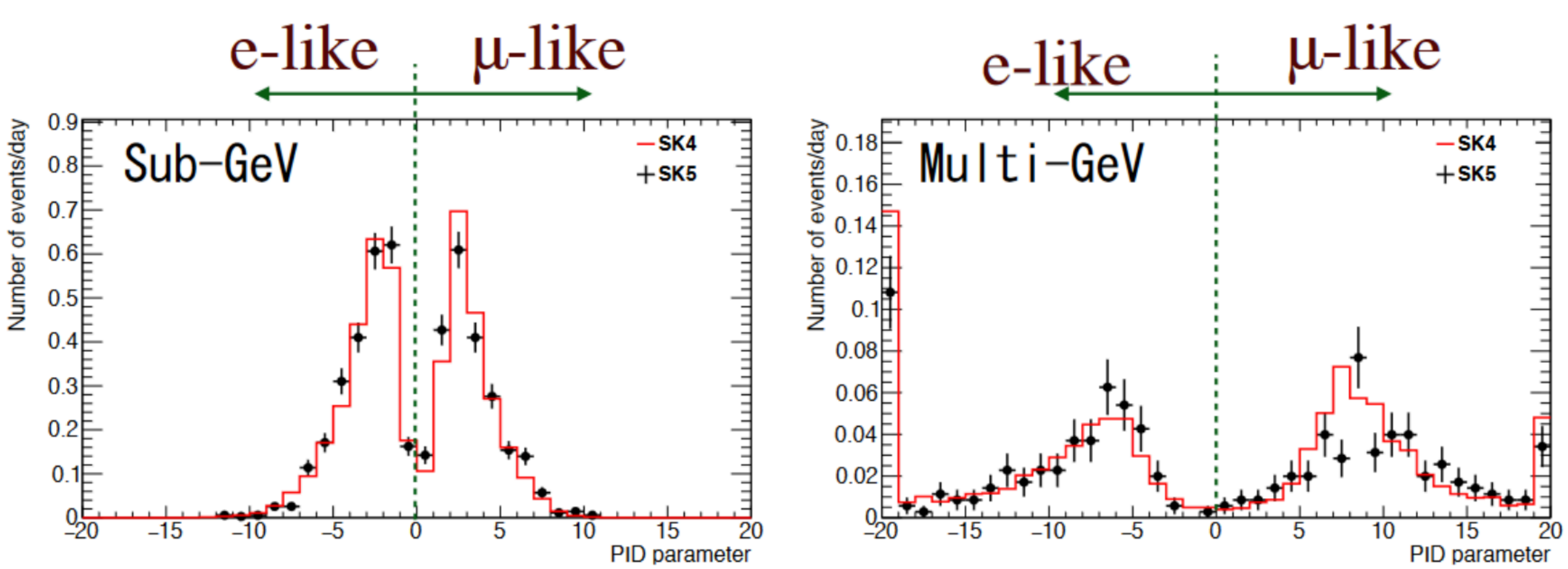
2.5 km under water
7 Mton
64k PMTs (2000 OMs)
~20m horizontal
~9m vertical
Under construction (15%)
(>3y partial)

Super-K

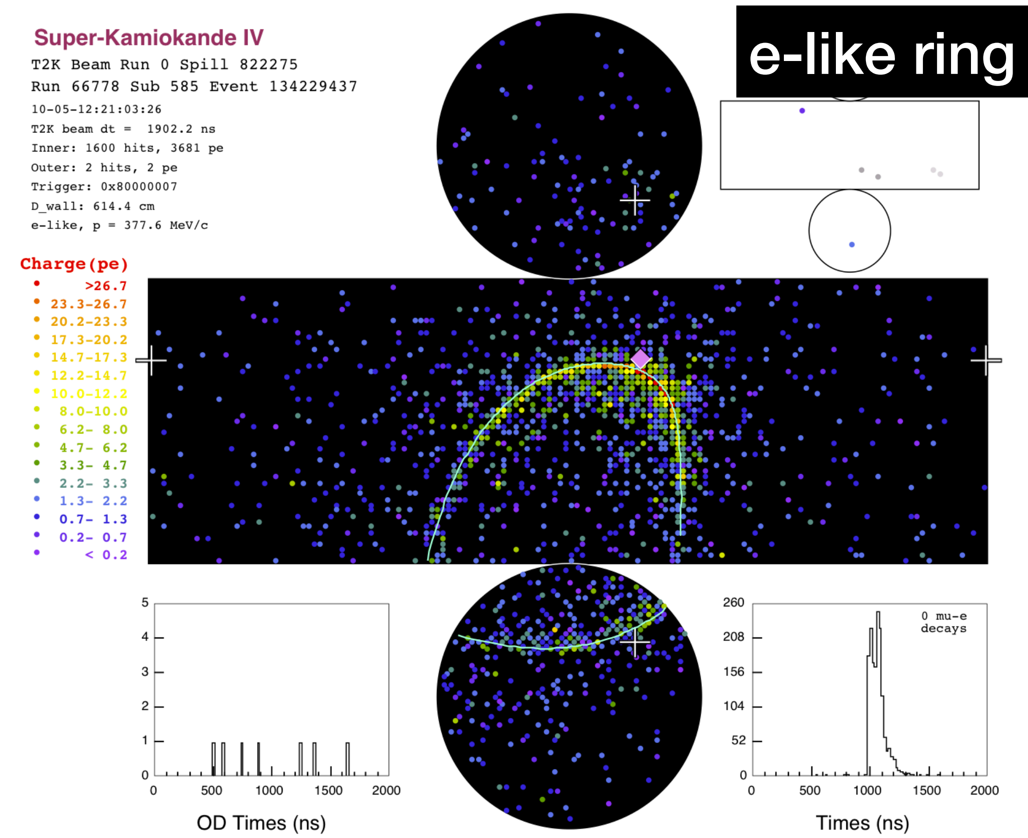
- Three event topologies:
  - Veto from outer detector plays crucial role.
  - FC -> best energy estimator.



- Features of Cerenkov rings allow to distinguish electron/muon neutrinos.

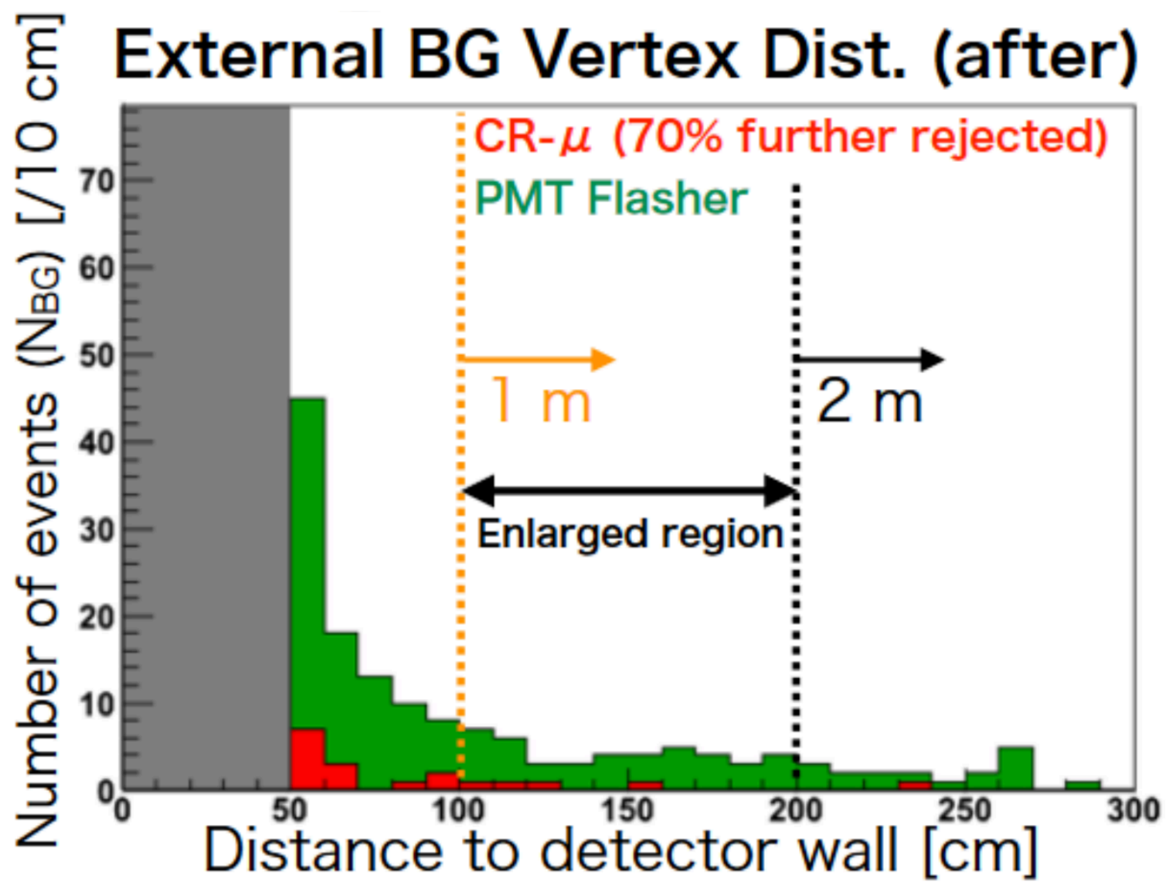


L. Wan (Neutrino 22)



Super-K

- Expanded fiducial volume (20%).

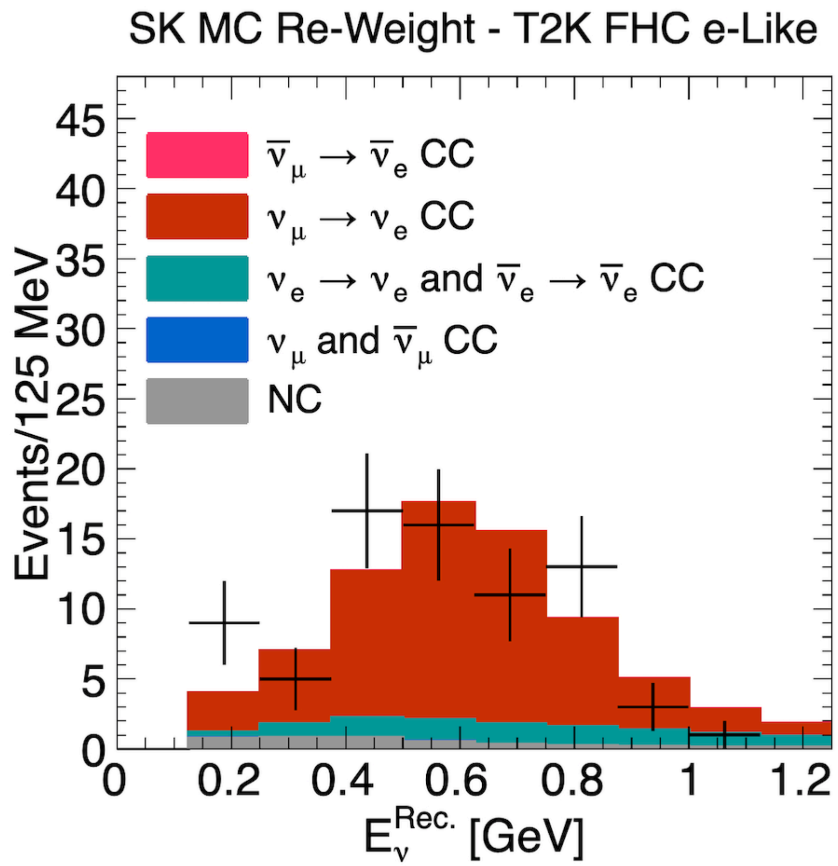


L. Wan (Neutrino 22)

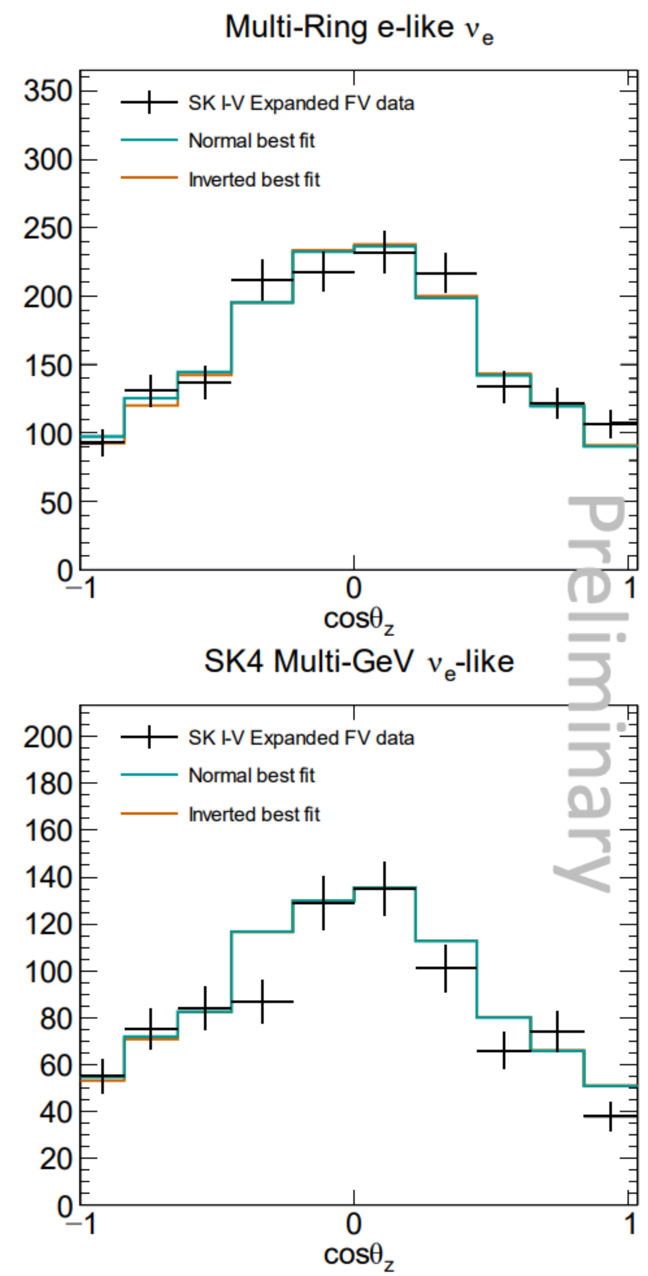
- Currently working on late signals for ν/ν̄ separation:
  - Electron from muon decays (450 ns time window).
  - Neutron capture (2.2 MeV photons ~200μs, only possible from SK-IV).

Super-K

- Analysis strategy:
  - 930 bins in zenith, energy, and samples with >190 systematics.
  - Grid scan in θ_{13}, θ_{23}, $\Delta m_{31/32}$, δ_{CP}.
  - Also analysis combining with T2K.



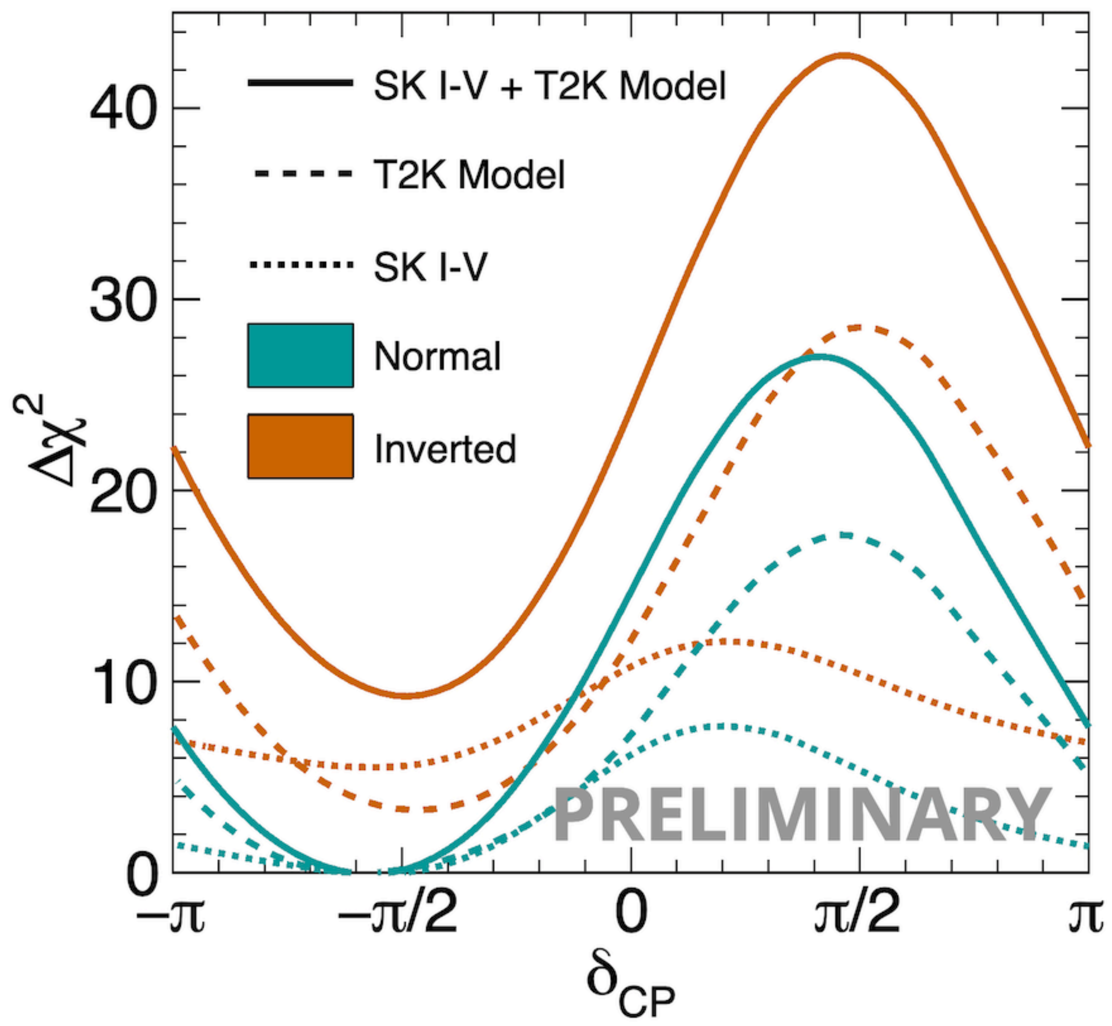
T. Wester (Neutrino 22)



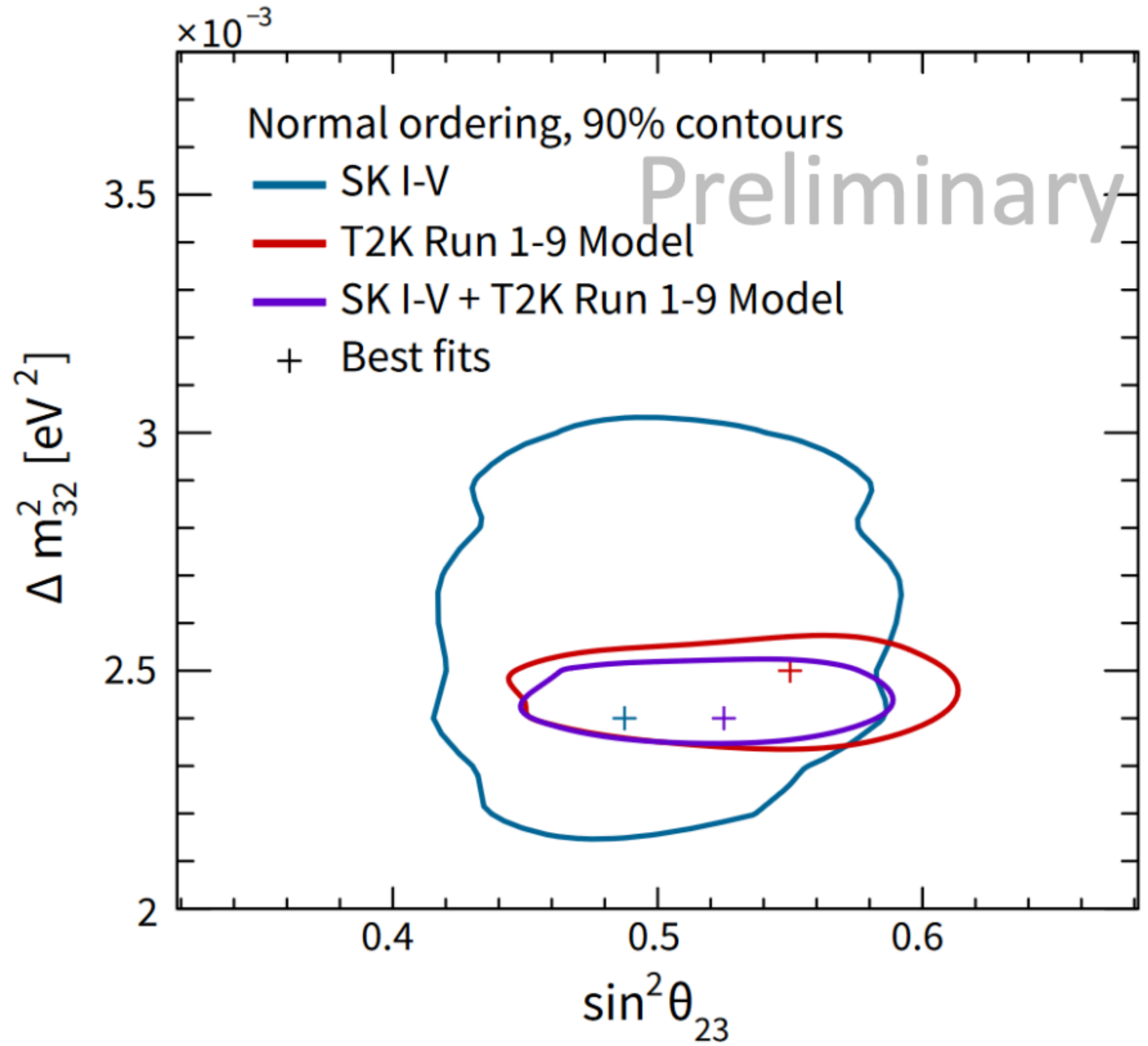
L. Wan (Neutrino 22)

Super-K

- Results using constraints on θ_{13} from reactor experiments:
  - SK only -> NO ($\Delta\chi 2 = 5.8$).
  - Combining with T2K -> NO ($\Delta\chi 2 = 8.9$).



T. Wester (Neutrino 22)

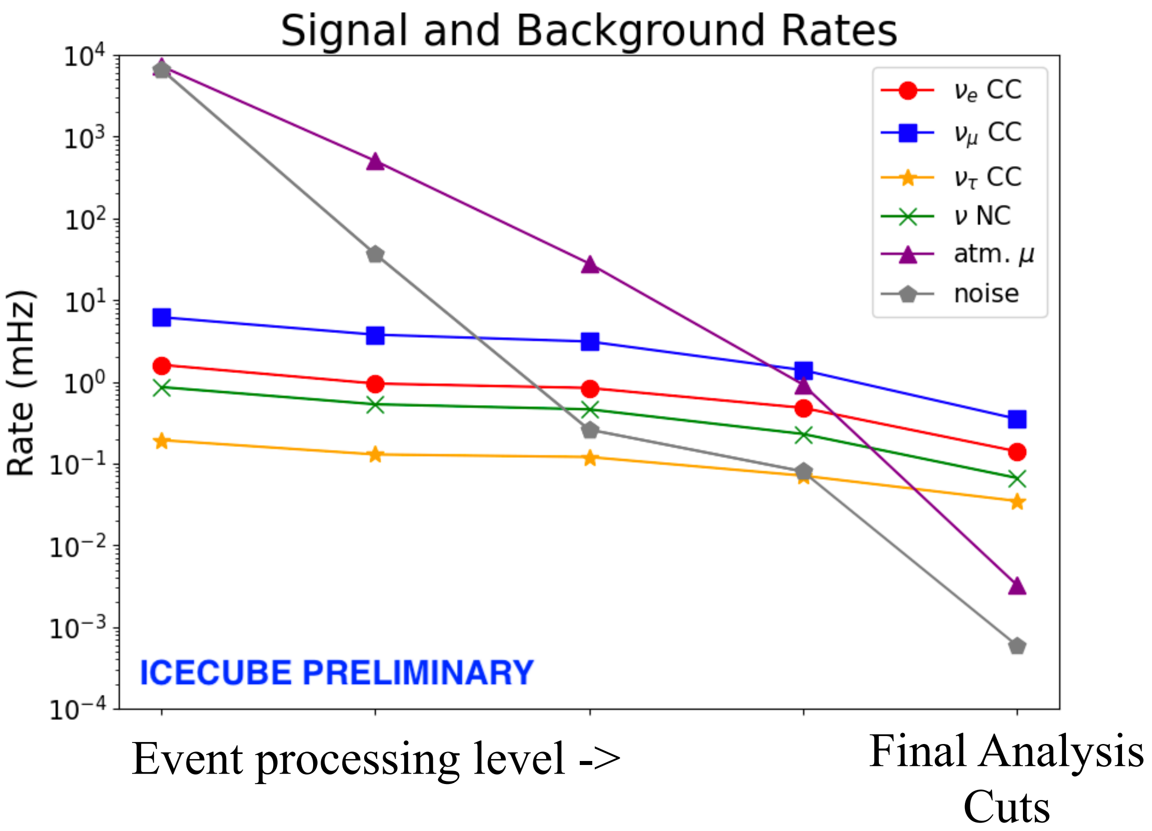


L. Wan (Neutrino 22)

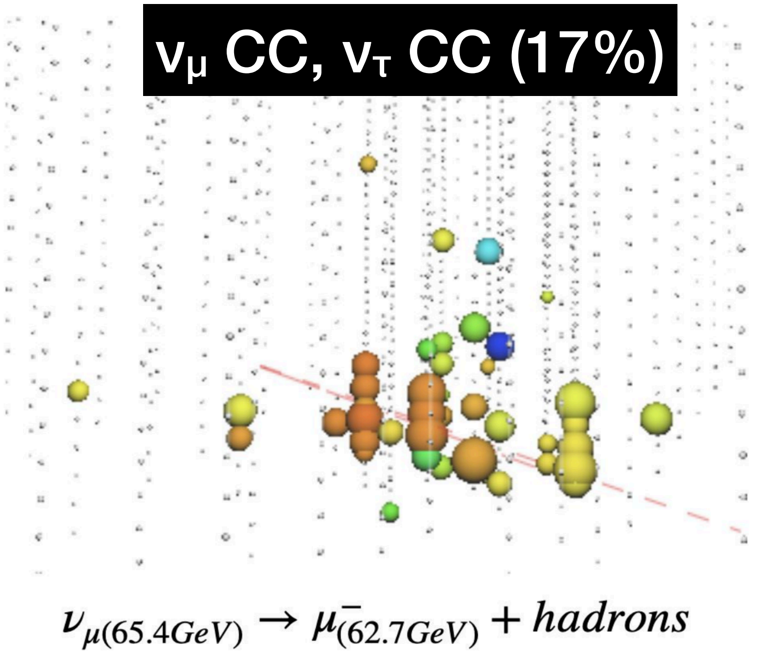
IC-DeepCore

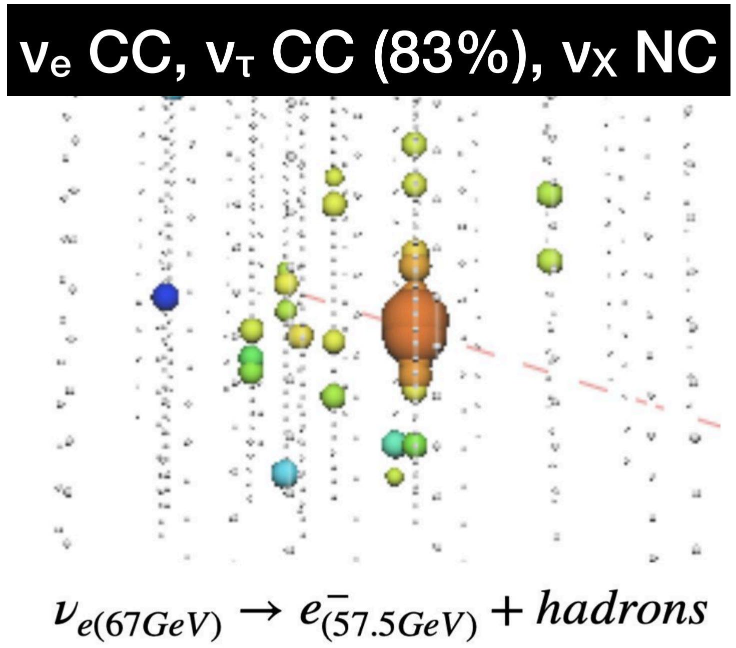
- $>$150k events in 9 years:
  - background contamination $<$1%

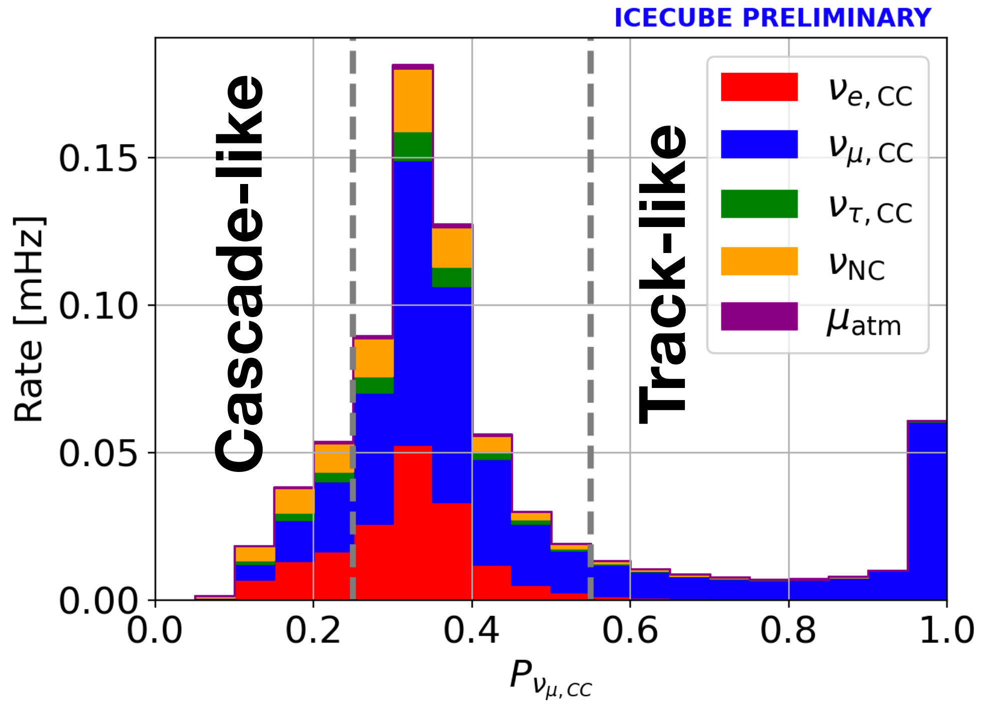
- Two main topologies: track and cascades



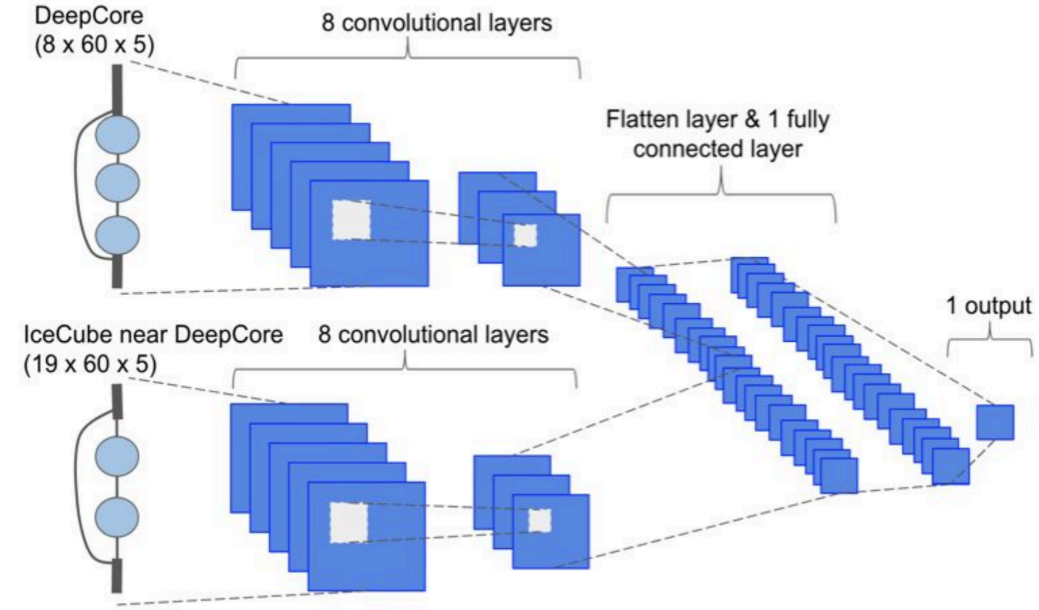
S. Yu and J. Micallef (ICRC 23)



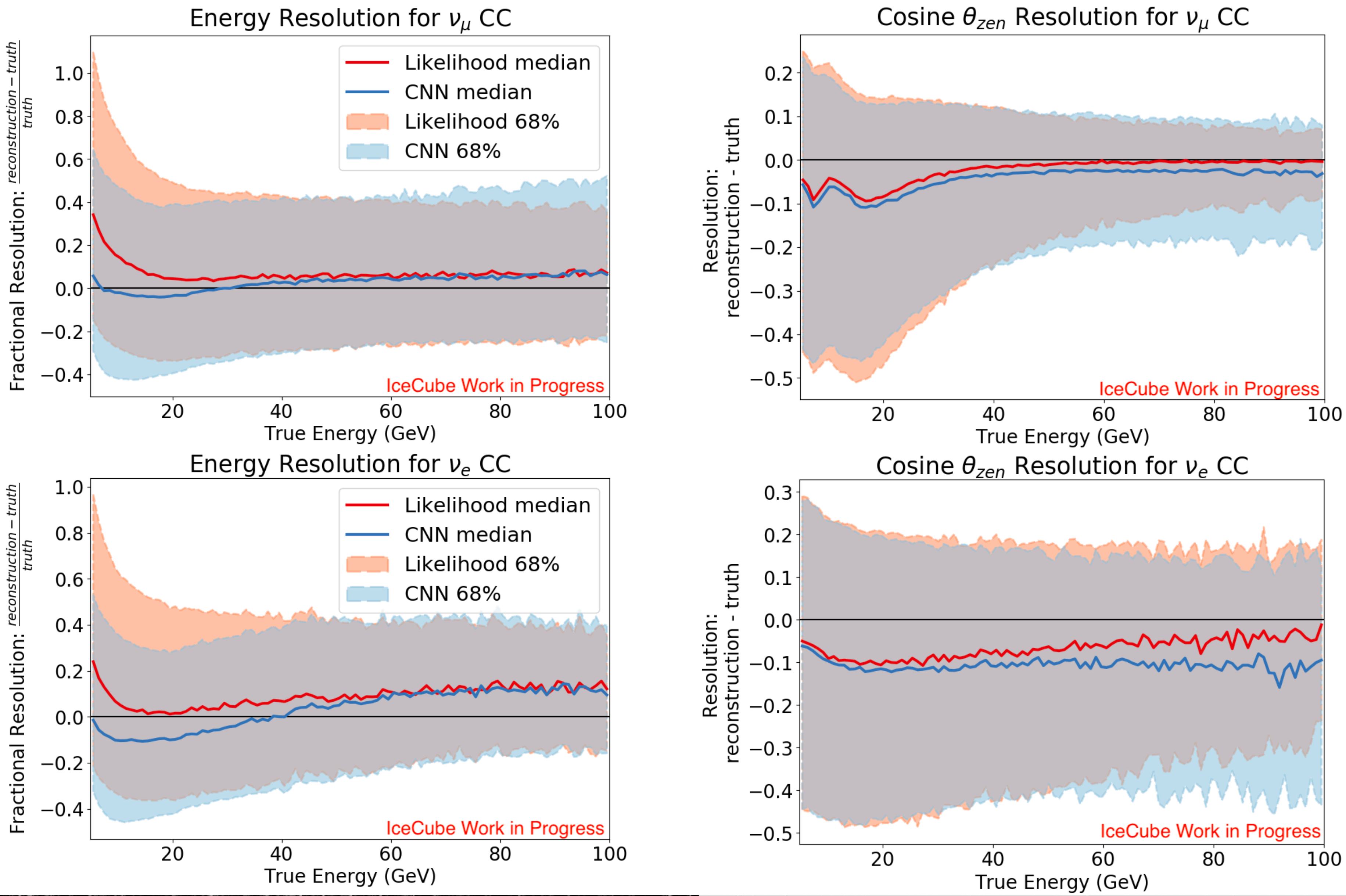




IC–DeepCore



- Profit from machine-learning techniques
  - Energy and direction extracted from CNN.

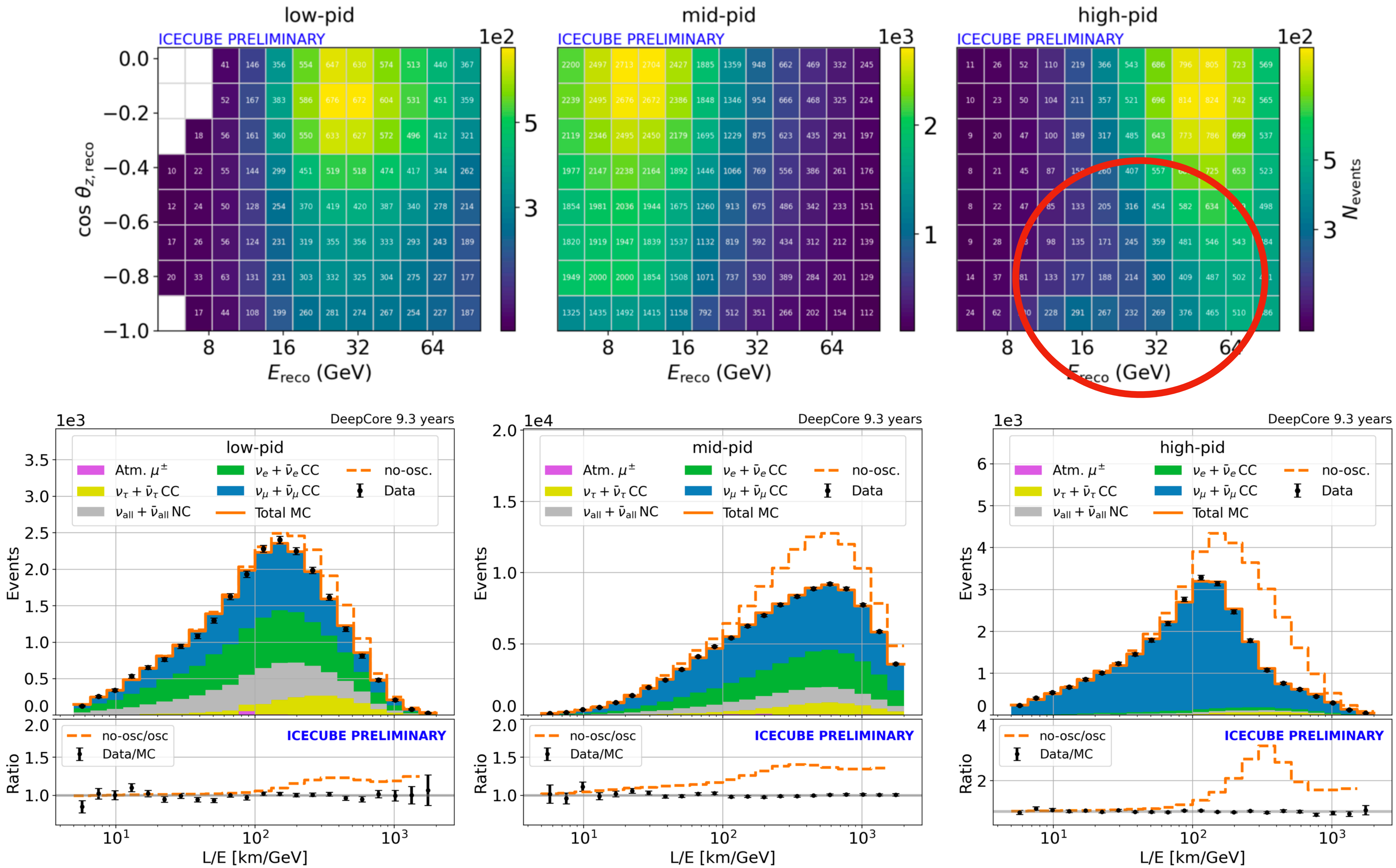


S. Yu
and
J. Micallef
(ICRC 23)

IC-DeepCore

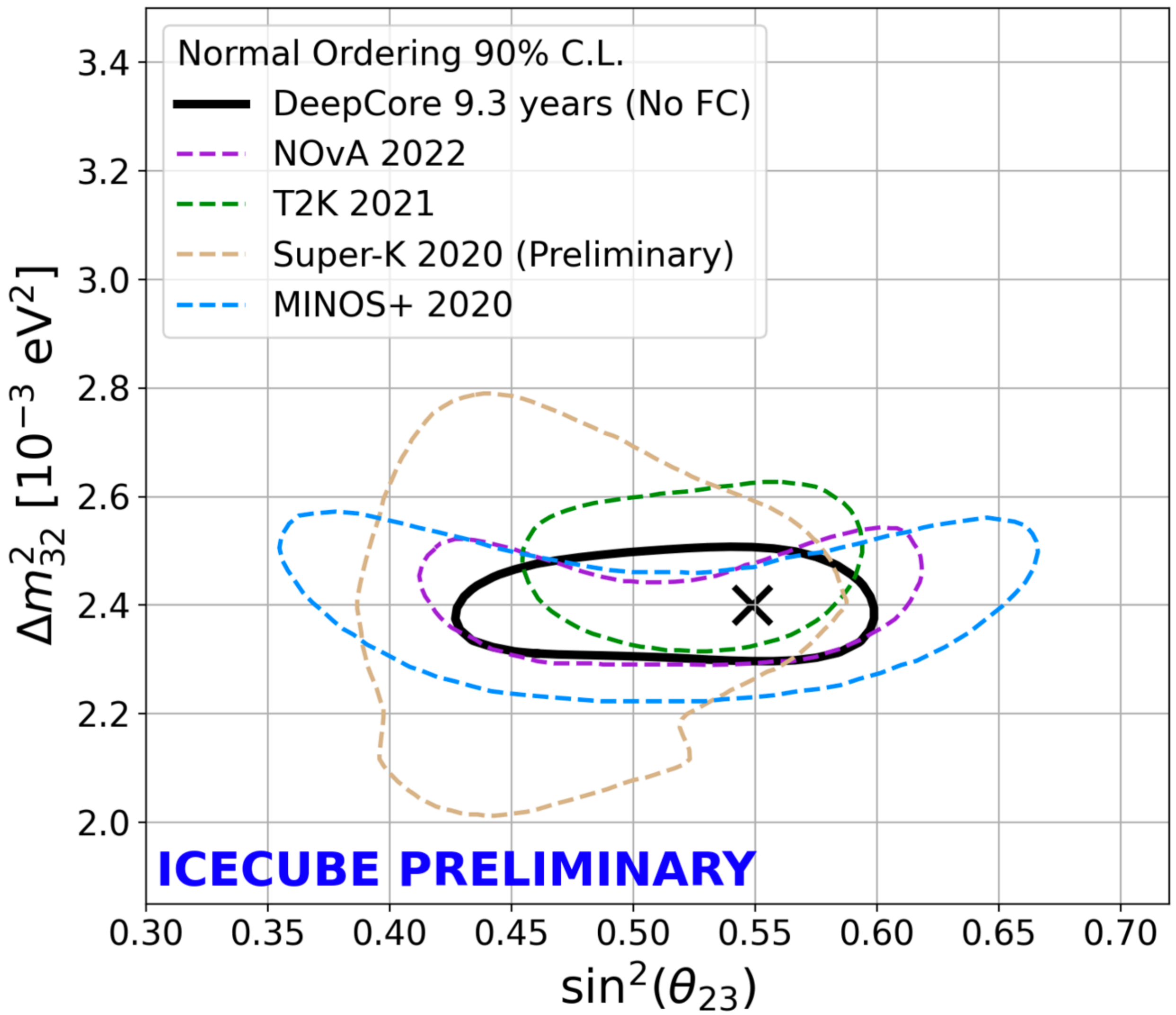
- Analysis strategy:
  - Bins zenith, energy, and samples with 17 systematics.

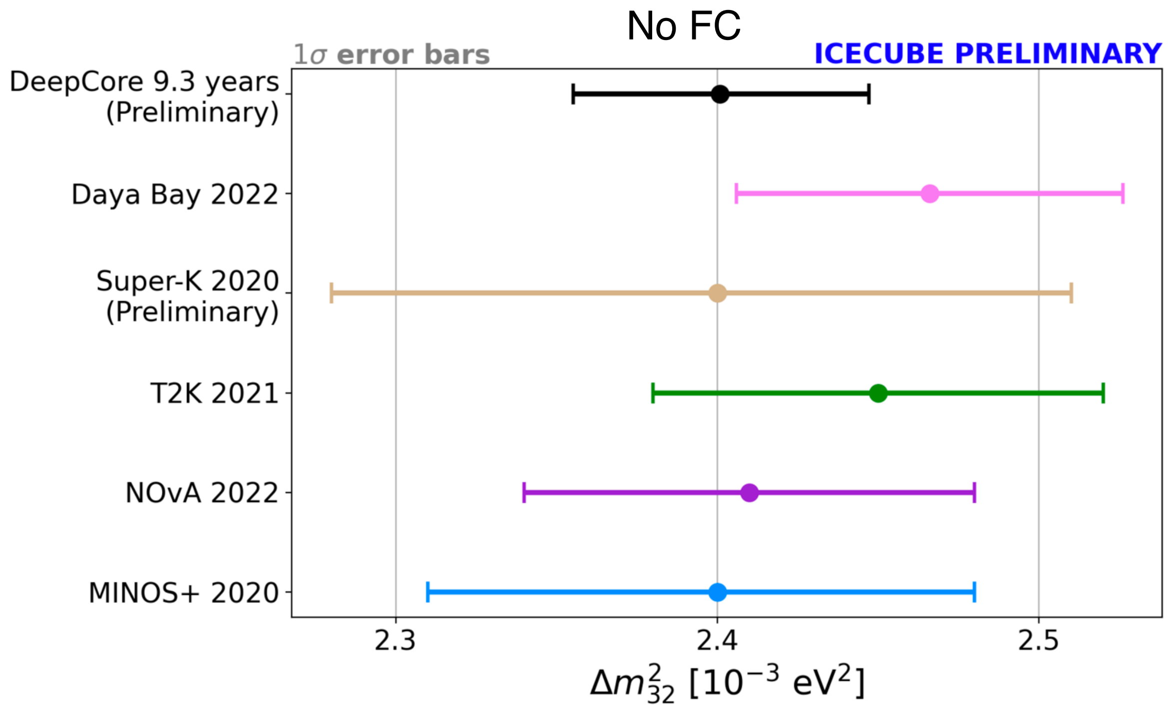
S. Yu and J. Micallef (ICRC 23)



IC-DeepCore

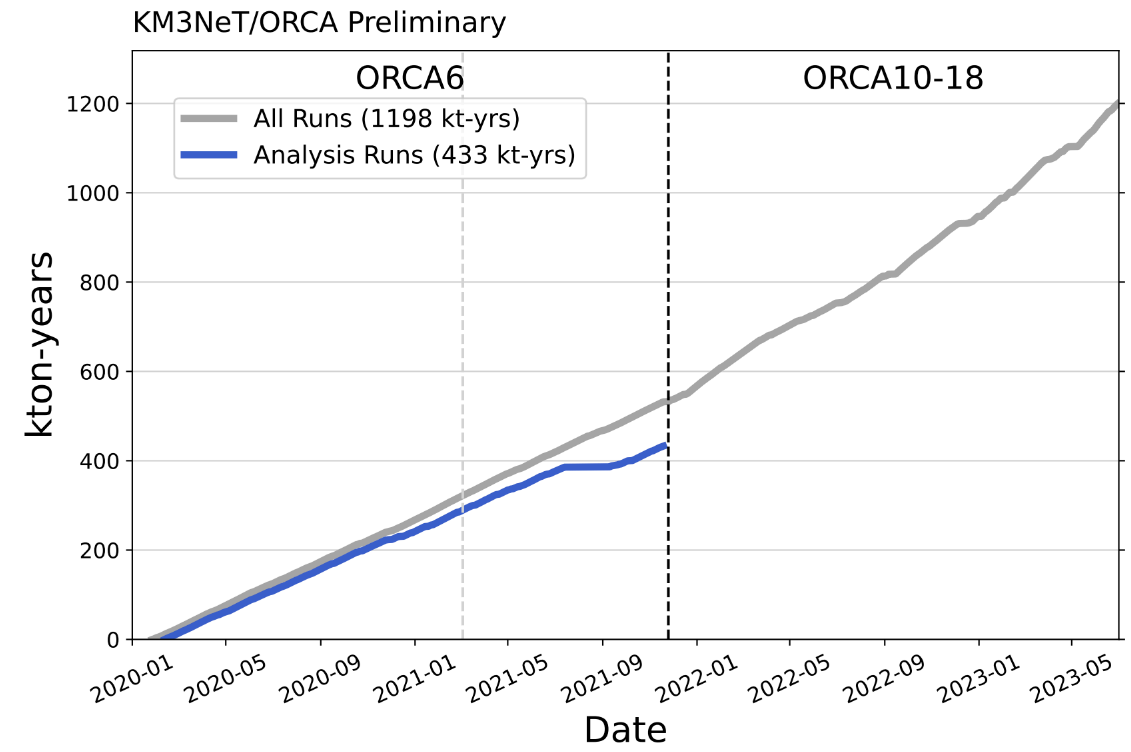
- Results:
  - Compatible with the existing measurement -> very competitive mass splitting!
  - Complementarity with long baseline: different energy range and systematics.
  - Mass ordering -> See Maria Prado's talk





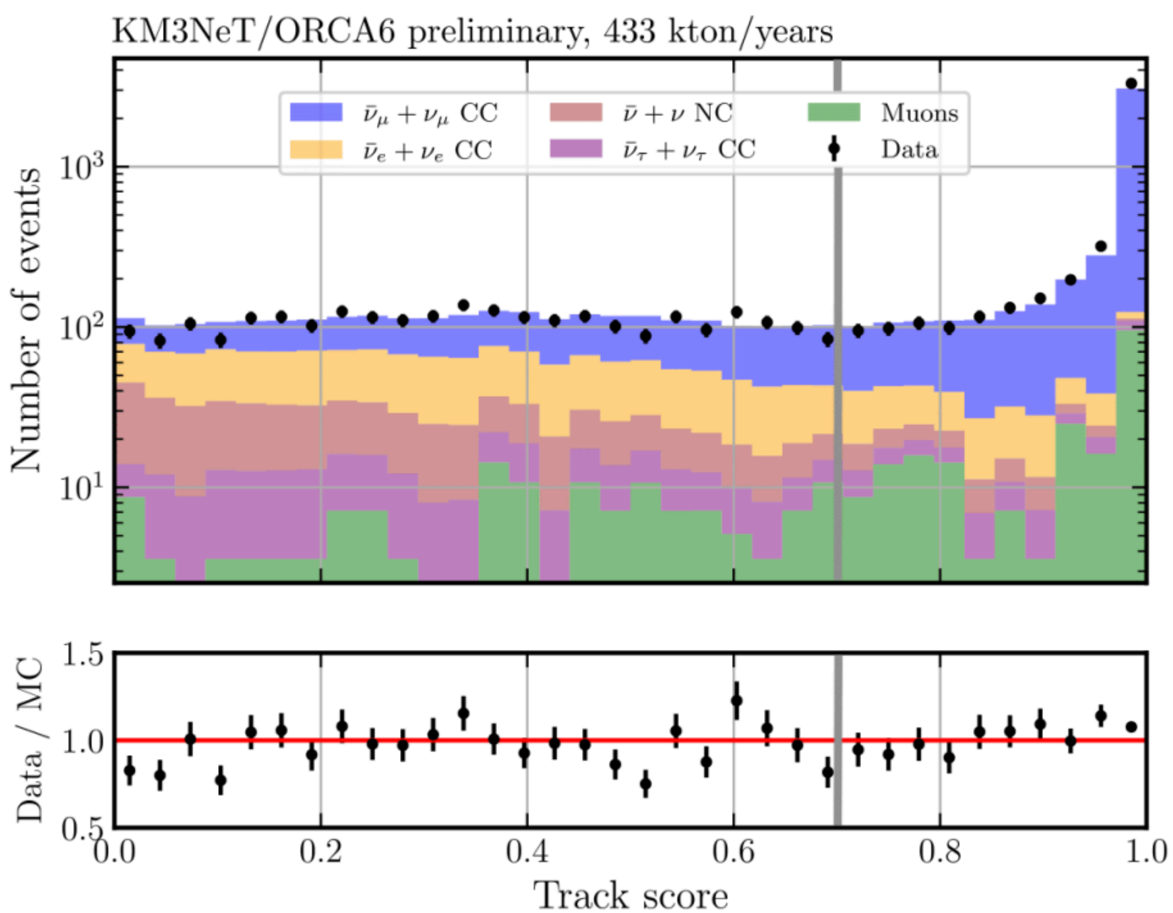
S. Yu and J. Micallef (ICRC 23)

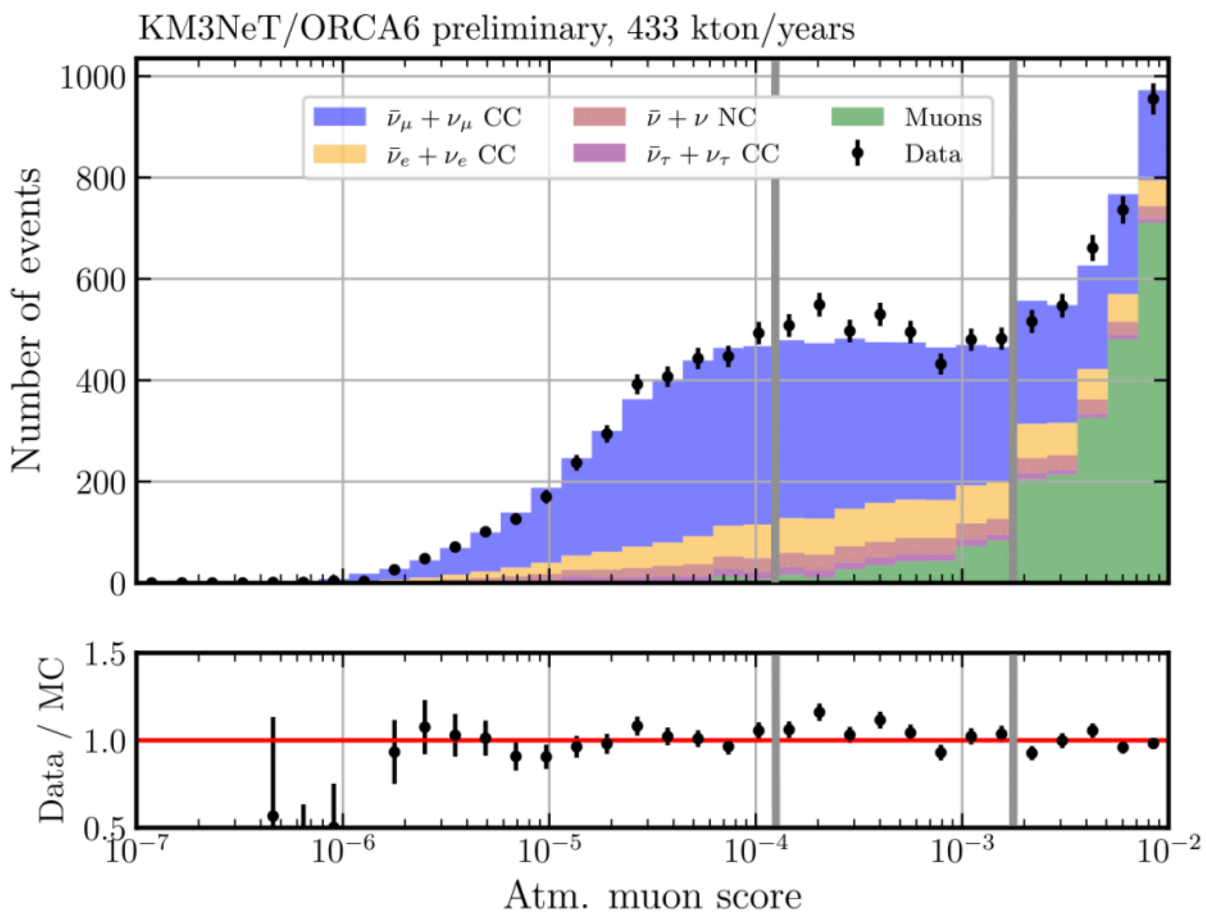
KM3NeT-ORCA



- 6k events in 3 years with 6 DUs:
  - ORCA18 already online (3x more data)!
- Understanding of detector and background.

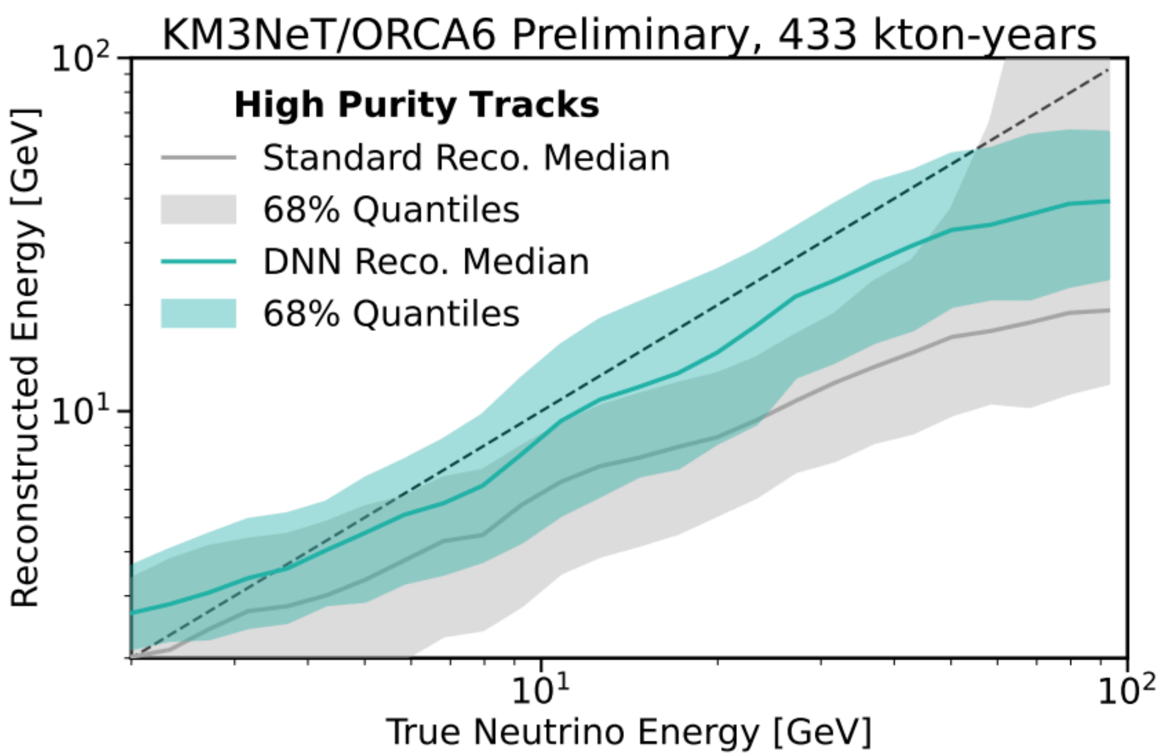
V. Carretero (ICRC 23)



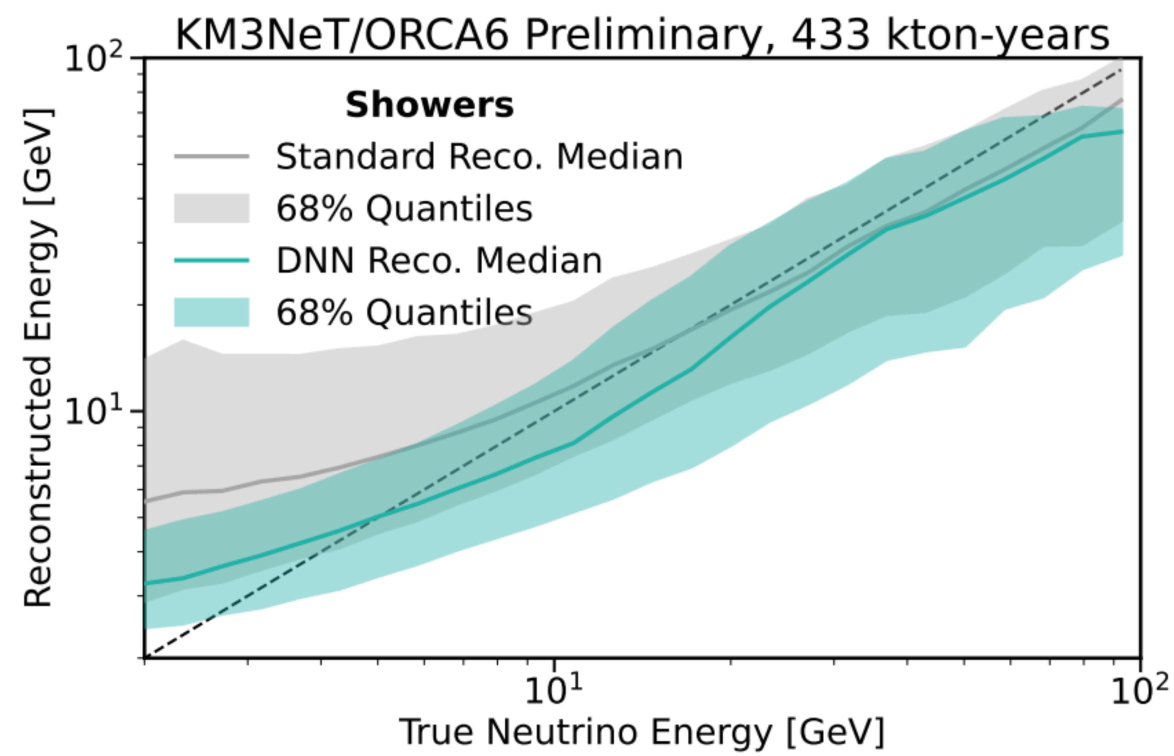


KM3NeT–ORCA

- Reconstruction based on likelihood estimation.
  - DNNs show promising performance for future analyses.



Tracks



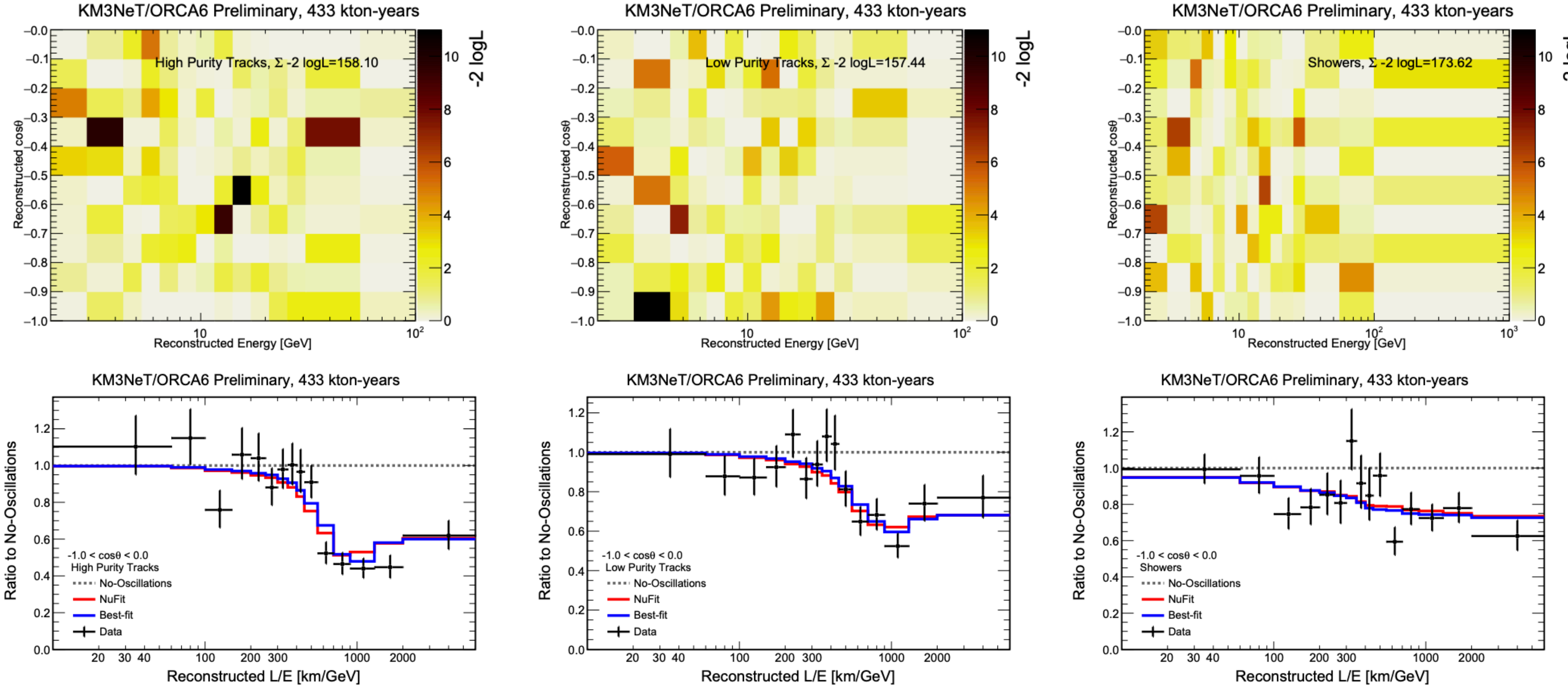
Showers

S. Peña (ICRC 23)

KM3NeT-ORCA

- Analysis strategy:
  - Bins zenith, energy, and samples with 13 systematics.

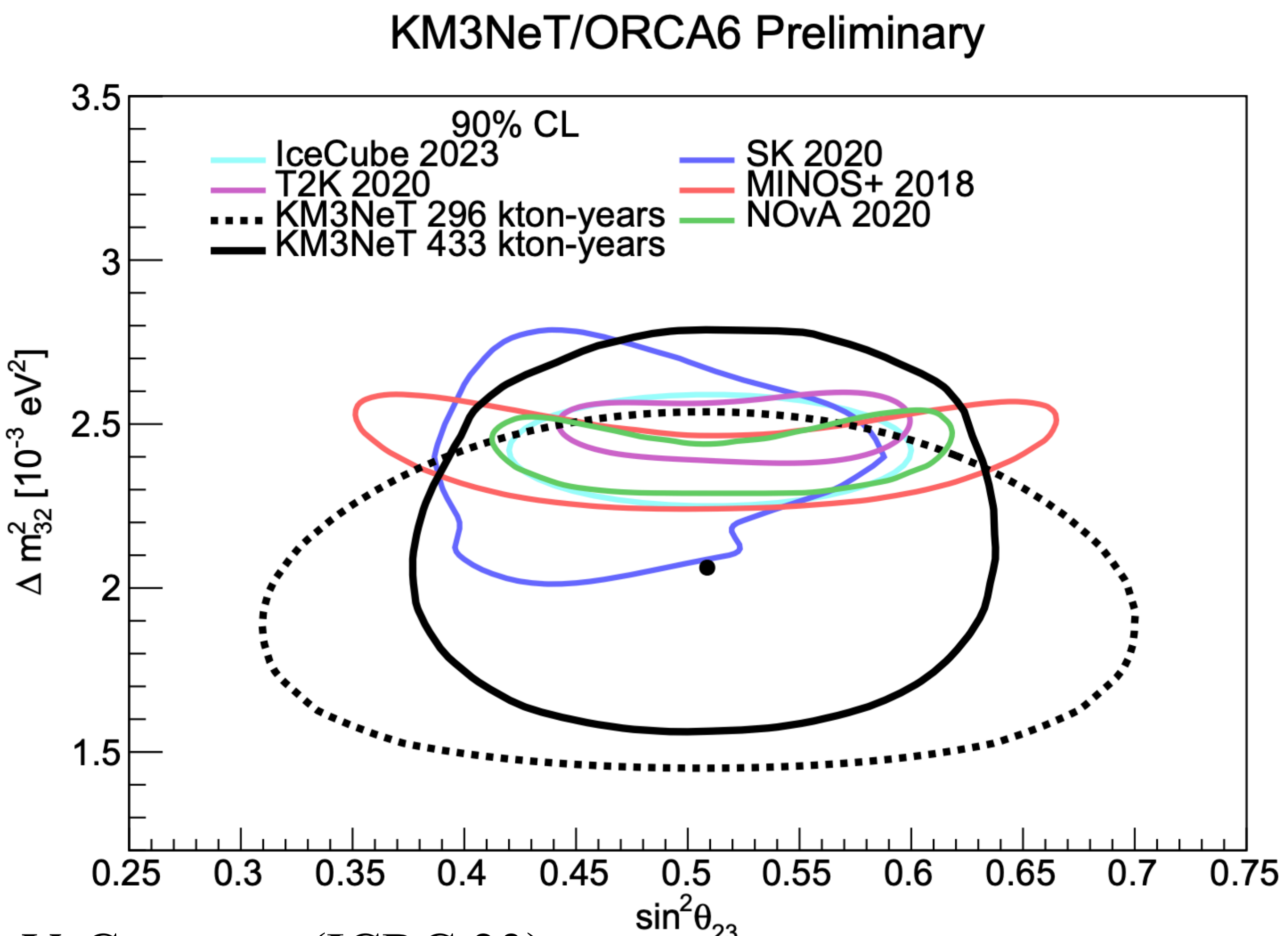
V. Carretero (ICRC 23)



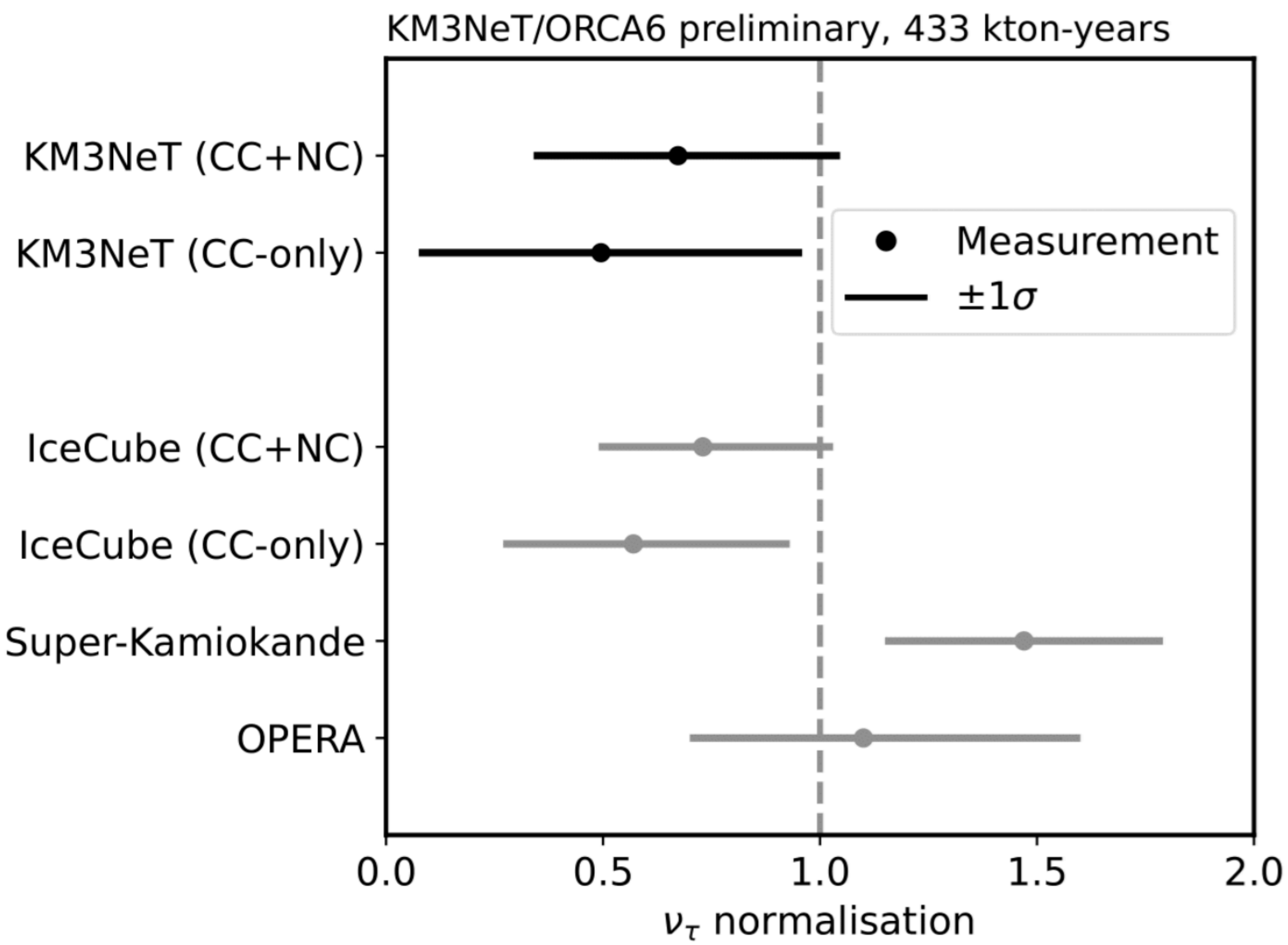
High Purity Tracks | Low Purity Tracks | Showers

KM3NeT-ORCA

- Results:
  - Compatible with the existing measurement
  - Very competitive tau appearance!



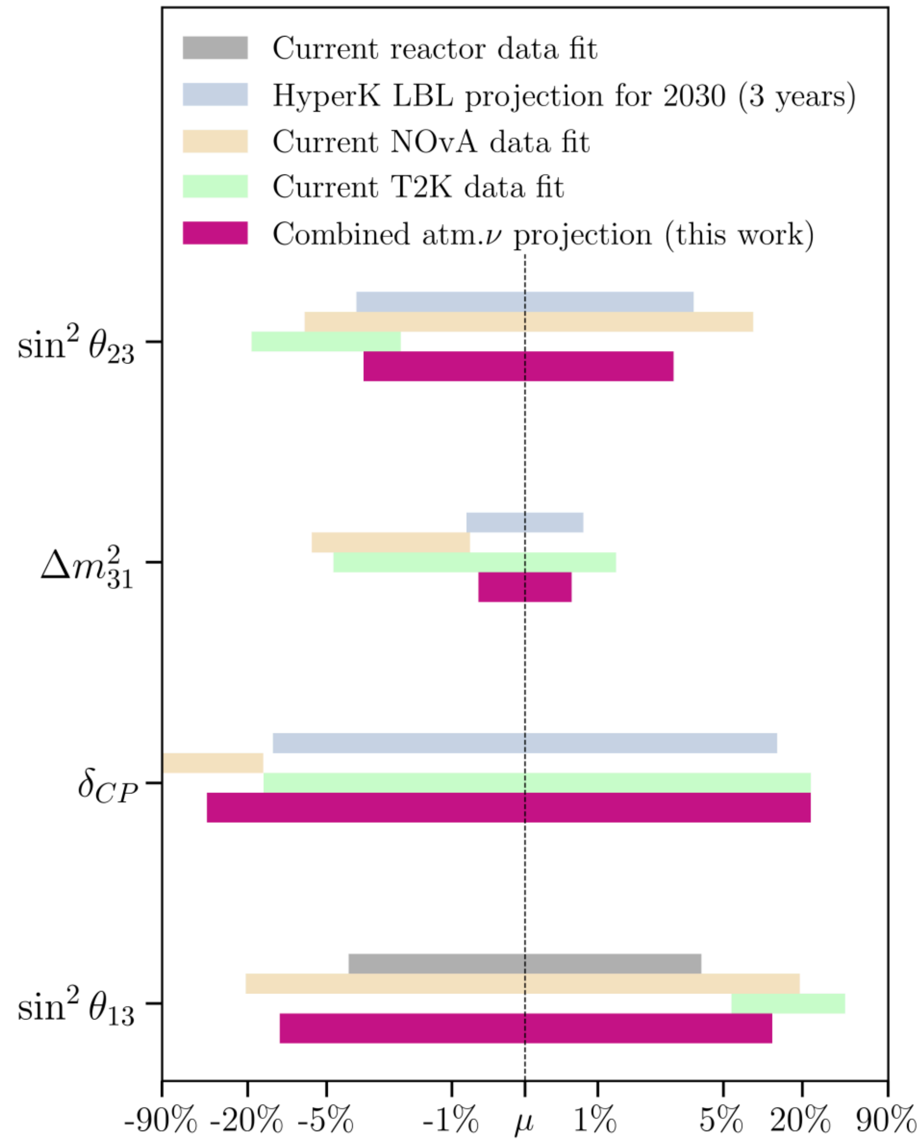
V. Carretero (ICRC 23)

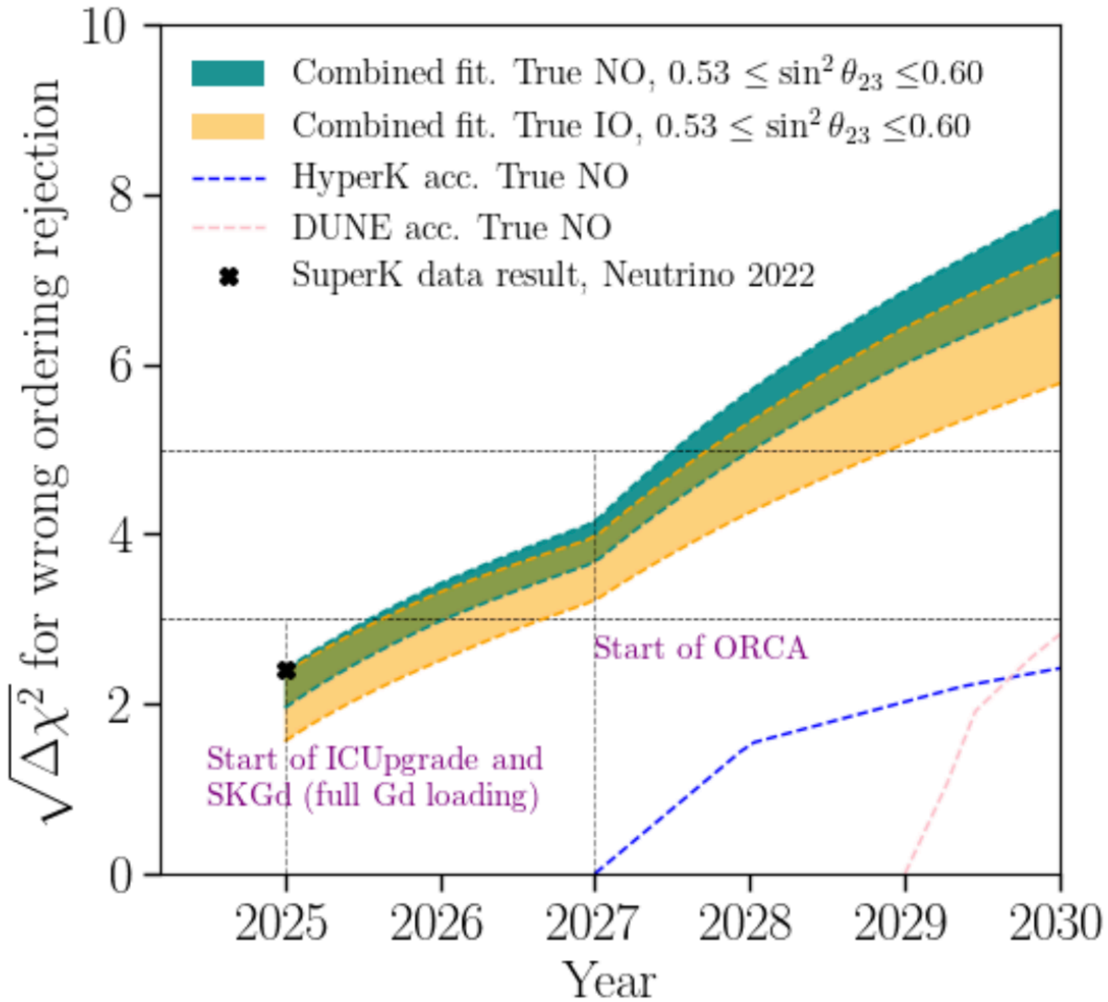


N. Geiselbrecht (ICRC 23)

Future

- Prospects in the next years:
  - More detectors: SuperK-Gd, IC-Upgrade (deploy in 25/26), and KM3NeT-ORCA115.
  - Combination with JUNO enhances NMO sensitivity.



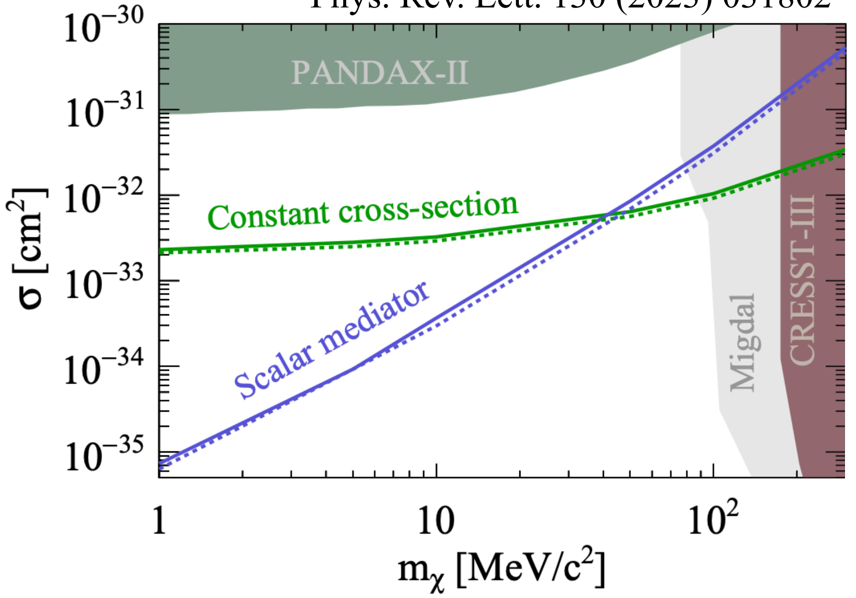


arXiv:2211.02666

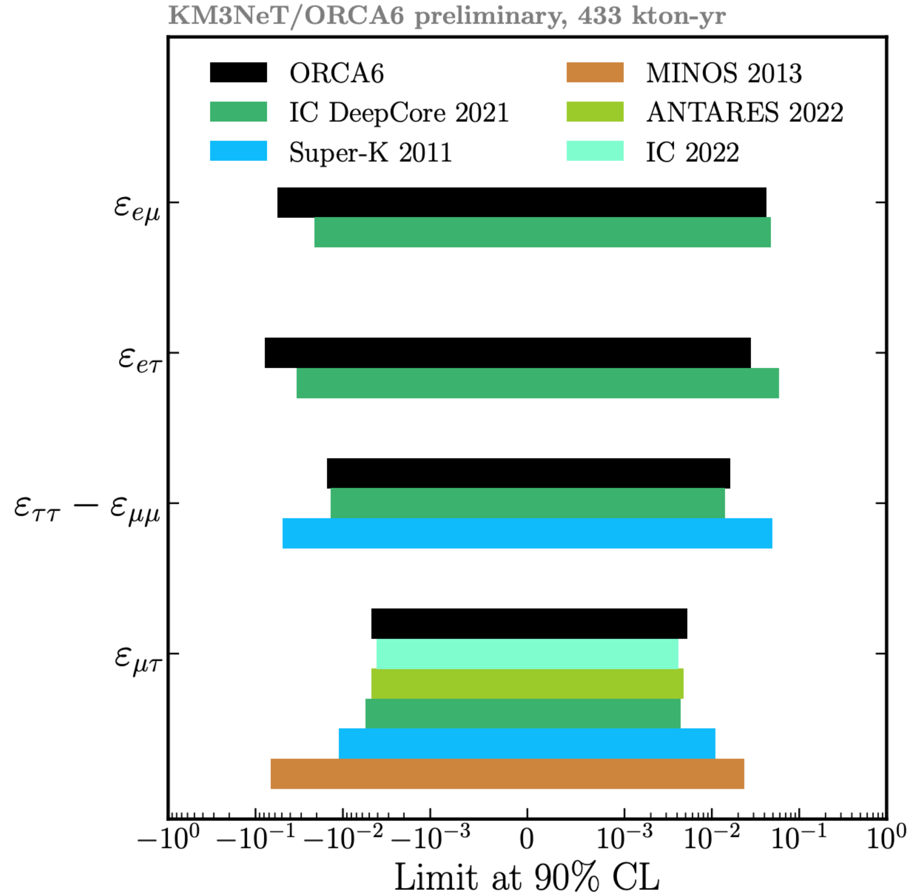
New physics

- Atmospheric neutrinos very suitable to do BSM searches:
  - Sterile neutrinos, NSI, quantum gravity, Lorentz invariance, dark matter, etc.
  - Stay tuned -> IceCube and KM3NeT new results underway!!!

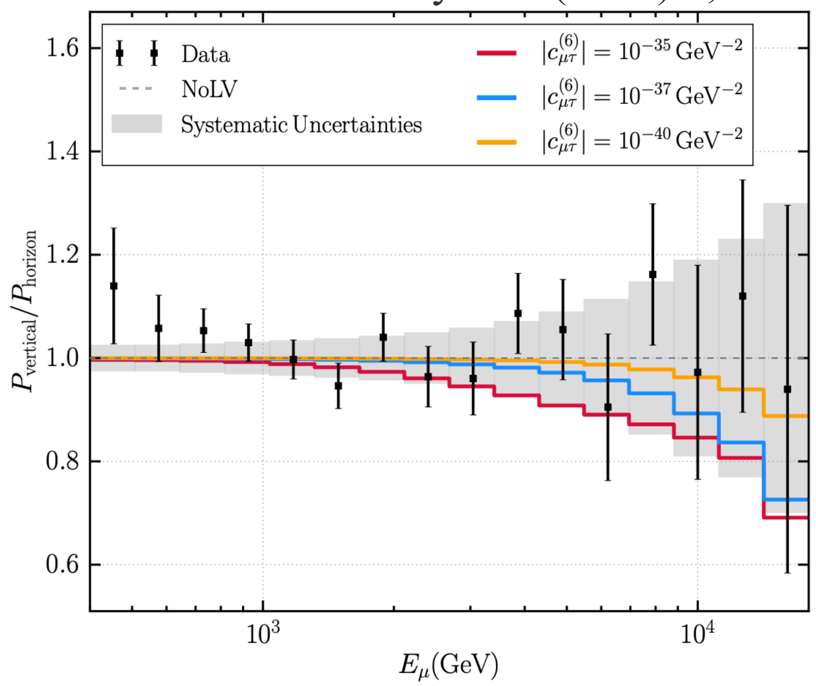
Phys. Rev. Lett. 130 (2023) 031802



A. Lazo (ICRC 23)



Nature Phys. 14 (2018) 9, 961



Conclusions

- Atmospheric neutrinos very valuable to understand neutrino oscillations.
- Samples with large statistics -> systematics are primary challenge
- New technologies are coming online!


Thanks

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101025085.