

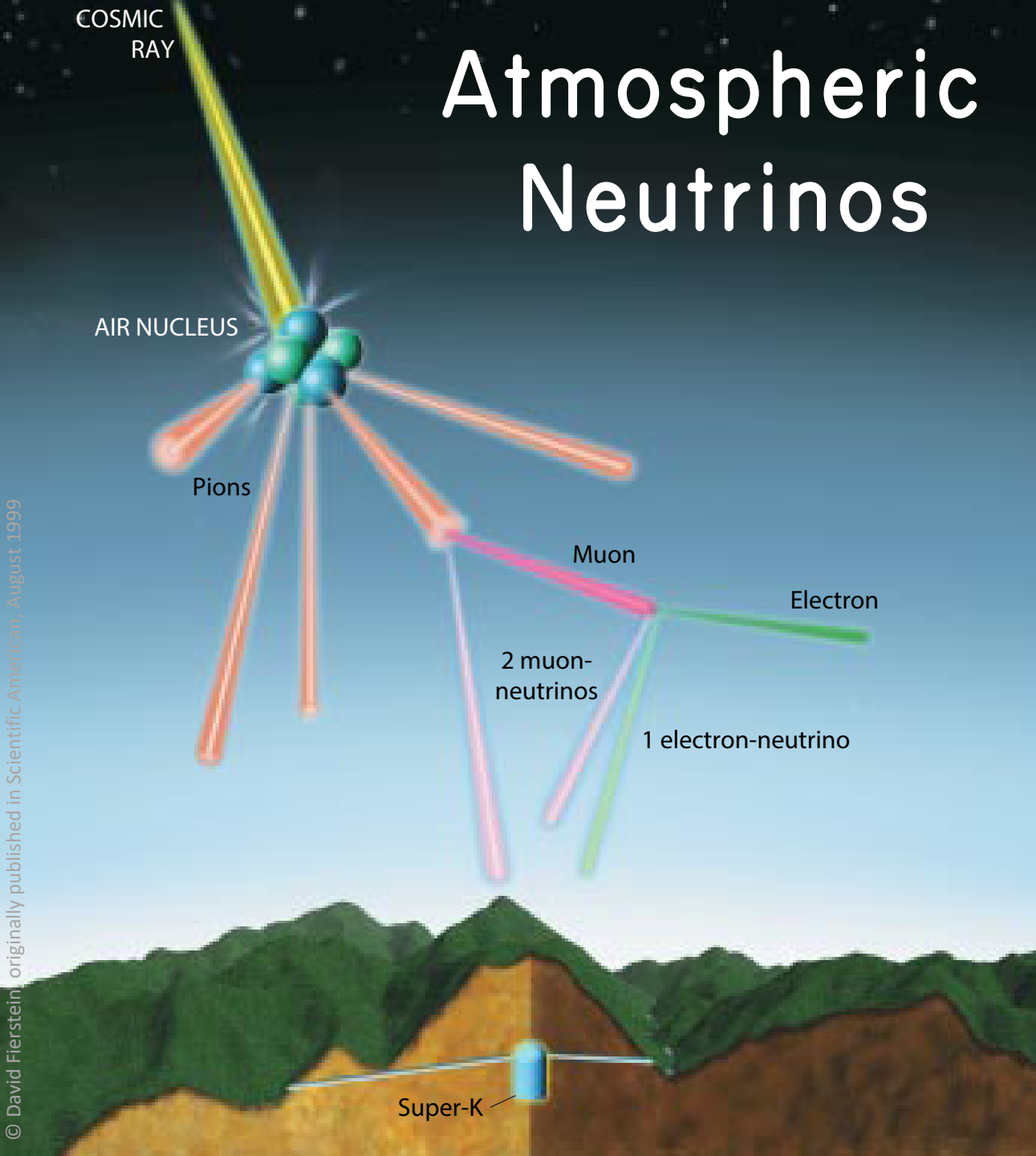
**14th
International Neutrino
Summer School
at the Fermilab NPC**

07–19 August 2023

Ed Kearns
Boston University
kearns@bu.edu

CDF, MACRO, Super-K, K2K, T2K,
MiniCLEAN, LBNE, LAriAT, Hyper-K,
EMPHATIC, DUNE

LECTURE 2



Atmospheric Neutrinos

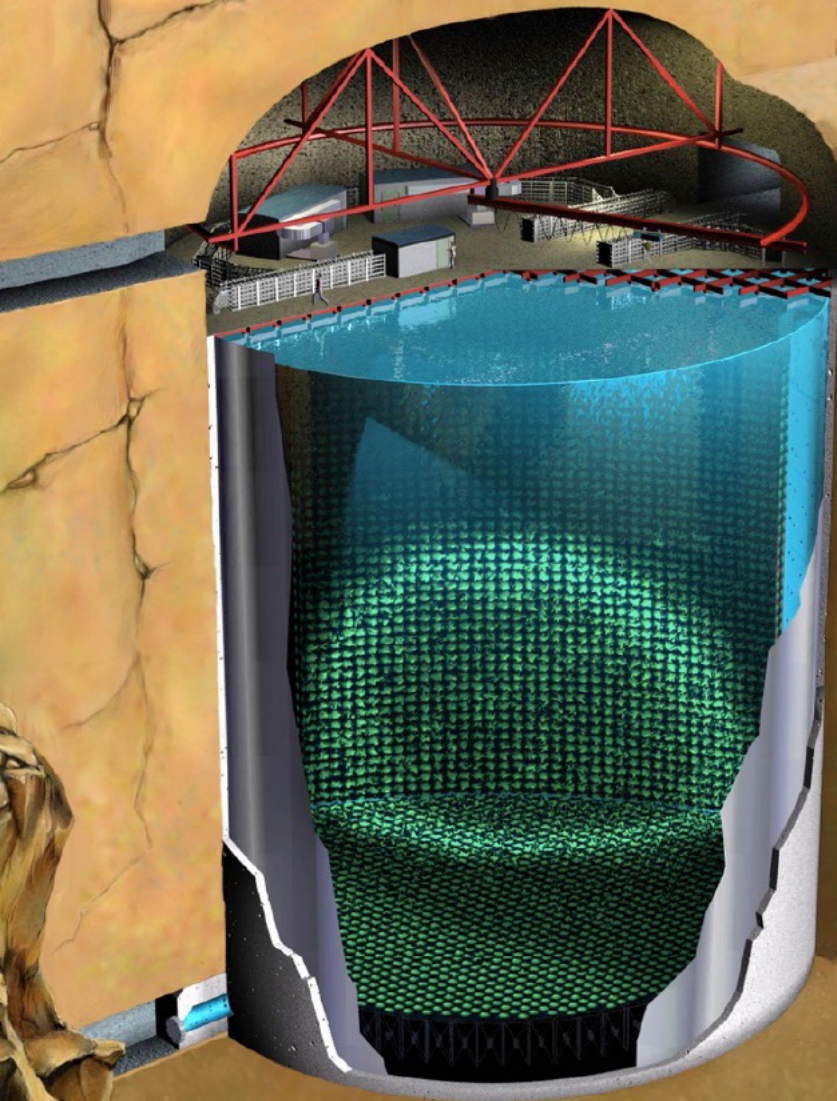
Lecture 1:

Early stuff – history
Atmospheric ν Anomaly
Elements of the Experiment

Lecture 2:

Resolution of the Anomaly
Current results
Future experiments

Super-Kamiokande



**IMB and Kamiokande collaborations merged
(plus, new collaborators added)**

50000 tons of water (22.5 kton fiducial)

11000 50-cm PMTs

Outer detector (1900 smaller PMTs from IMB)

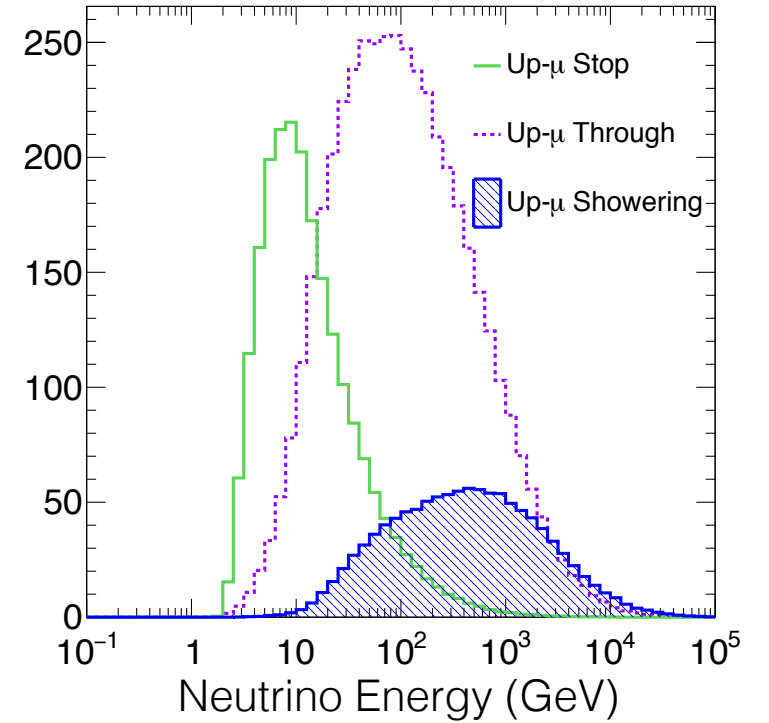
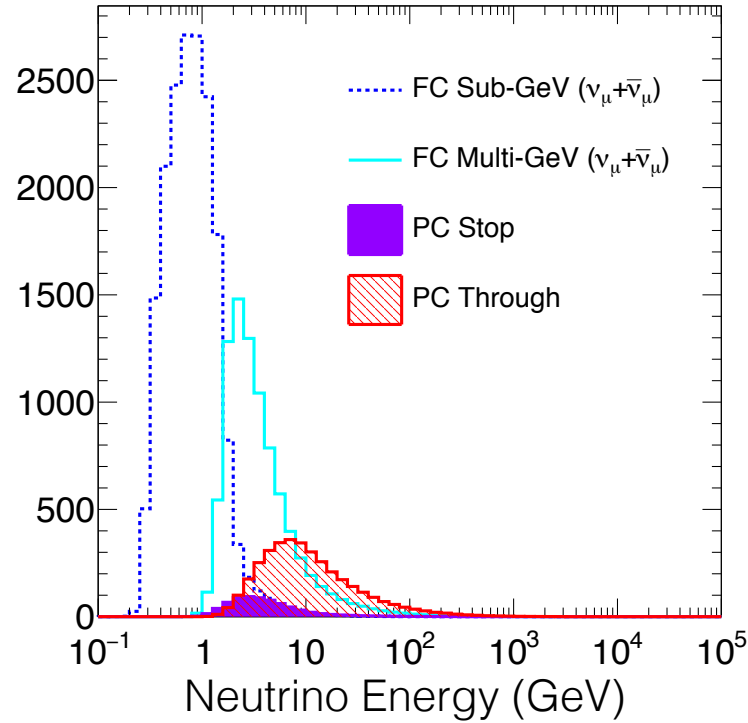
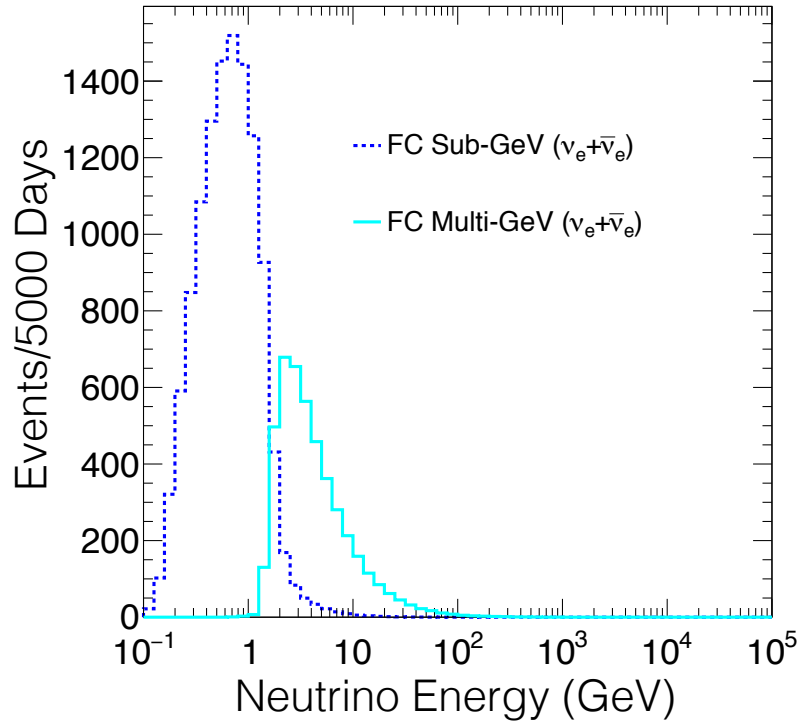
Energy threshold (solar) ~ 5 MeV

10 atmospheric neutrinos per day

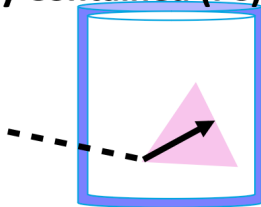
7.5×10^{33} protons, 6×10^{33} neutrons

Several upgrades (+ one destructive accident)

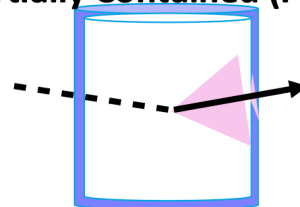
Event Categories → Neutrino Energy



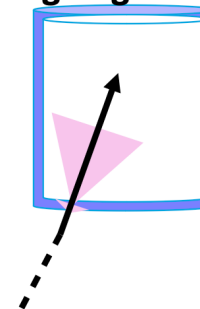
Fully Contained (FC)



Partially Contained (PC)



Upward-going Muons (Upmu)



1st Super-K paper – March 1998

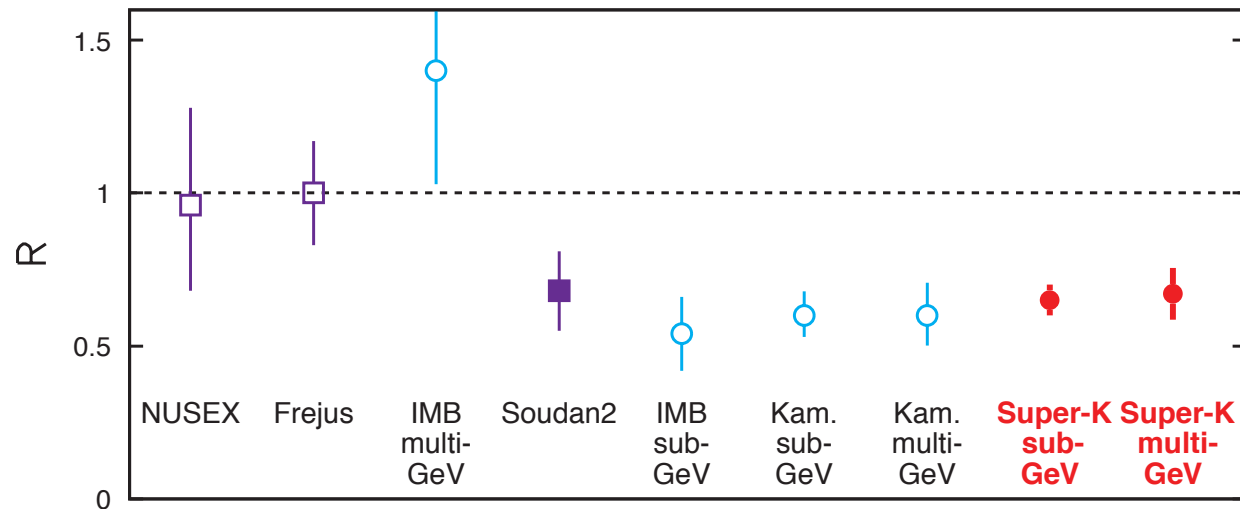
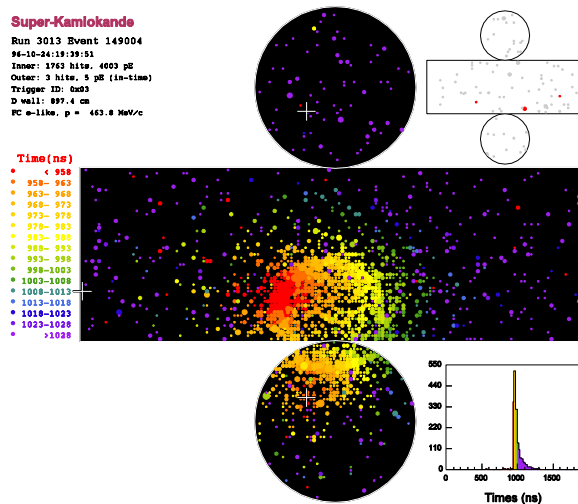
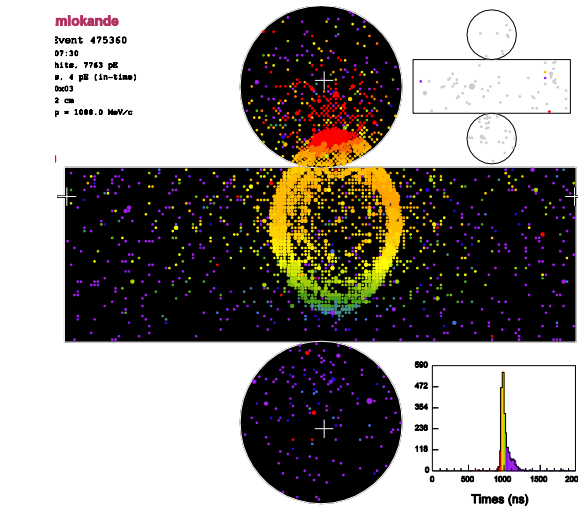
Measurement of a small atmospheric ν_μ/ν_e ratio

firmed the existence of a smaller atmospheric ν_μ/ν_e ratio than predicted. We obtained $R = 0.61 \pm 0.03(\text{stat.}) \pm 0.05(\text{sys.})$ for events in the sub-GeV range. The Super-Kamiokande detector has much greater fiducial mass and sensitivity than prior experiments. Given the relative certainty in this result, statistical fluctuations can no longer explain the deviation of R from unity.

25.5 kton yr (414 days data)

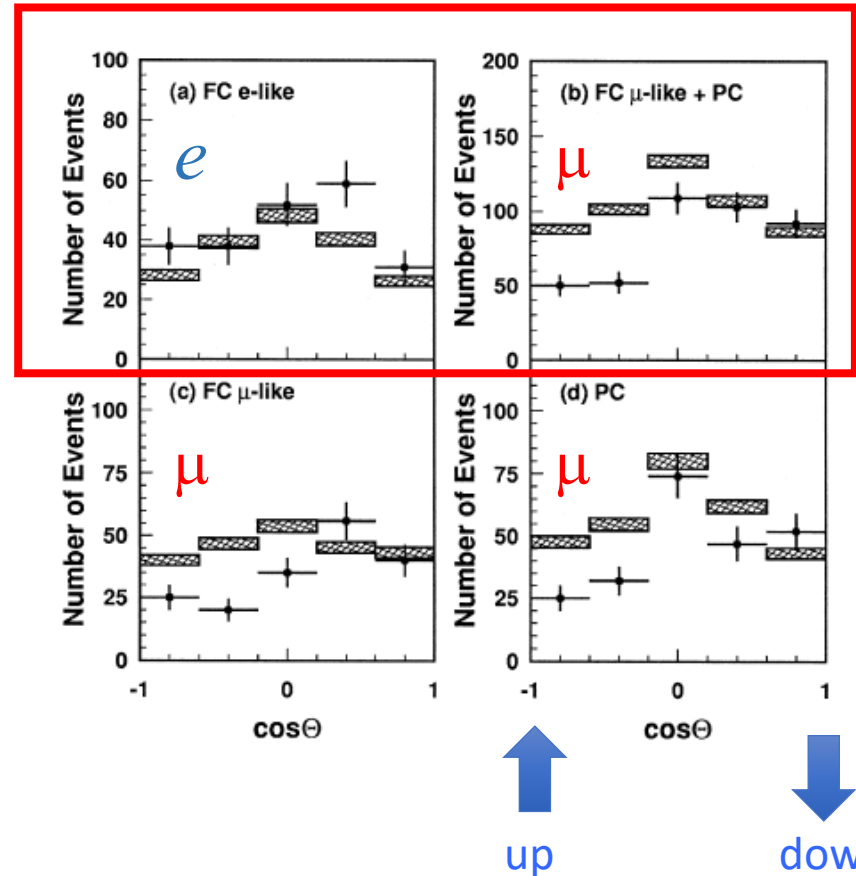
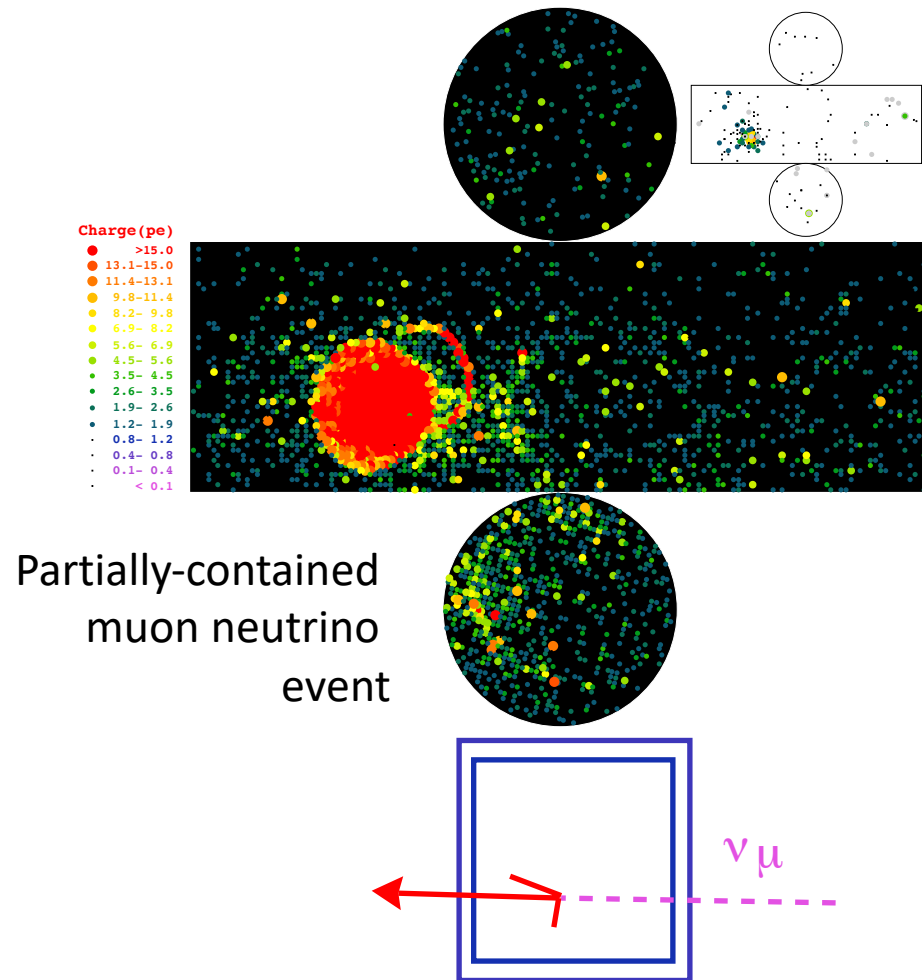
Sub-GeV only

Two independent analyses



2nd Super-K paper – May 1998

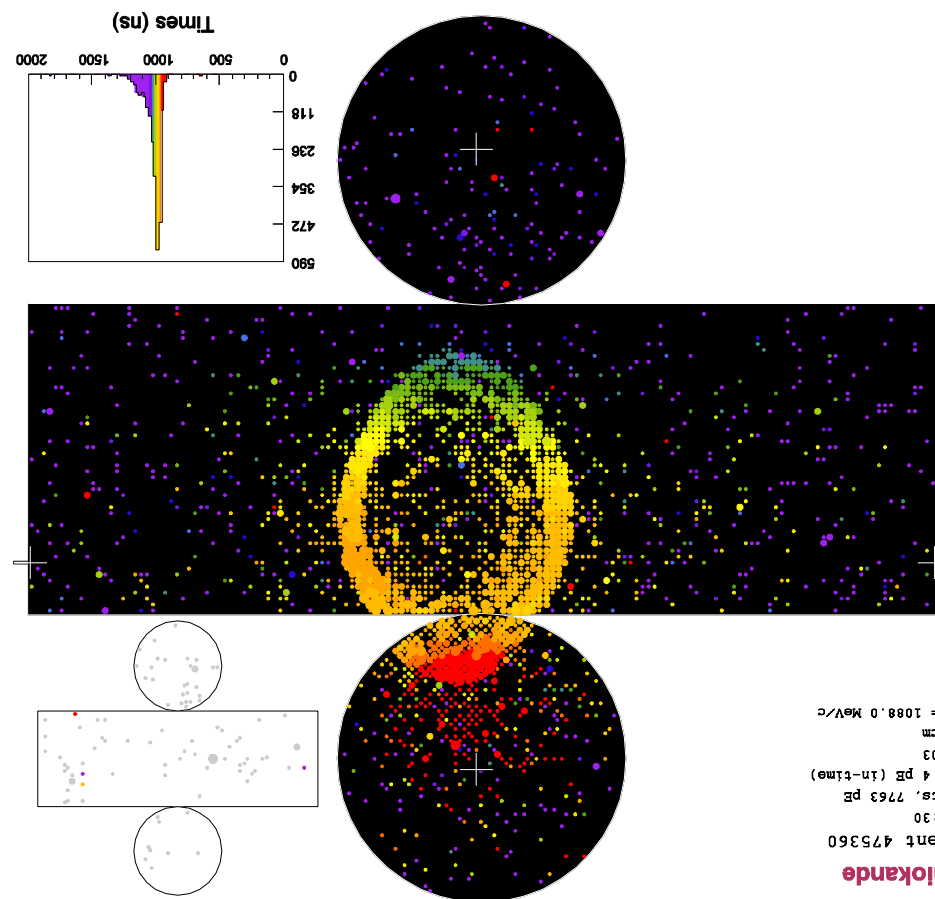
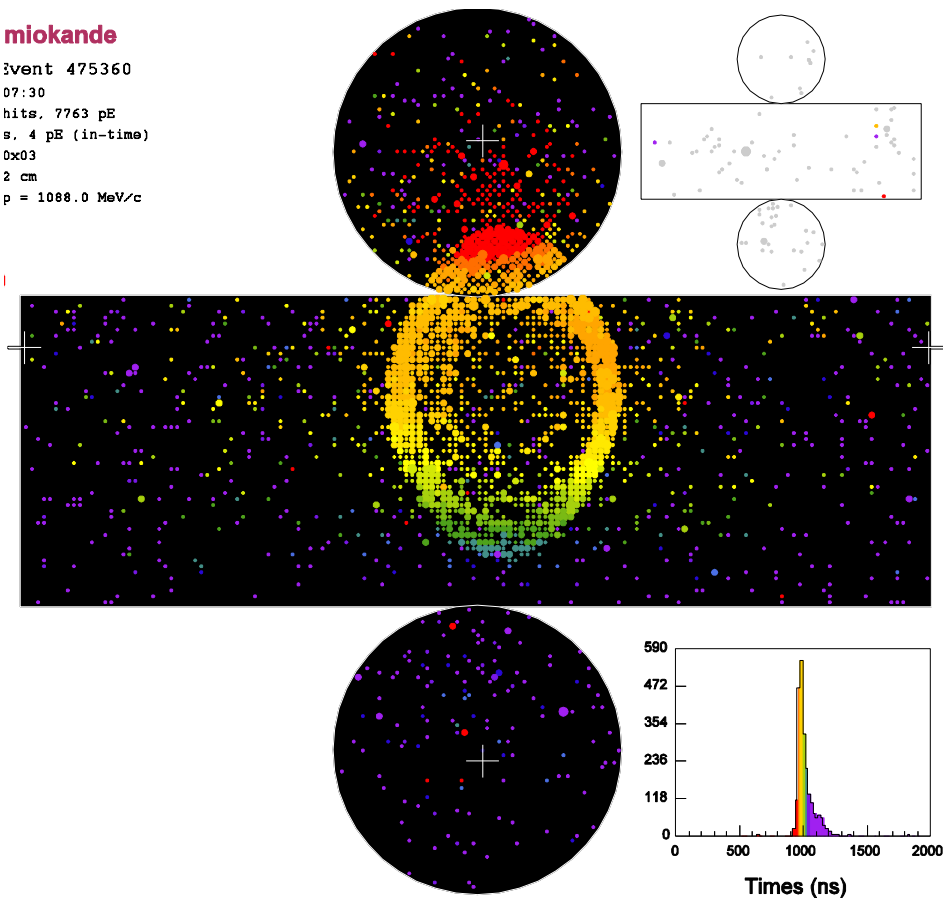
Study of the atmospheric neutrino flux
in the multi-GeV energy range





miokande

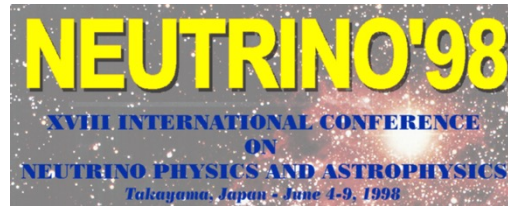
Event 475360
07:30
hits, 7763 pE
s, 4 pE (in-time)
0x03
2 cm
p = 1088.0 MeV/c



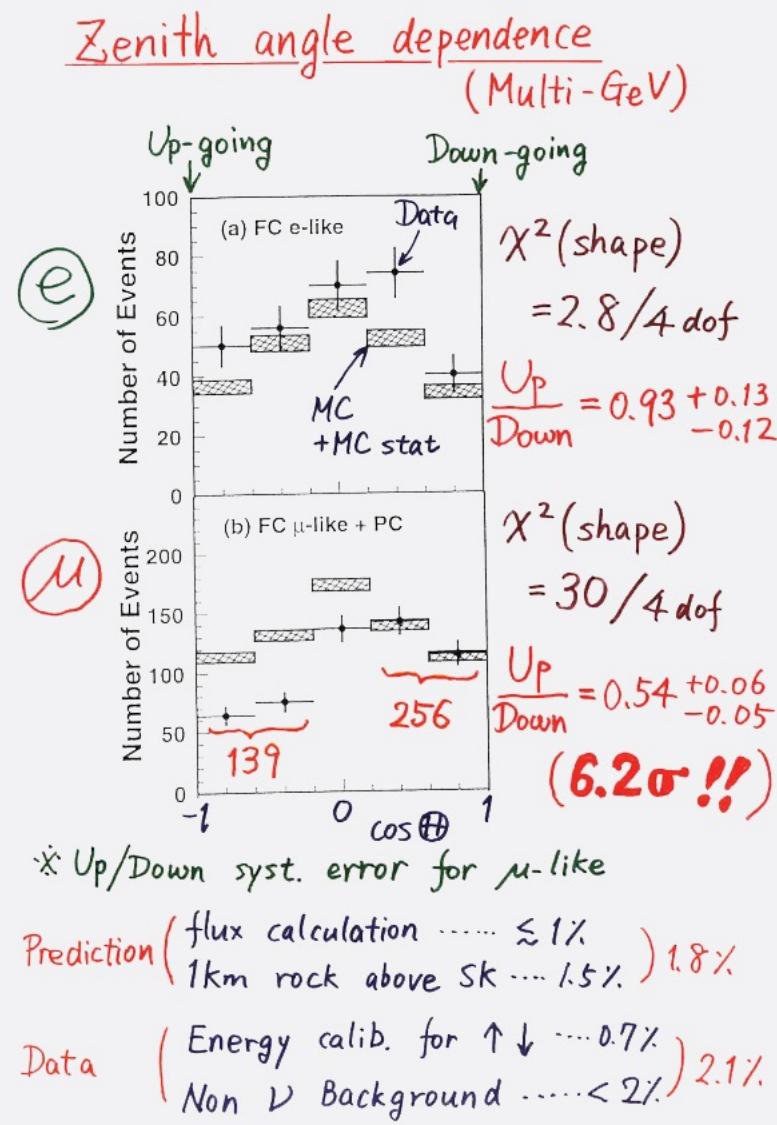
miokande
Event 475360
07:30
hits, 7763 pE
s, 4 pE (in-time)
0x03
2 cm
p = 1088.0 MeV/c

hard to imagine counting half as many of the right compared to the left

Discovery of Neutrino Oscillations



2015 Nobel Prize:
Takaaki Kajita



"All the News That's Fit to Print"

The New York Times

Vol. CLXXIV No. 52,779 NEW YORK, FRIDAY, JUNE 5, 1998 \$5.00

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE
TAKAYAMA, Japan, June 5

For the first time, scientists have found evidence that neutrinos, the most abundant particles in the universe, can change their identity as they travel. This discovery, announced today by a team of Japanese and American physicists, challenges a fundamental principle of physics and suggests that the universe may be very different from what we thought it was.

The discovery was made using the Super-Kamiokande detector, a massive underground observatory in Japan. It consists of a series of tanks filled with water, through which light from neutrino interactions is detected. The team found that neutrinos coming from the South Pole (up-going) had a different flavor composition than those coming from the North Pole (down-going).

This result is a major breakthrough in particle physics. It implies that neutrinos have mass, which was previously assumed to be zero. This has profound implications for our understanding of the universe, including the formation of galaxies and the evolution of the cosmos.

The discovery also challenges the Standard Model of particle physics, which has been the foundation of modern physics for decades. Scientists are now working to understand the implications of this discovery and how it fits into the larger picture of the universe.

The team's findings were presented at a conference in Japan, where they were met with great interest and excitement. The discovery is expected to have a significant impact on the field of particle physics and our understanding of the universe.

The team's findings were also reported in the New York Times, which provided a detailed account of the discovery and its implications. The article highlighted the significance of the discovery and the challenges it poses to existing theories.

The discovery is a testament to the power of scientific inquiry and the importance of international collaboration in research. It shows that even the most fundamental principles of physics can be challenged and revised in the face of new evidence.

The team's findings are expected to lead to further research and discovery in the field of particle physics. Scientists are now working to understand the mechanisms behind neutrino oscillations and how they relate to the mass of neutrinos.

The discovery is a major milestone in the history of particle physics and a testament to the human spirit of exploration and discovery. It shows that there is still much to be learned about the universe and the fundamental laws that govern it.

The team's findings are expected to have a significant impact on the field of particle physics and our understanding of the universe. They are also expected to lead to further research and discovery in the field of particle physics.

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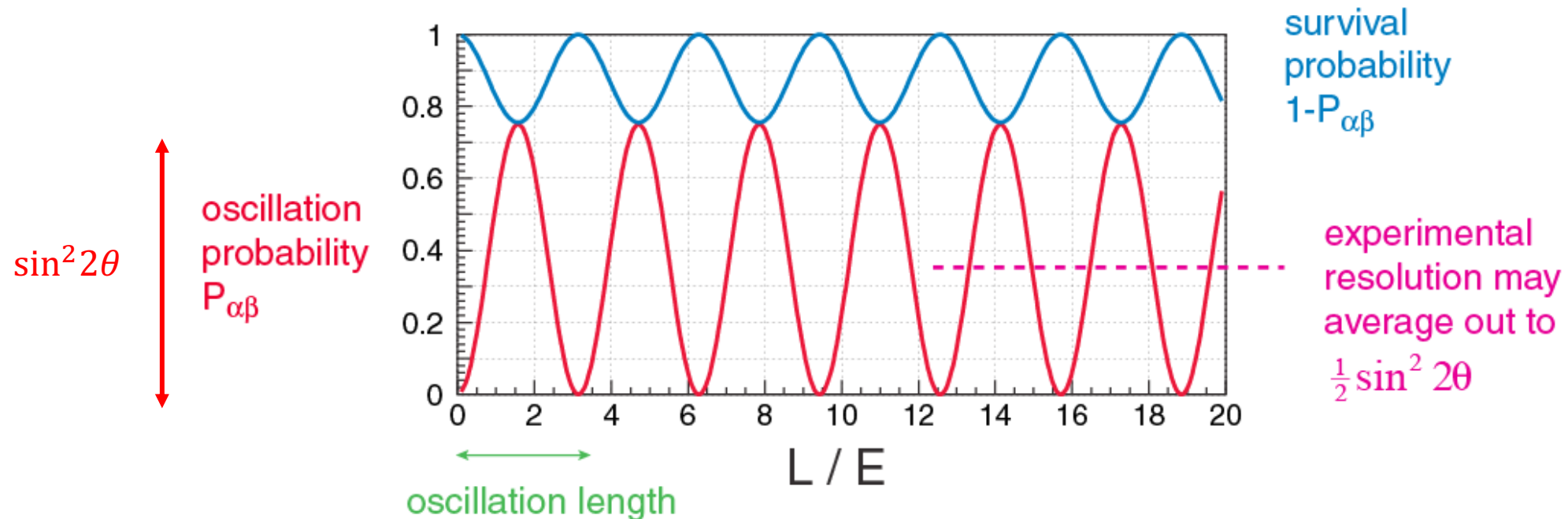
The discovery is a major milestone in the history of particle physics and a testament to the human spirit of exploration and discovery. It shows that there is still much to be learned about the universe and the fundamental laws that govern it.

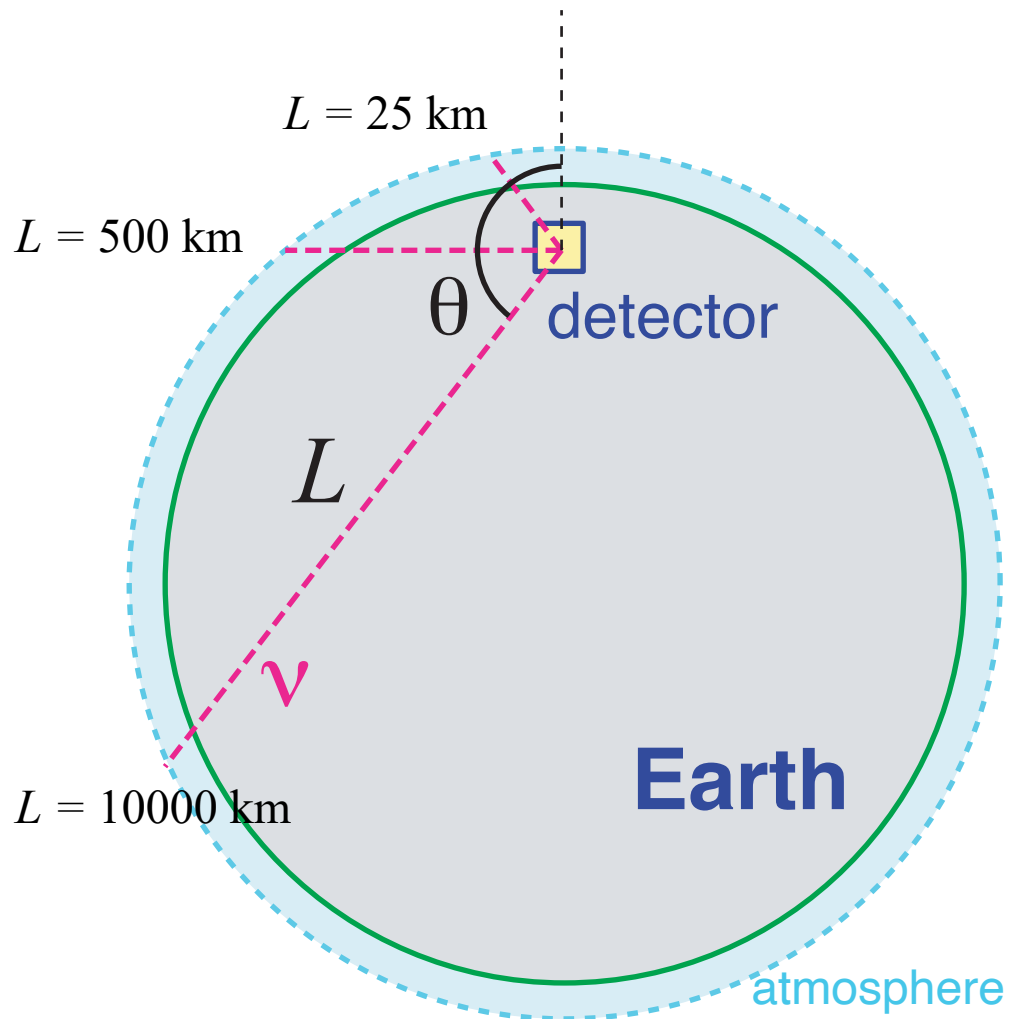
The team's findings are expected to have a significant impact on the field of particle physics and our understanding of the universe. They are also expected to lead to further research and discovery in the field of particle physics.

1-Slide Review: Two Flavor Neutrino Oscillations

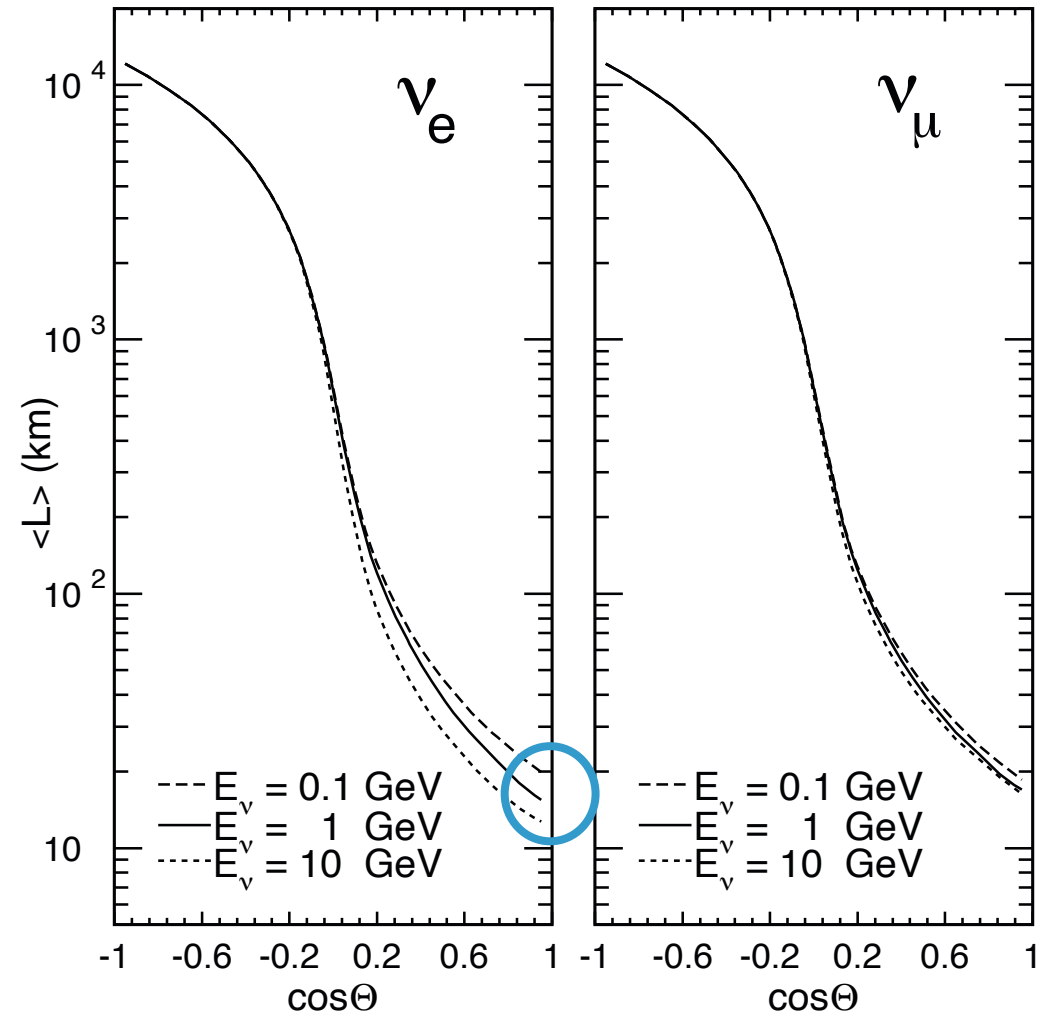
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

km and GeV or
m and MeV

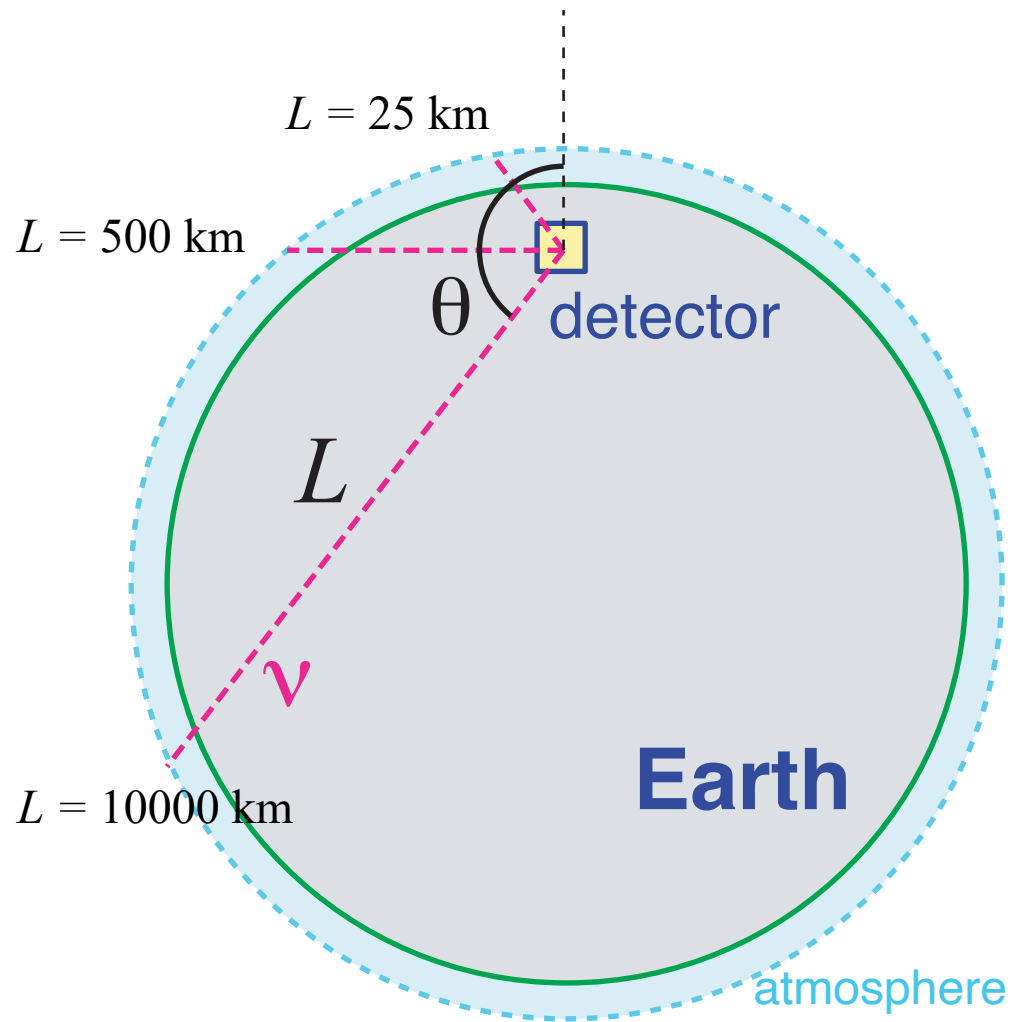




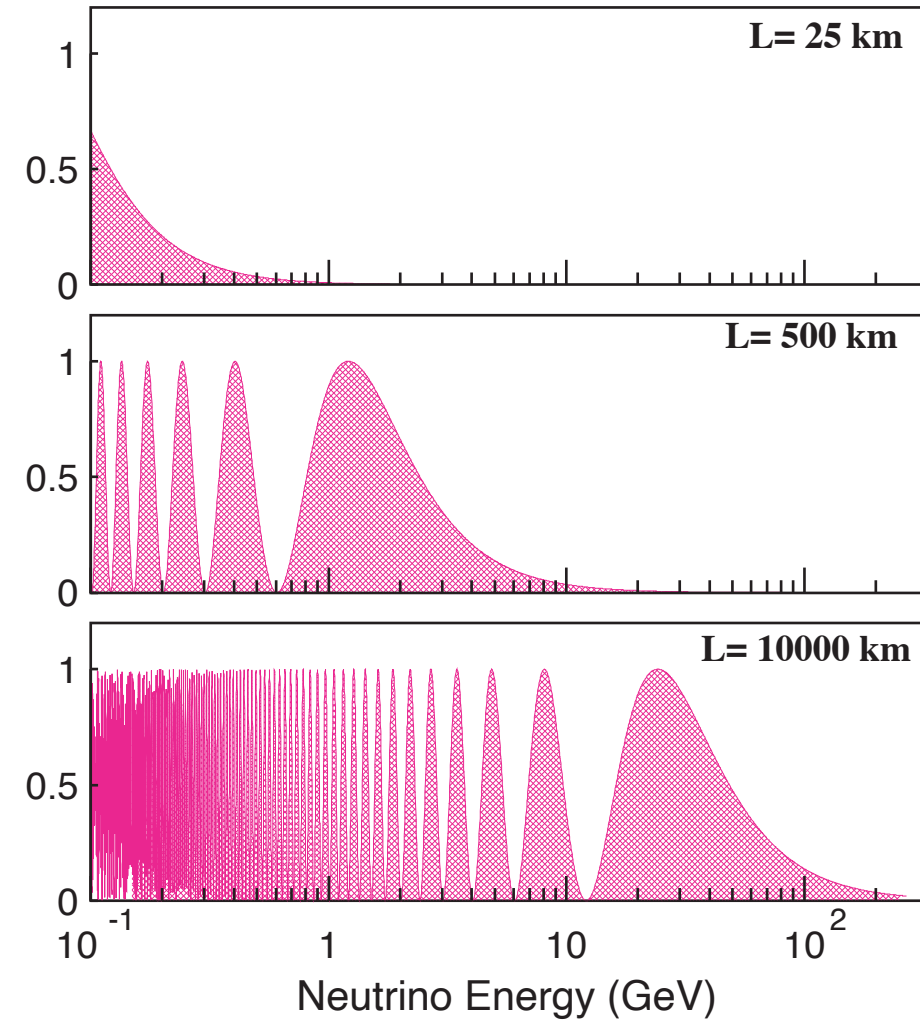
$$L(\theta) = -R \cos \theta + \sqrt{2Rh + h^2 + R^2 \cos^2 \theta}$$



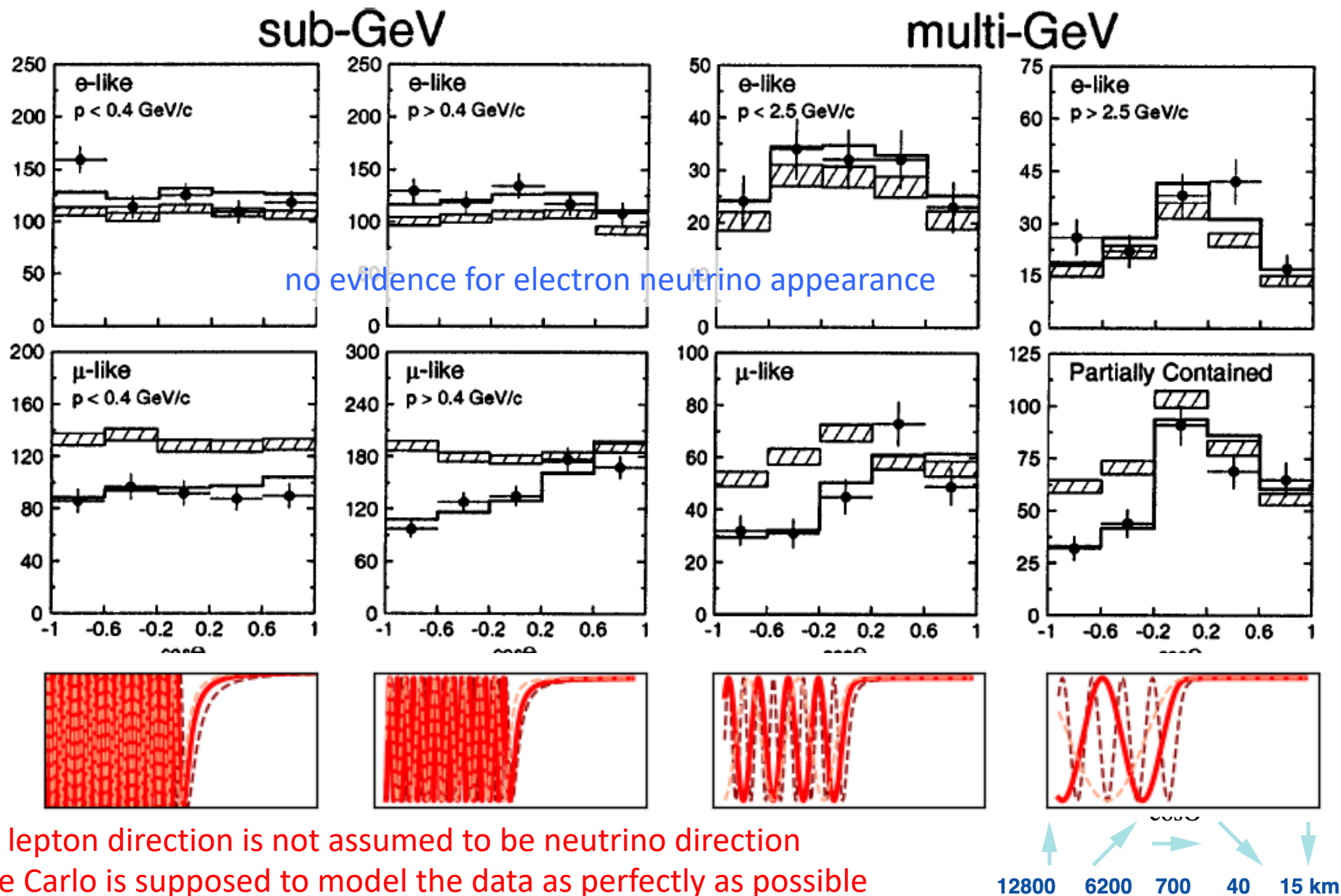
model production height
(depends on energy,
important for down-going ν)



$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E}$$



3rd Super-K paper – August 1998



3rd Super-K paper – August 1998

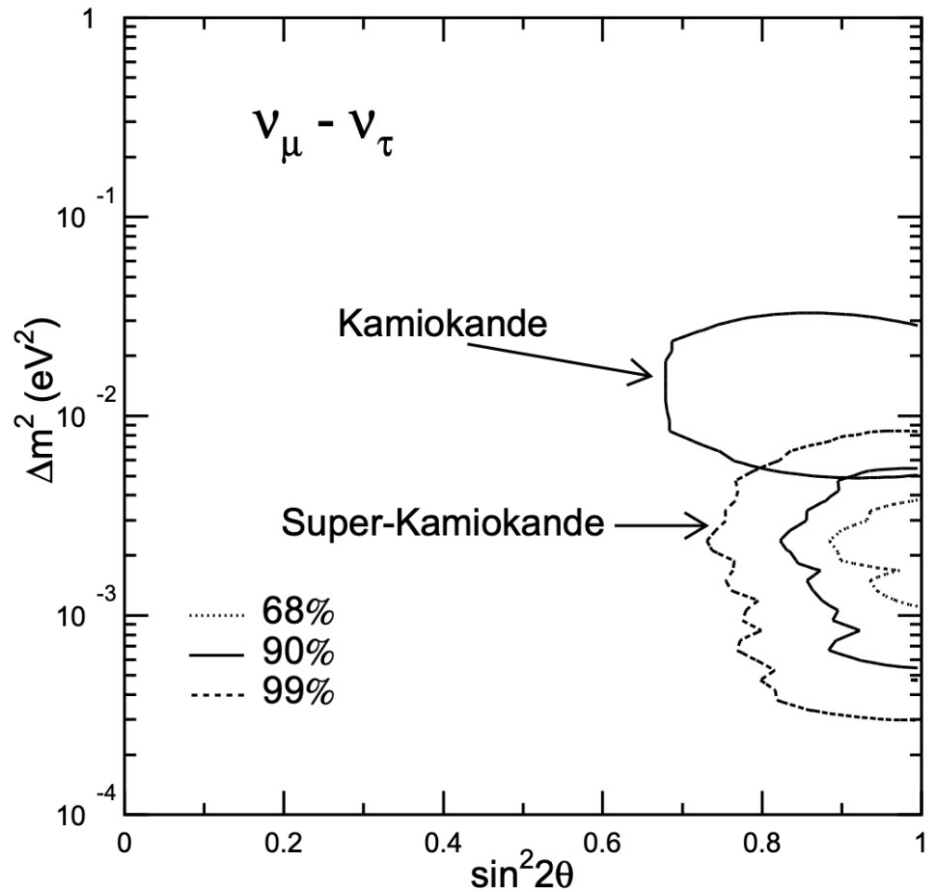
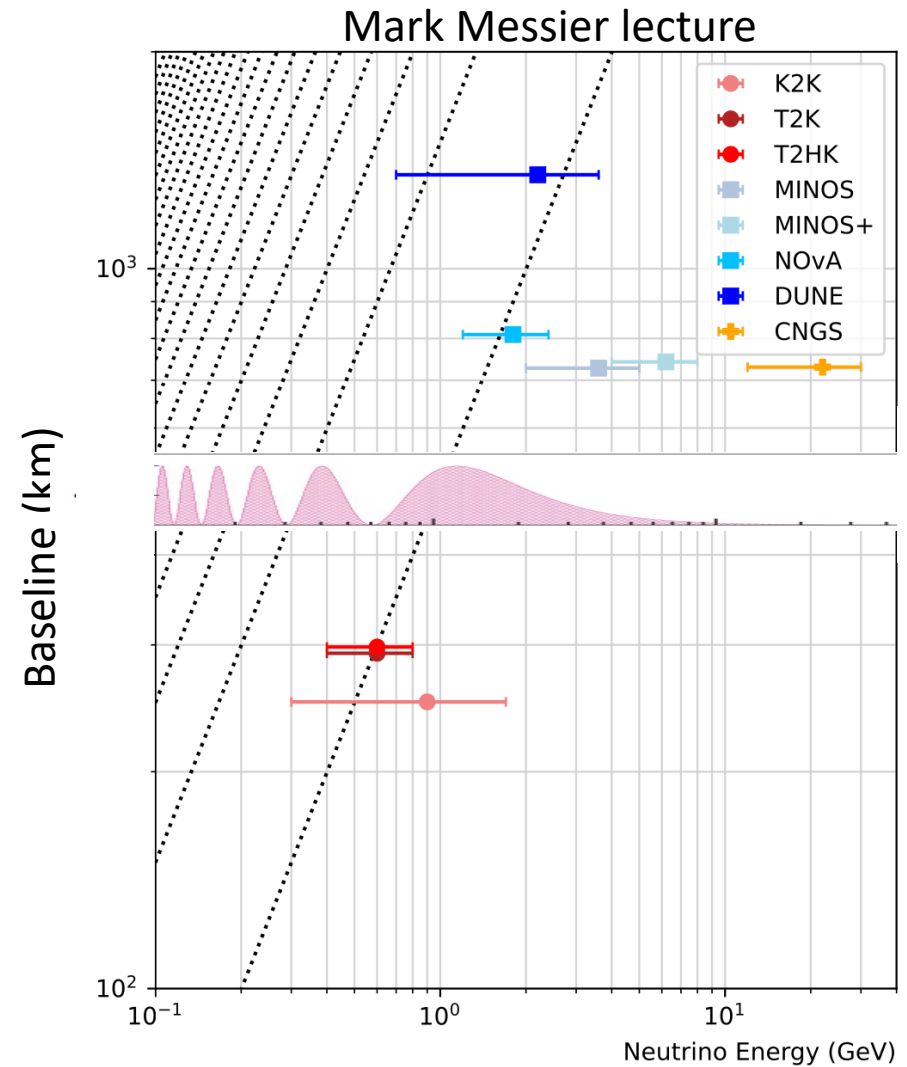


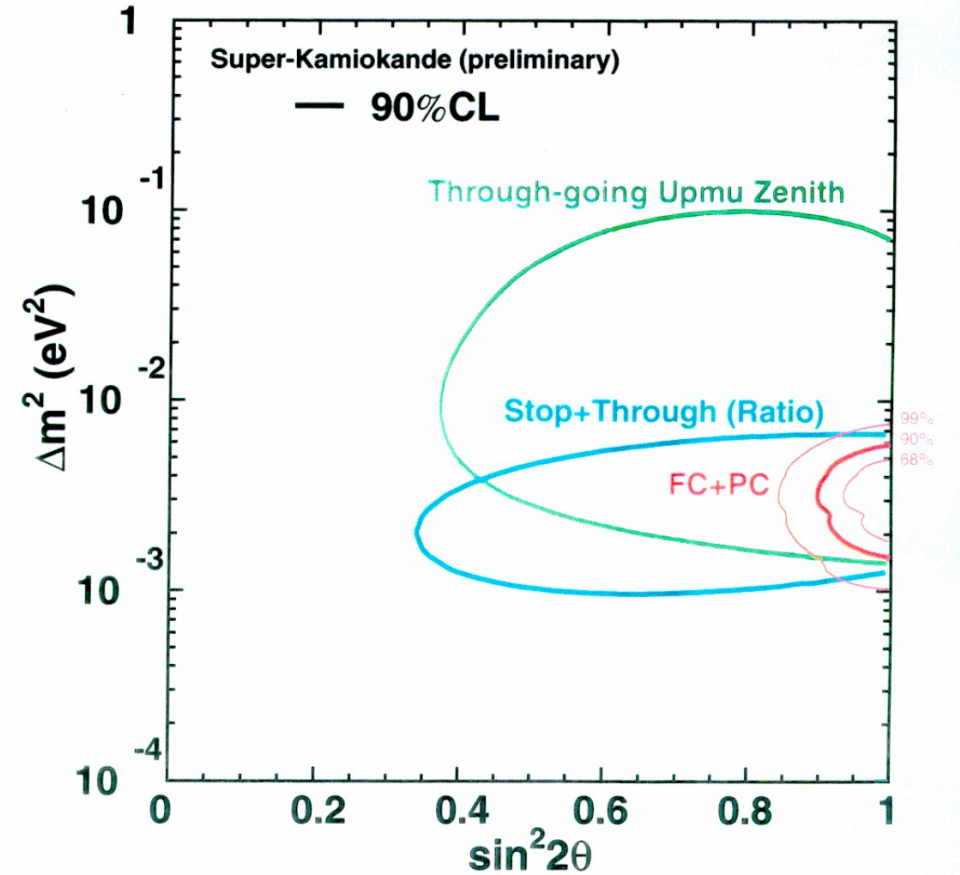
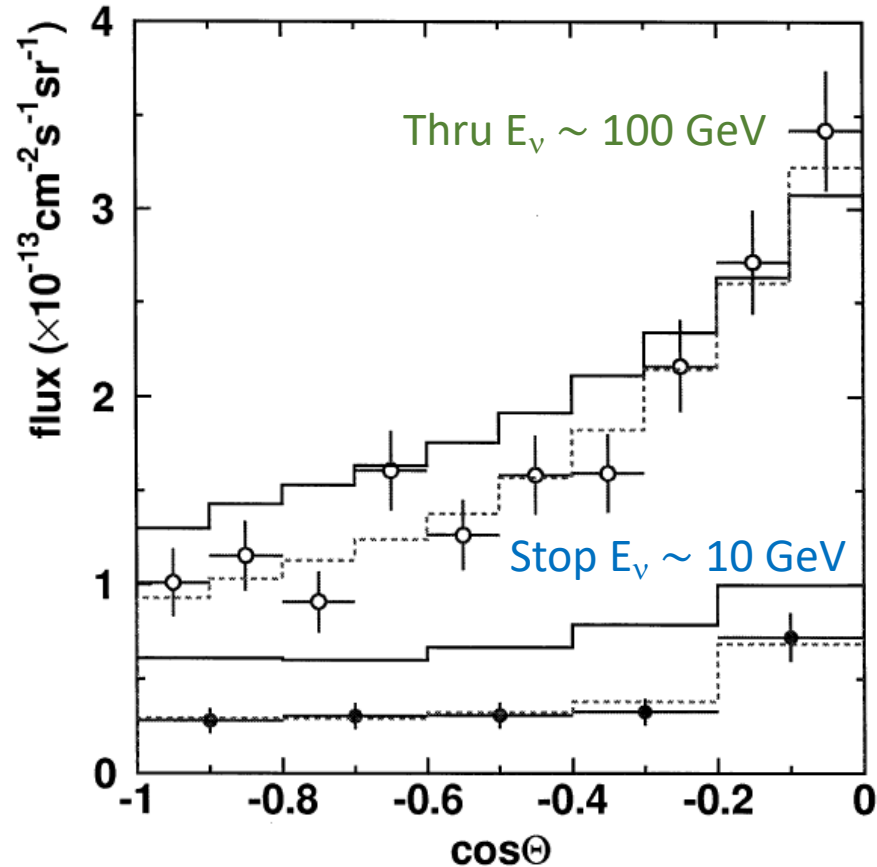
FIG. 2. The 68%, 90% and 99% confidence intervals are shown for $\sin^2 2\theta$ and Δm^2 for $\nu_\mu \leftrightarrow \nu_\tau$ two-neutrino oscillations based on 33.0 kiloton-years of Super-Kamiokande data. The 90% confidence interval obtained by the Kamiokande experiment is also shown.



Long-Baseline Experiments must adapt to low Δm^2

4th and 5th papers – Upward Going Muons

December 1998 and August 1999

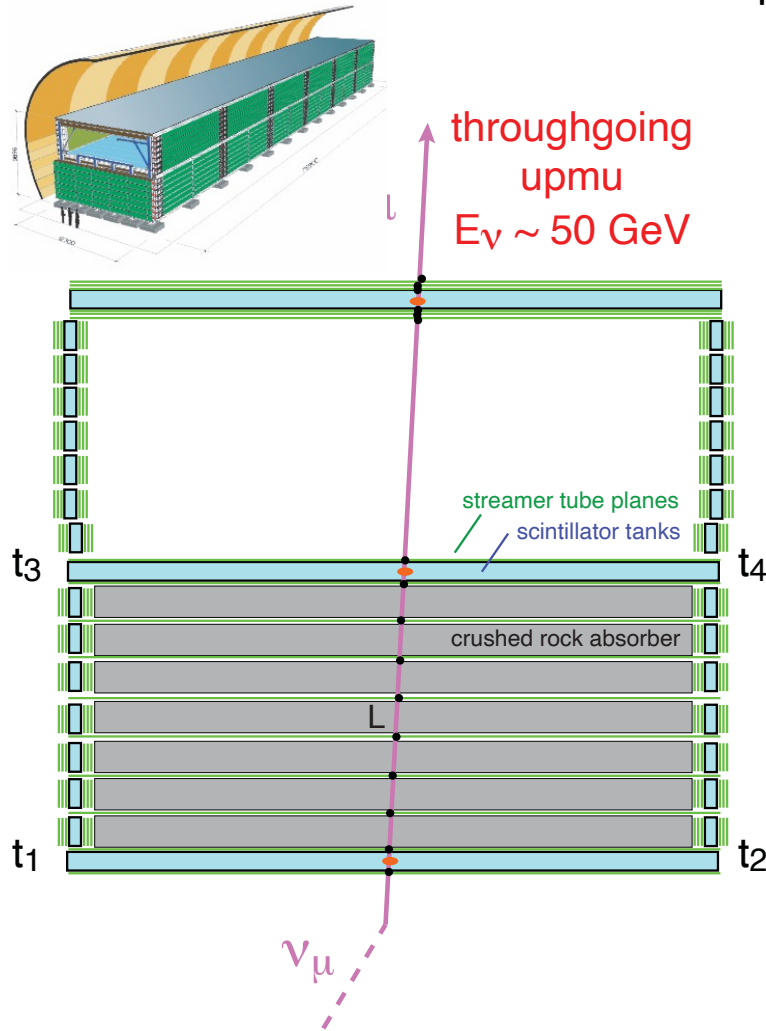


confirmed oscillations parameters with statistically and systematically different data set

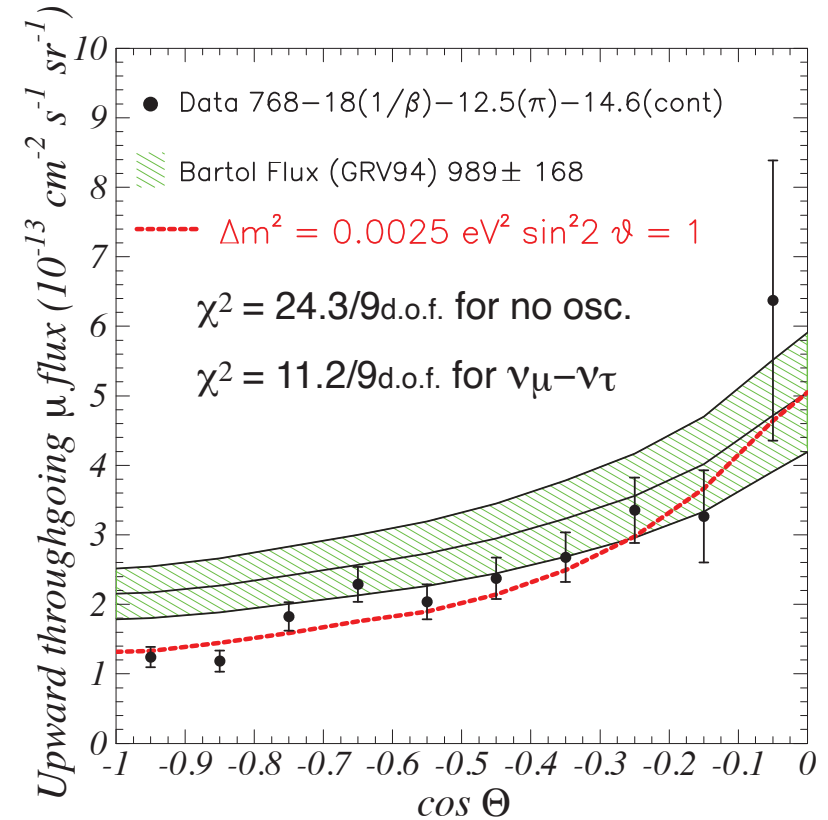
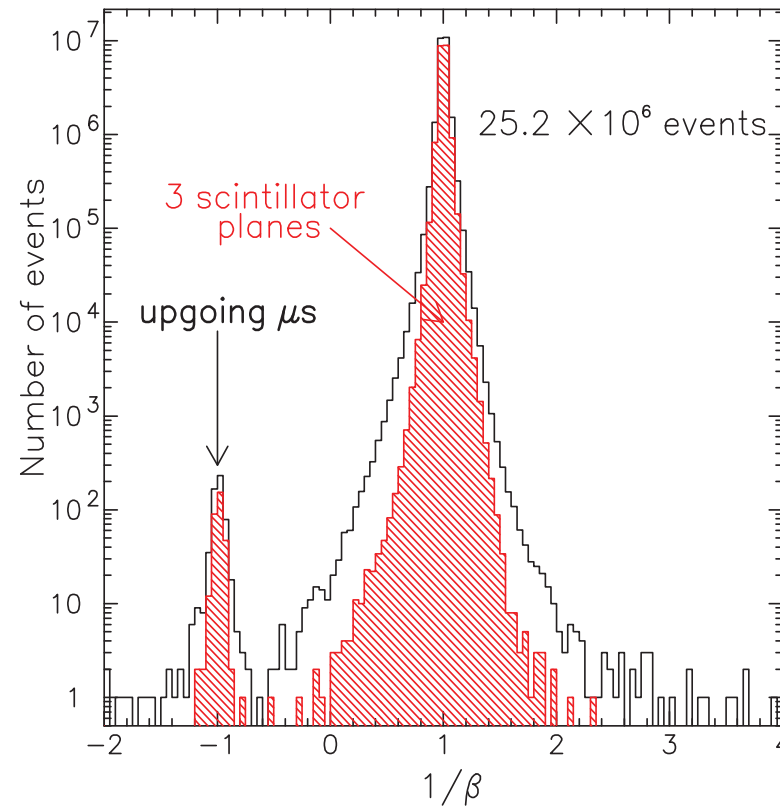
Independent Confirmation – MACRO upward- μ

Phys.Lett.B 434 (1998)

Monopole Astrophysics Cosmic Ray Observatory

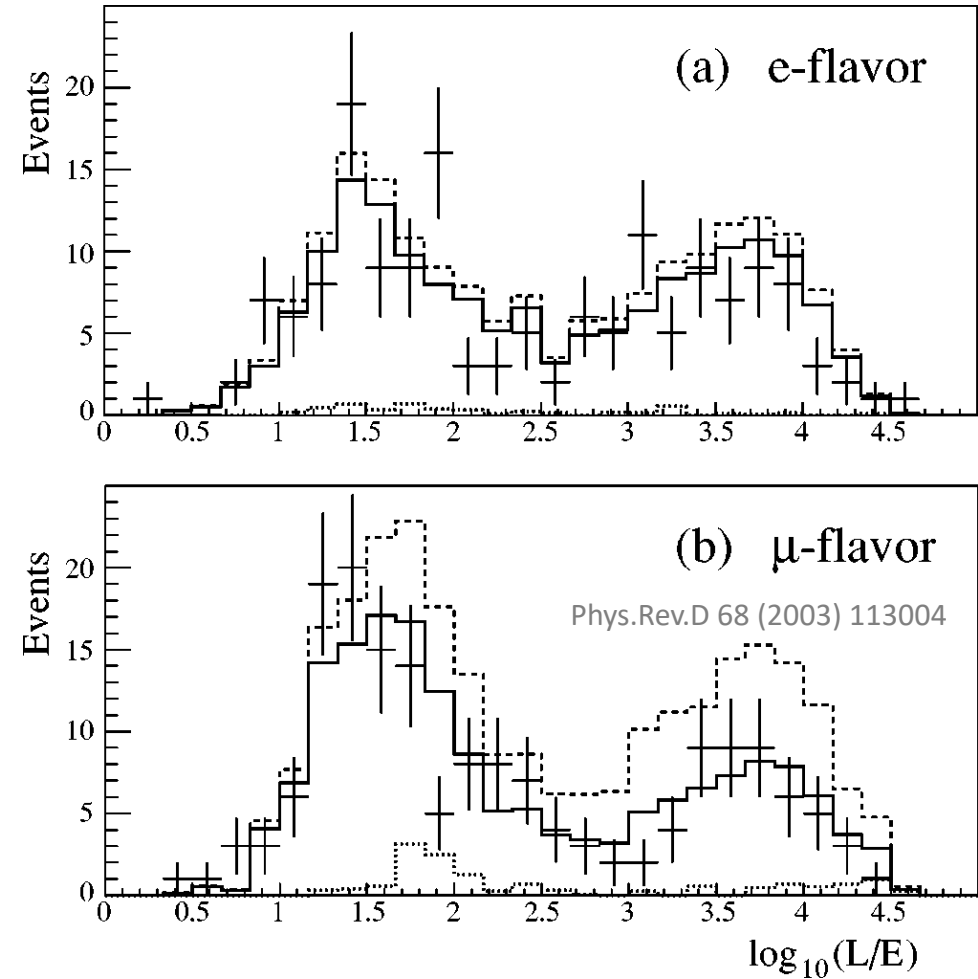
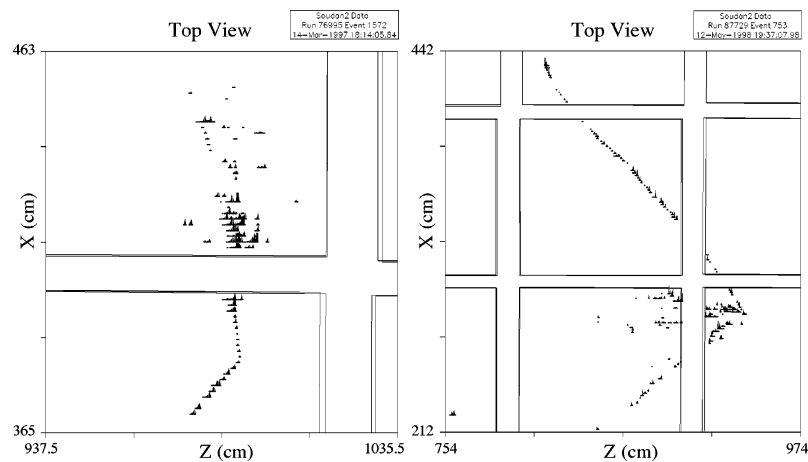
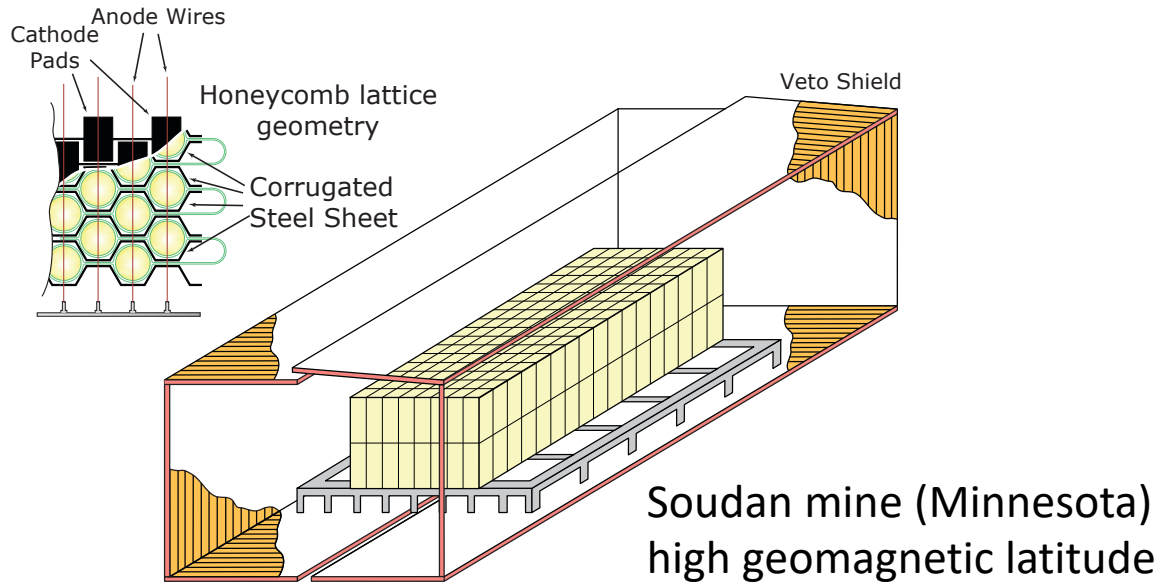


$$\frac{1}{\beta} = \frac{(t_1 + t_2 - t_3 - t_4)}{2L}$$



Independent Confirmation – Soudan 2

Phys.Lett.B449:137–144,1999

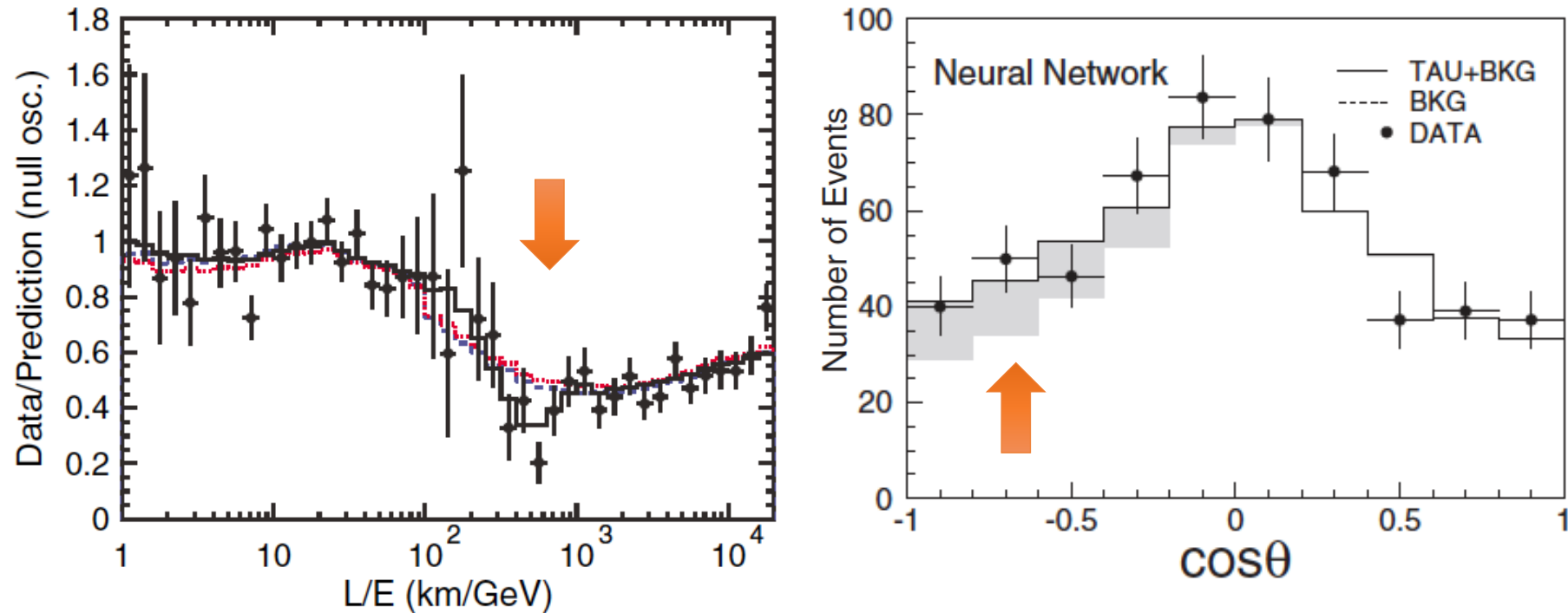


μ/e double ratio resolves iron target issue from 1980's
Later: zenith angle dependence

2000 Tau Neutrinos Favored over Sterile Neutrinos in Atmospheric Muon Neutrino Oscillations

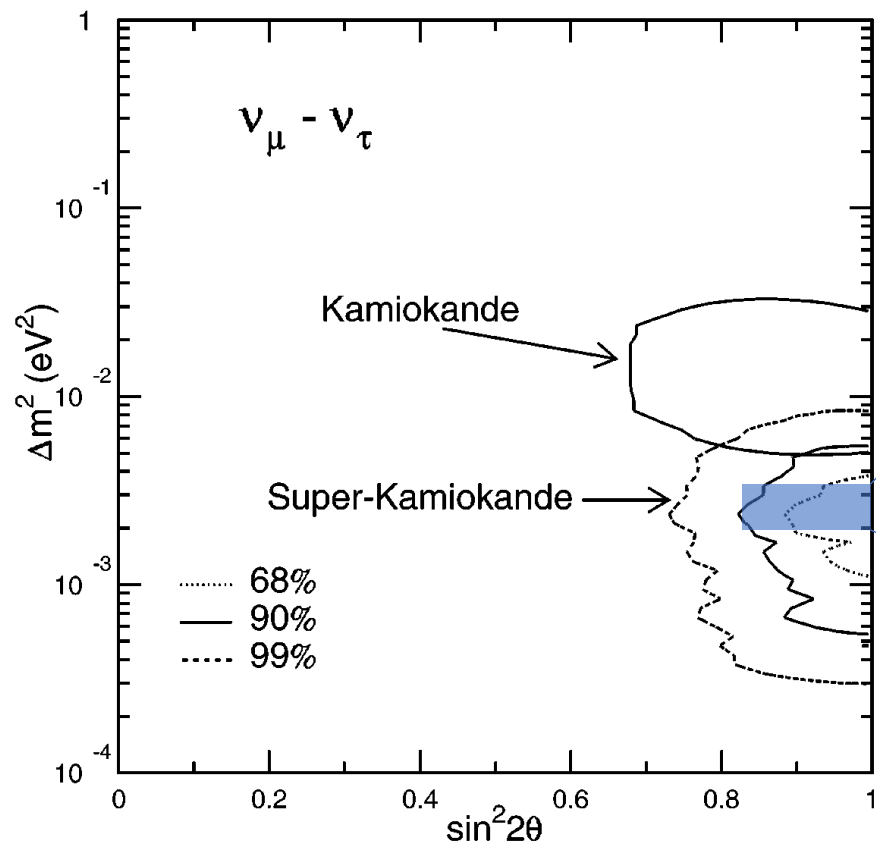
no matter effect suppression for $E > 15$ GeV & no NC disappearance

2004 Evidence for an Oscillatory Signature in Atmospheric Neutrino Oscillations

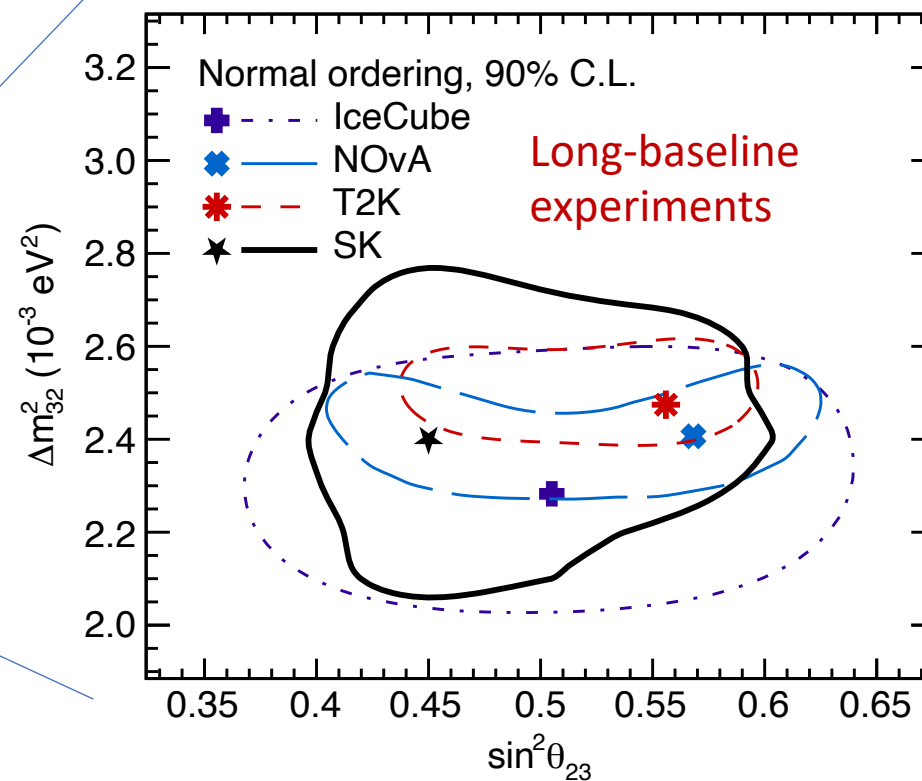


2006 Measurement of Atmospheric Neutrino Flux Consistent with Tau Neutrino Appearance

1998



2023



Next: 2023 and beyond
3-flavors, matter effects, mass ordering

The Three Unknowns of 3-flavor ν Oscillation

“Mass Ordering” a.k.a.
“Mass Hierarchy”
or sign of Δm^2 ?

“Octant”: is θ_{23}
different from 45° ?

CP violation?

Parameter	best-fit	rough 1σ uncertainty
Δm_{21}^2 [10^{-5} eV ²]	7.37	± 0.17 (2.3%)
$ \Delta m^2 $ [10^{-3} eV ²]	2.50 (2.46)	± 0.06 (2.4%)
$\sin^2 \theta_{12}$	0.297	± 0.017 (5.7%)
$\sin^2 \theta_{23}, \Delta m^2 > 0$	0.437	+8%
$\sin^2 \theta_{23}, \Delta m^2 < 0$	0.569	-5%
$\sin^2 \theta_{13}, \Delta m^2 > 0$	0.0214	+5%
$\sin^2 \theta_{13}, \Delta m^2 < 0$	0.0218	-9%
δ/π	1.35 (1.32)	± 0.0012 (5.5%)
		$0 \leftrightarrow 2\pi$ at 1σ

From 2016 RPP by PDG, based on 1601.07777 (Bari group)

We can investigate all of these with atmospheric neutrinos

Three Flavor Neutrino Oscillation in Matter

Freund, M. PRD 64 (2001) 053003

$$P(\nu_\mu \rightarrow \nu_e) \cong T_1 \sin^2 2\theta_{13} - T_2 \alpha \sin 2\theta_{13} + T_3 \alpha \sin 2\theta_{13} + T_4 \alpha^2$$

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

$$T_1 = \sin^2 \theta_{23} \frac{\sin^2 [(1-x)\Delta]}{(1-x)^2}$$

CP violating

$$T_2 = \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP conserving

$$T_3 = \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

for anti-neutrinos
sign of x and
sign of $\sin \delta_{cp}$
is changed

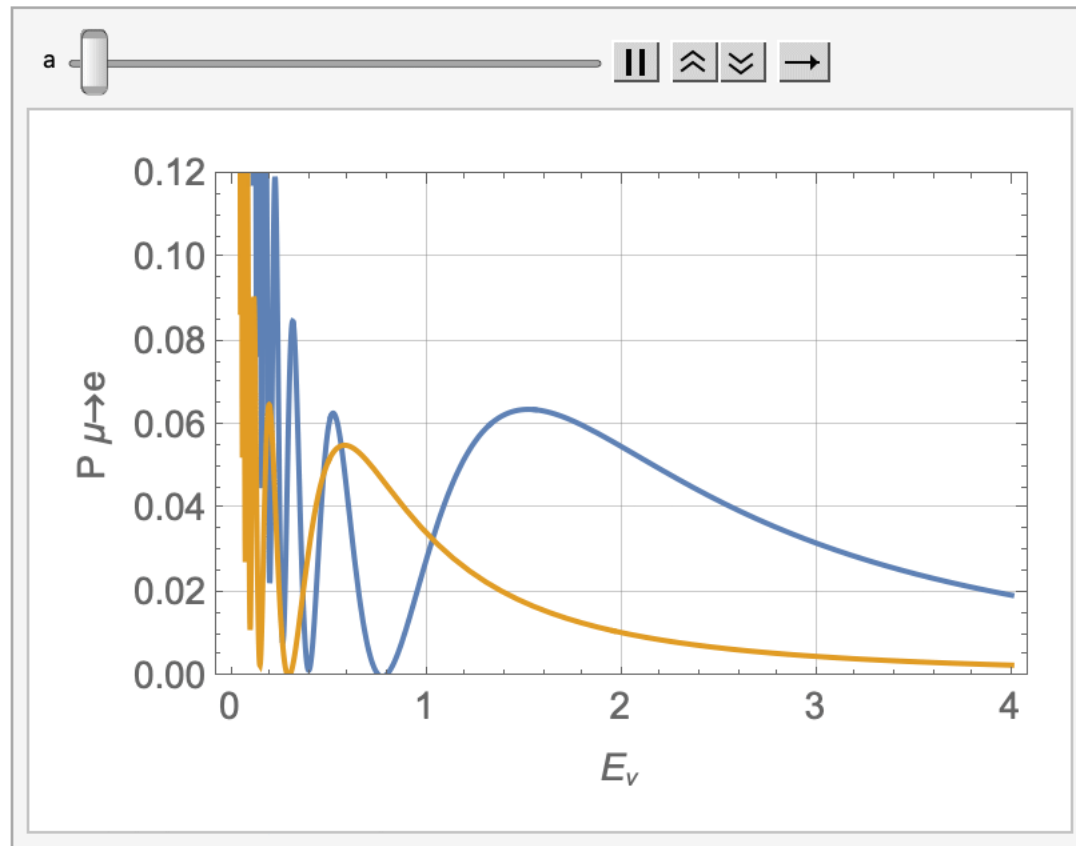
Resonance condition
for ν_e if normal ordering
for $\bar{\nu}_e$ if normal ordering

sign encodes
mass ordering:

$$\begin{aligned} \Delta m_{31}^2 &= m_3^2 - m_1^2 \\ &> 0 \text{ normal} \\ &< 0 \text{ inverted} \end{aligned}$$

$$\Delta = \frac{\Delta m_{31}^2 L}{4E} \quad x = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2} \sim \frac{E}{12 \text{ GeV}}$$

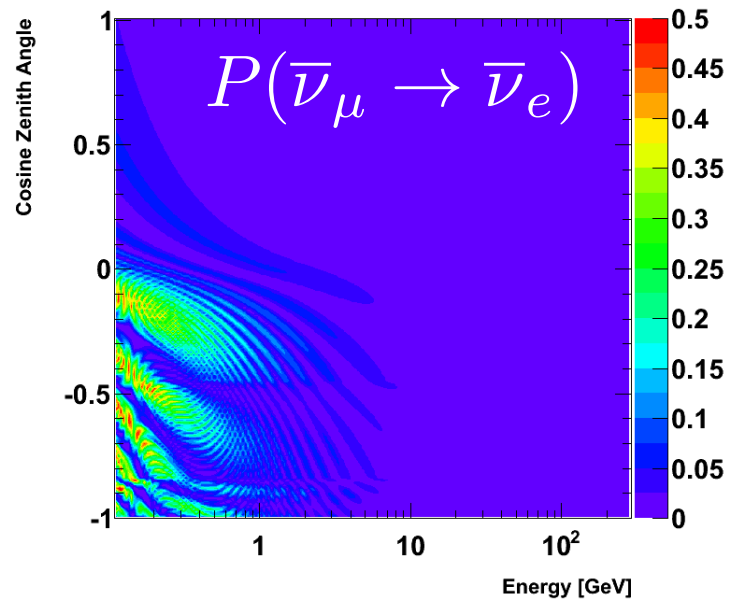
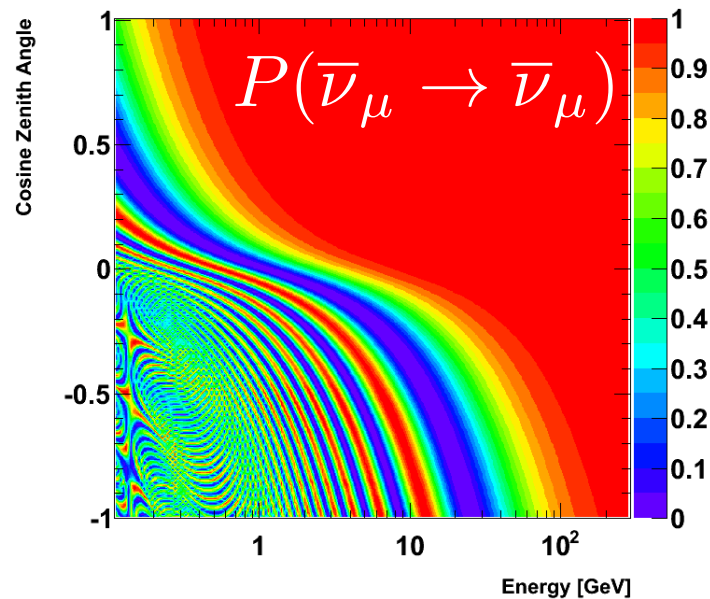
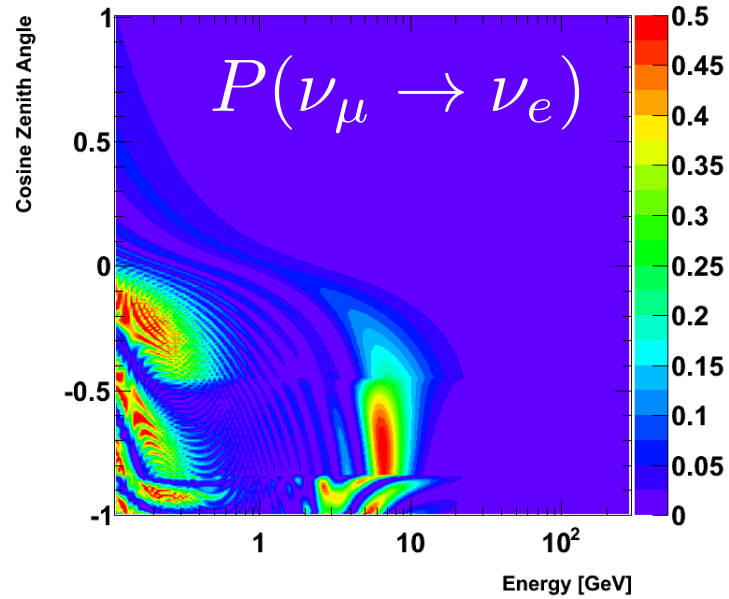
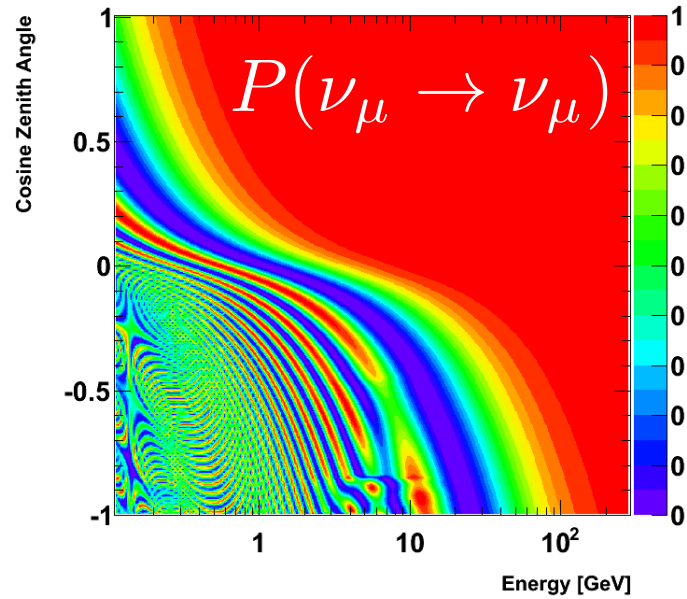
Try it out!



NOvA

T2K

Oscillograms



Remember:

Statistics is lower at high energy

Pointing is better at high energy

Matter effect
resonance in
 ν for normal ordering

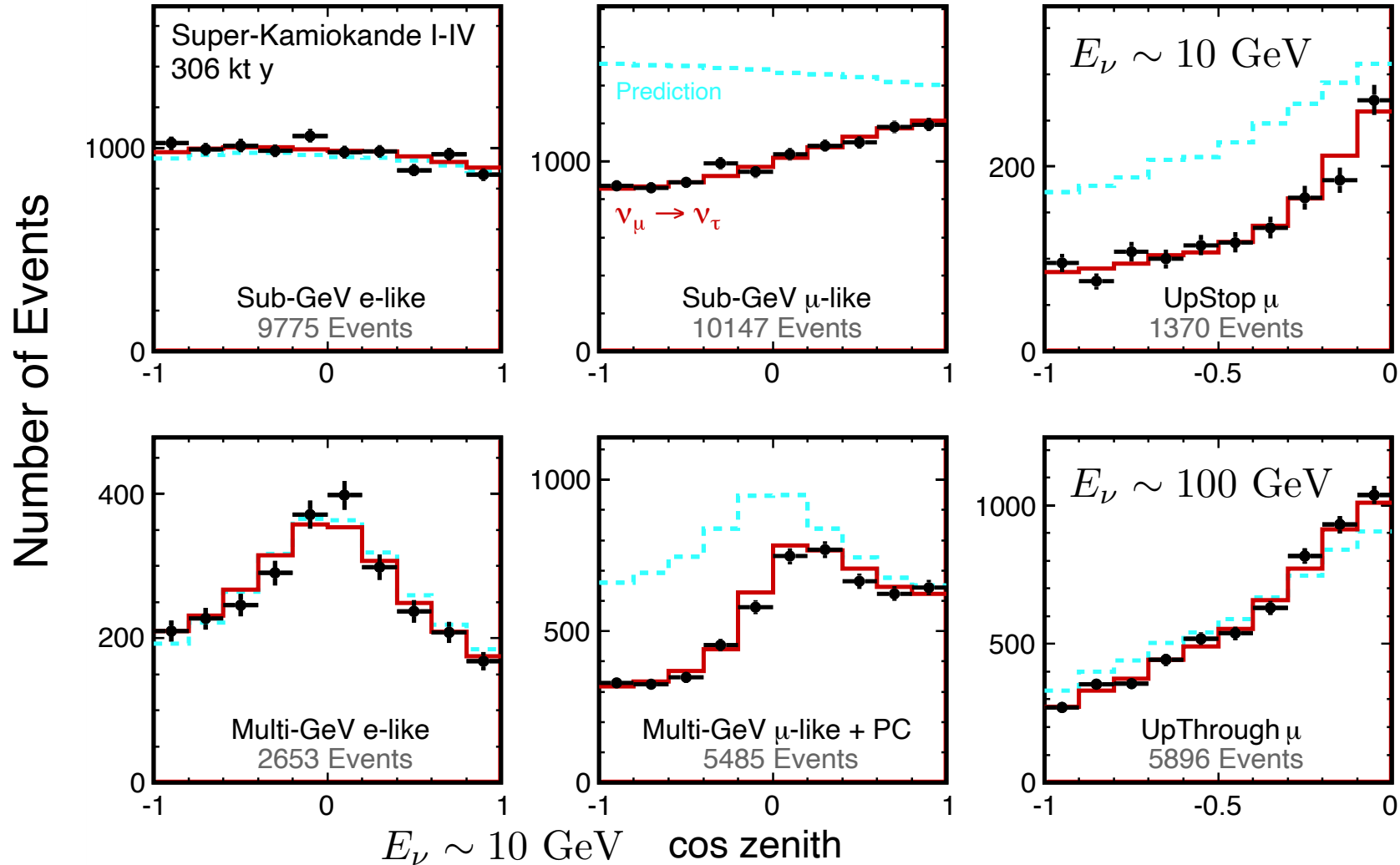


If inverted ordering,
top/bottom plots
exchange and the
resonance is in anti- ν

Super-K I-II-III-IV (1996-2018) data set

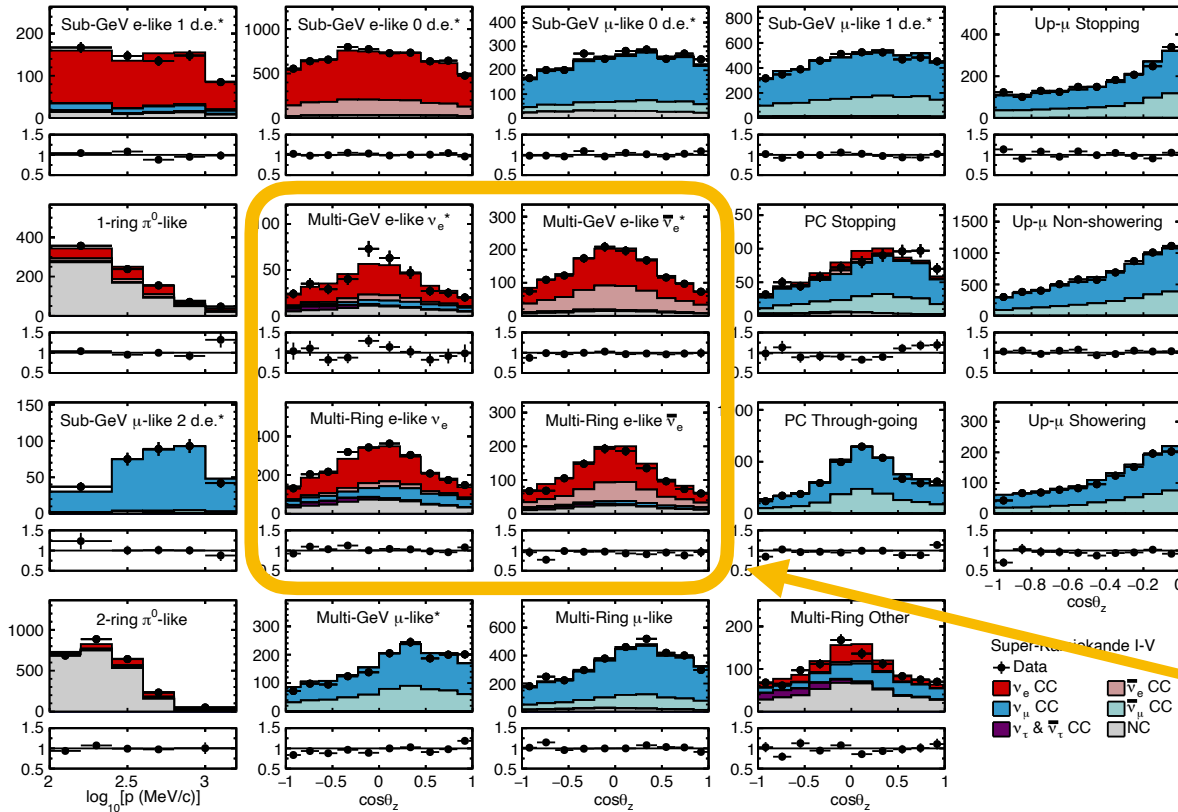
35000 atmospheric neutrinos

$E_\nu \sim 1 \text{ GeV}$



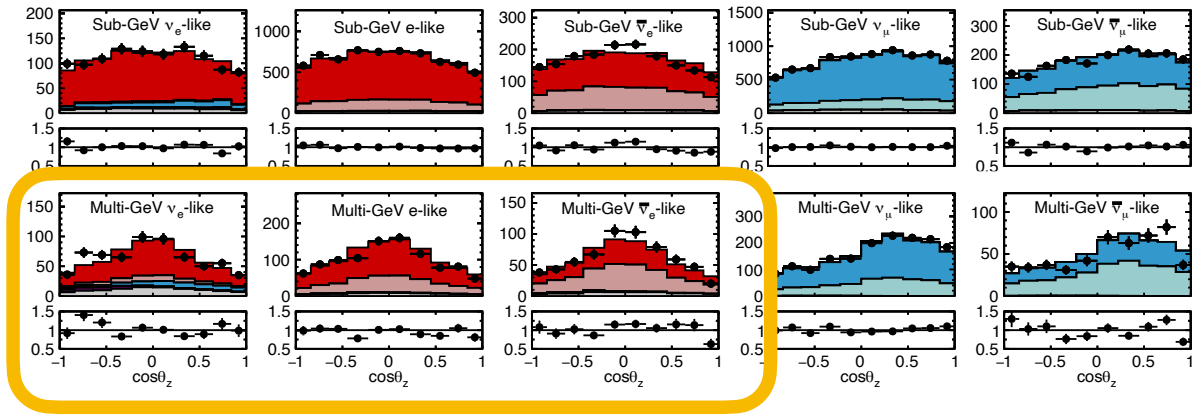
Blue contributions are muon neutrinos
 Drives 2-3 parameter determination
 Normalizes flux and cross section
 Built-in “near detector”)

T. Wester



Super-K I-V data set finely binned

*SK IV-V fully contained single ring samples
with neutron tagging selection*

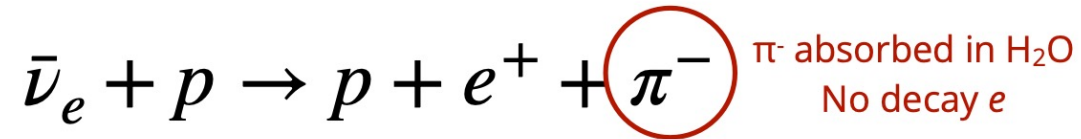
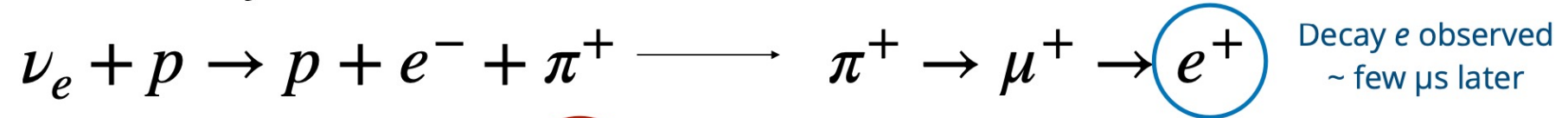


Red contributions are **electron neutrinos**
 Select categories with higher energy
 and good pointing

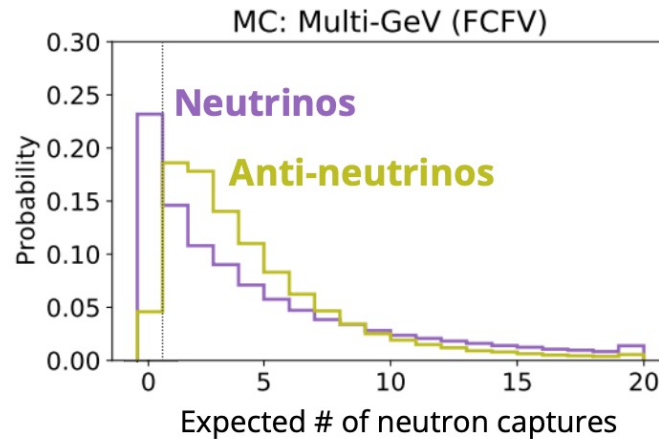
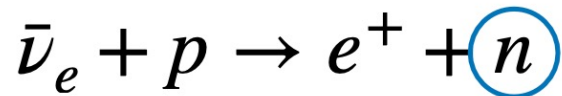
Contribution from ν_e appearance:
 200 events (normal ordering)
 50 events (inverted ordering)

Neutrino – Antineutrino in Water Cherenkov

Decay electrons: More from neutrinos than anti-neutrinos



Neutron captures: More for anti-neutrinos than neutrinos, observed in SK IV+

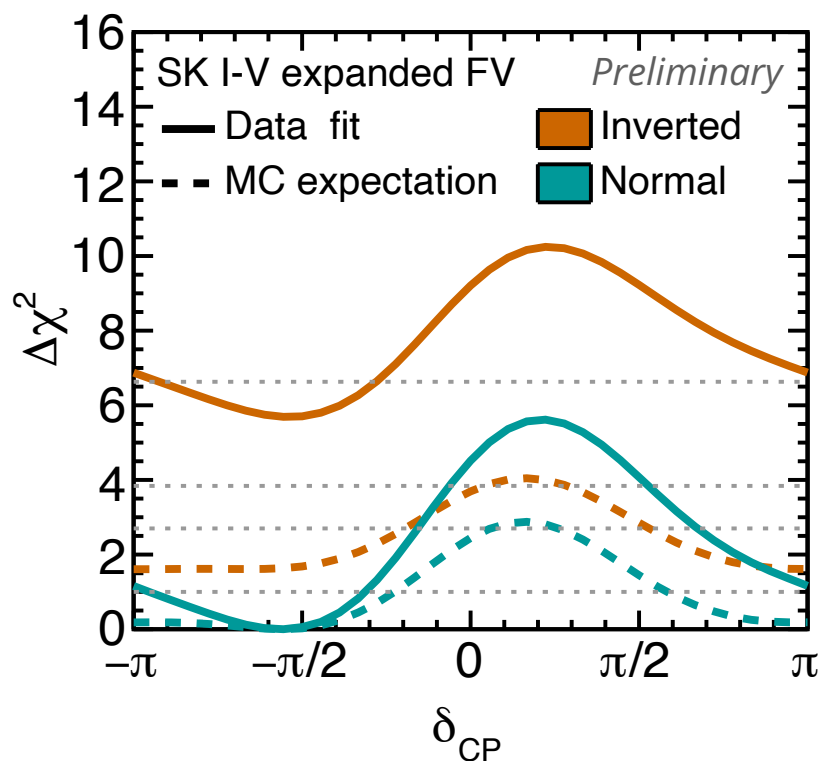


- ~200 μ s capture time on hydrogen
- 26% efficiency, neural net selection

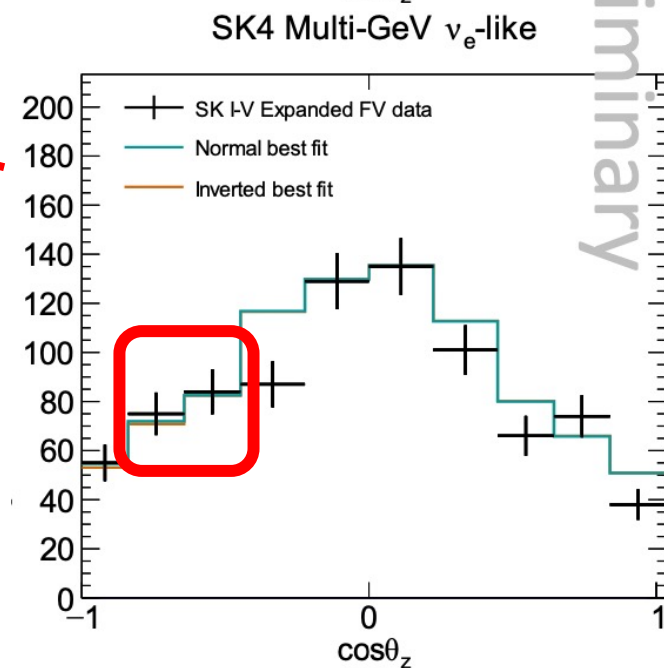
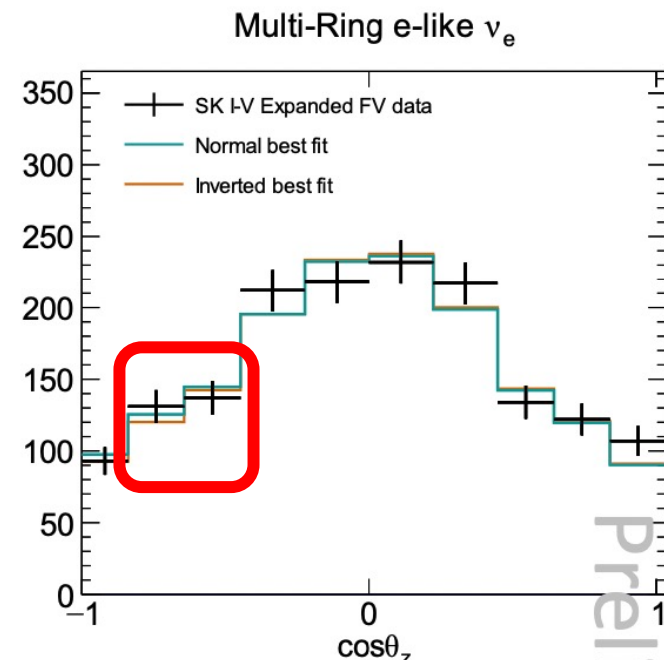
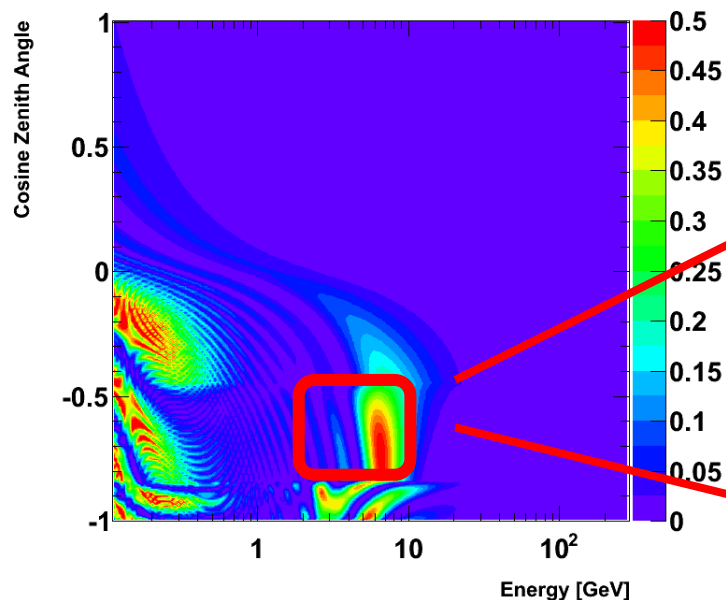
Super-K I-V Results

2-3 Parameters shown earlier this talk

Mass Ordering and δCP :
Prefer Normal ordering ~ 2 -sigma level*
Result exceeds sensitivity



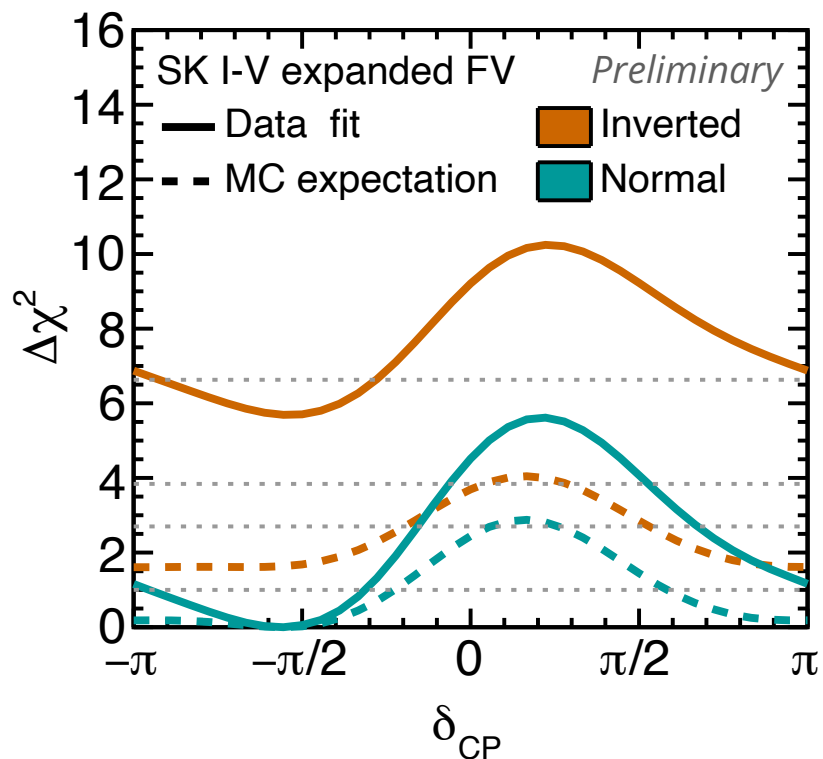
* See upcoming paper for precise statement



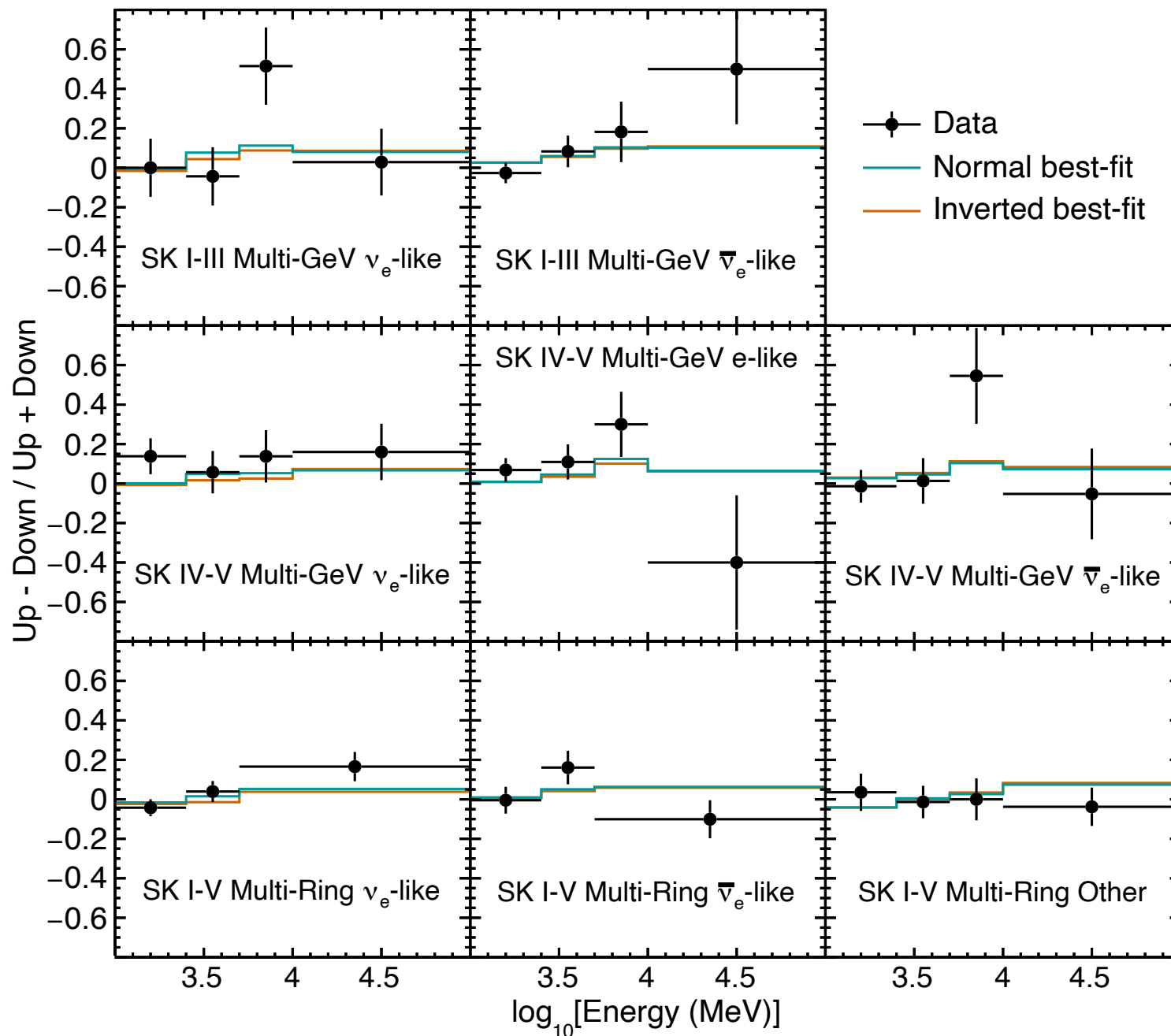
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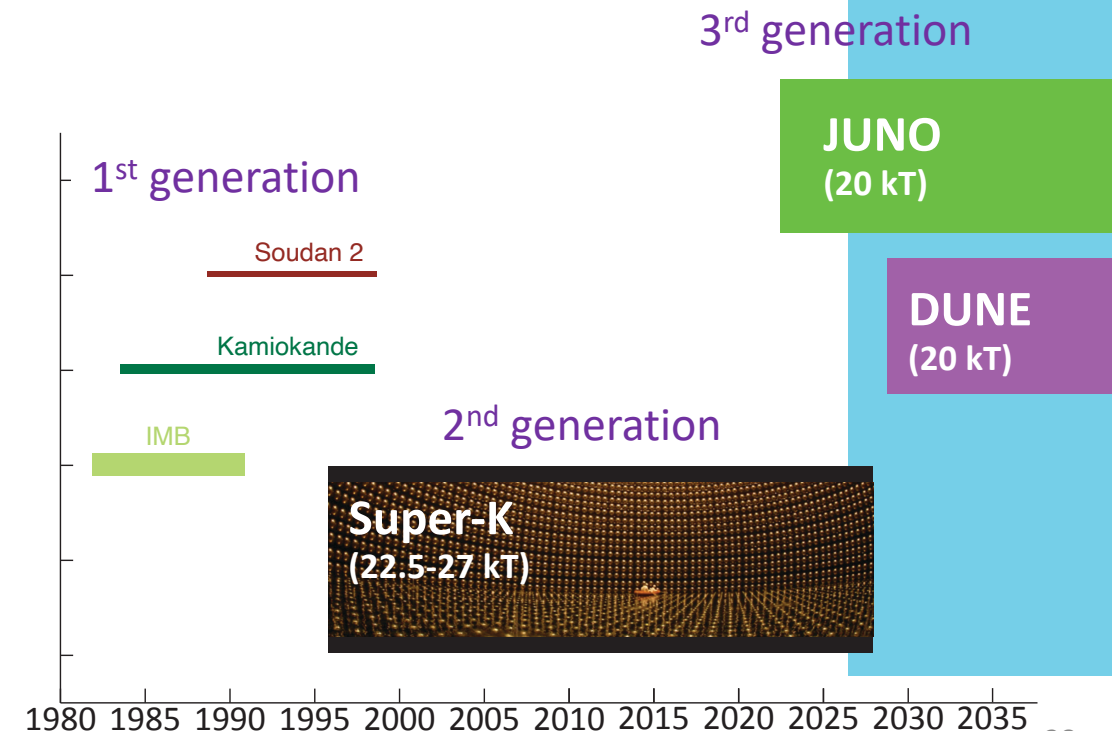
* See upcoming paper for precise statement



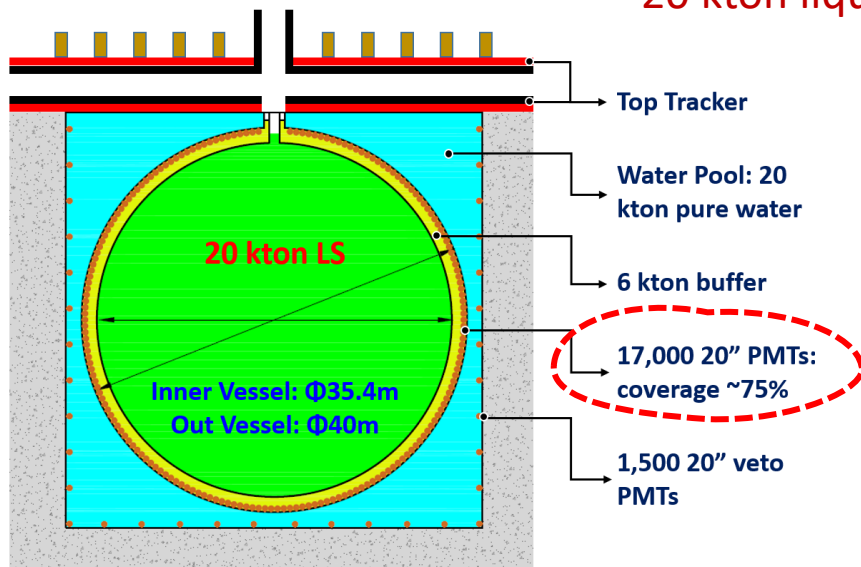
Third Generation Large Underground Detectors

Interest in neutrino oscillation has motivated a third generation of massive underground detectors.

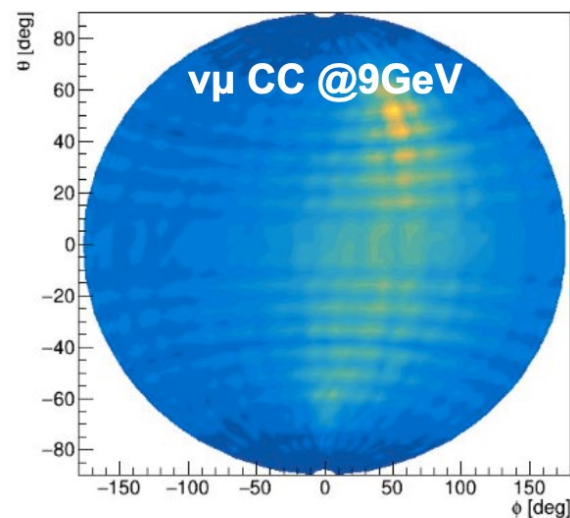
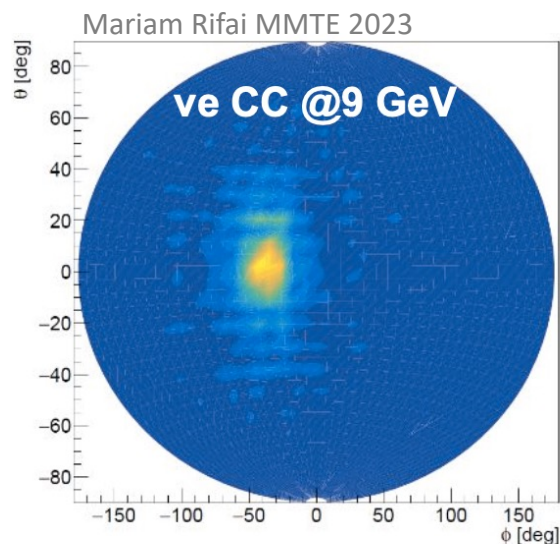
Off scale in mass: **IceCube, KM3Net**
but higher energy threshold (10 GeV-ish)
and limitations in detailed event identification
(i.e. not proton decay capable)



20 kton liquid scintillator detector



3" PMTs and 20" PMTs



Hitmap on 3" PMT system

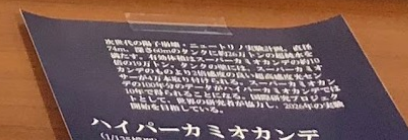
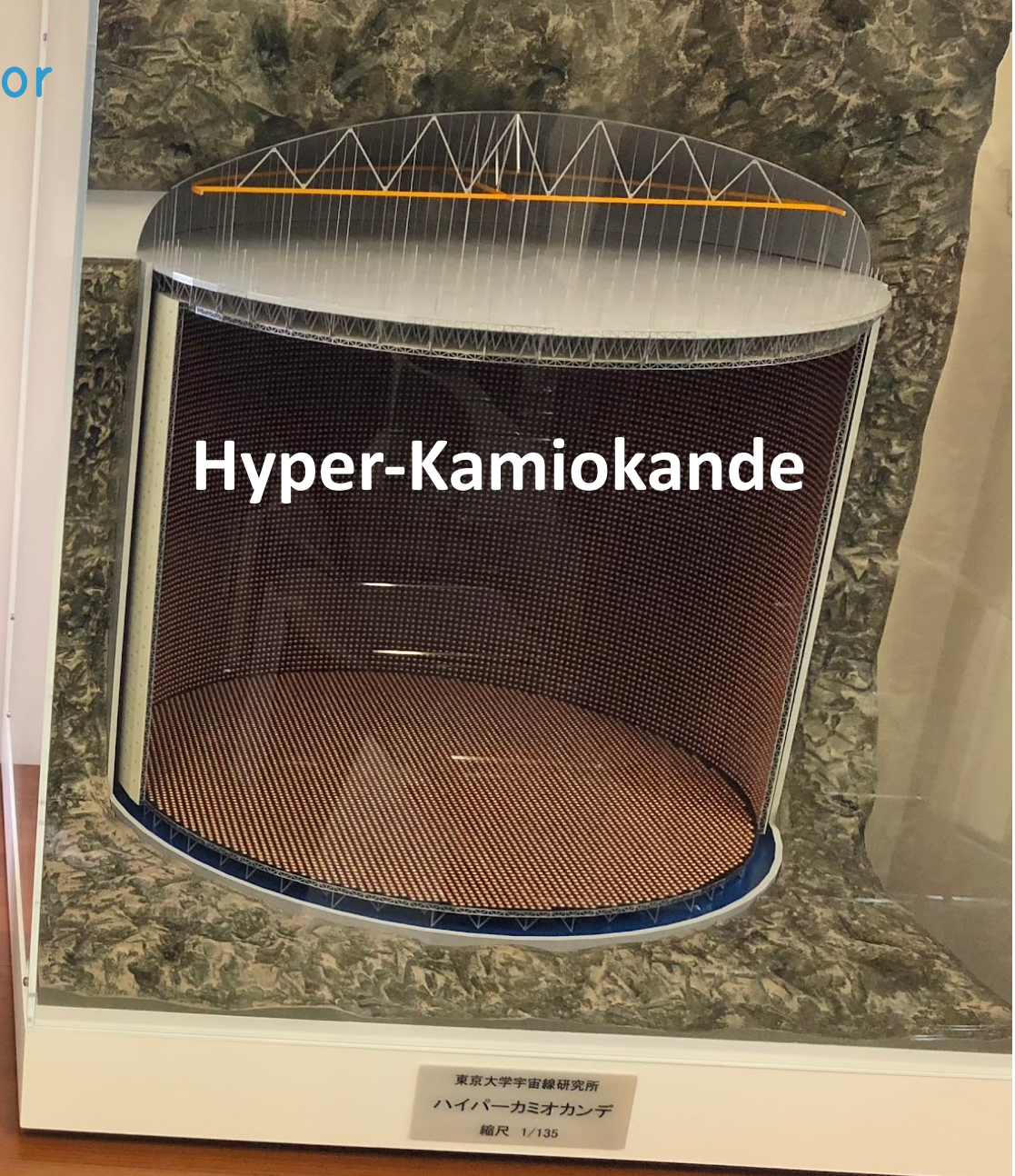
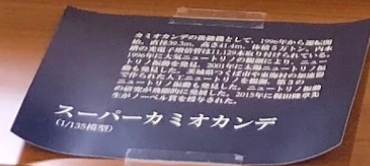
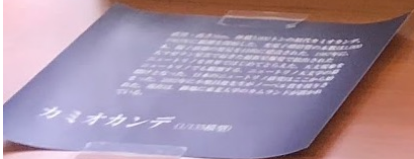
machine learning

Confusion matrix (Efficiency)

	ν_e -CC	$\bar{\nu}_e$ -CC	ν_μ -CC	$\bar{\nu}_\mu$ -CC	NC
ν_e -CC	0.70	0.24	0.03	0.00	0.03
$\bar{\nu}_e$ -CC	0.13	0.83	0.00	0.00	0.03
ν_μ -CC	0.03	0.00	0.74	0.20	0.03
$\bar{\nu}_\mu$ -CC	0.01	0.00	0.15	0.83	0.01
NC	0.07	0.05	0.03	0.02	0.83
Predicted label	ν_e -CC	$\bar{\nu}_e$ -CC	ν_μ -CC	$\bar{\nu}_\mu$ -CC	NC

Work in progress!

Three Generations of Water Cherenkov Detector in Kamioka Japan



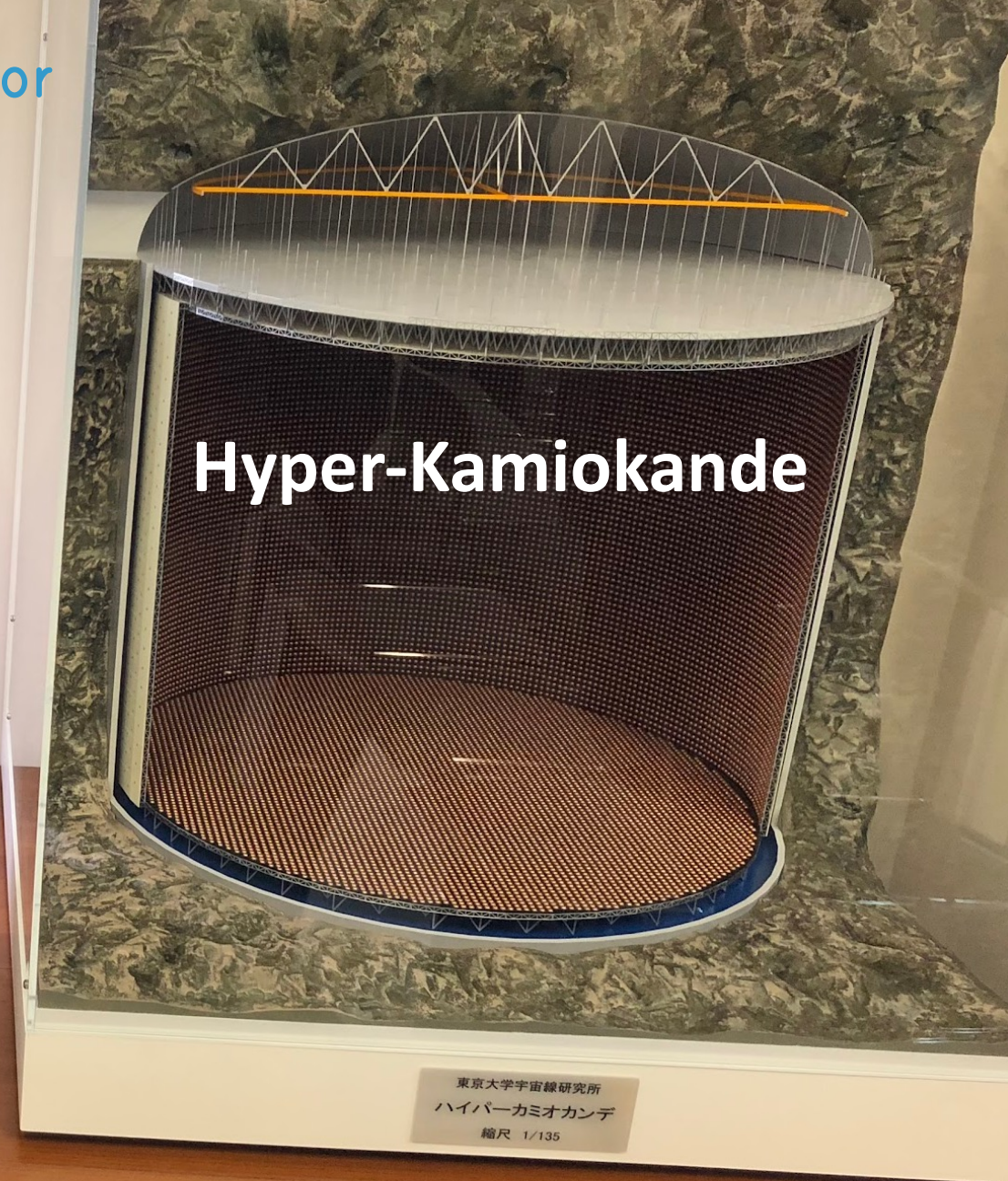
Three Generations of Water Cherenkov Detector in Kamioka Japan

- **186.5 kton** fiducial volume (258 kton total)
- Optically separated into
 - Inner Detector
 - **20,000** 50cm High QE B&L PMTs
 - + O(1) k mPMT Modules
 - Outer Detector 1885 8" PMTs
- Pure water neutron tagging > 40%
- Now **under construction** – Data taking in 2027

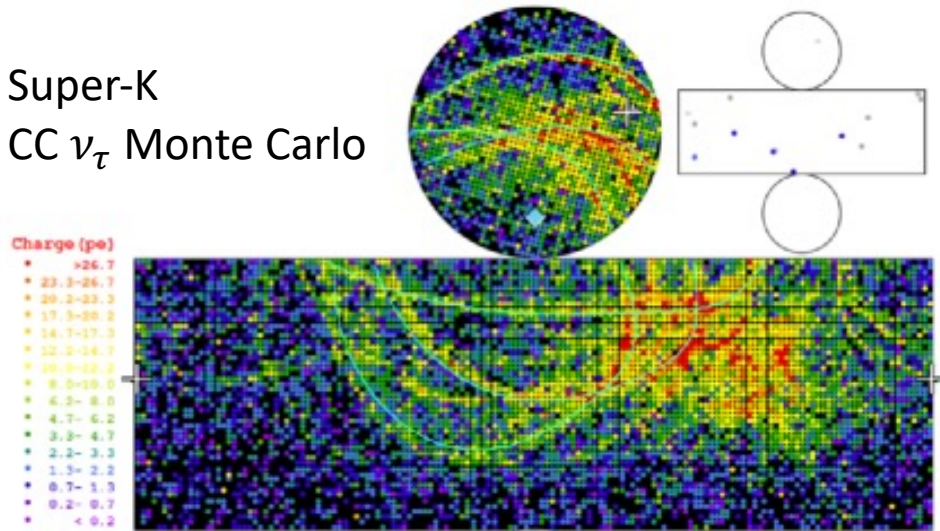


50 cm HQE
Box&Line PMT

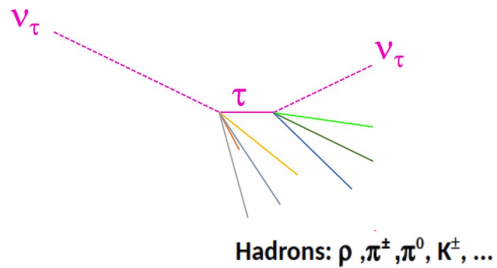
SK QE $\times 2$
SK σ_{τ} $\times 2$
SK Pres. Tol $\times 2$



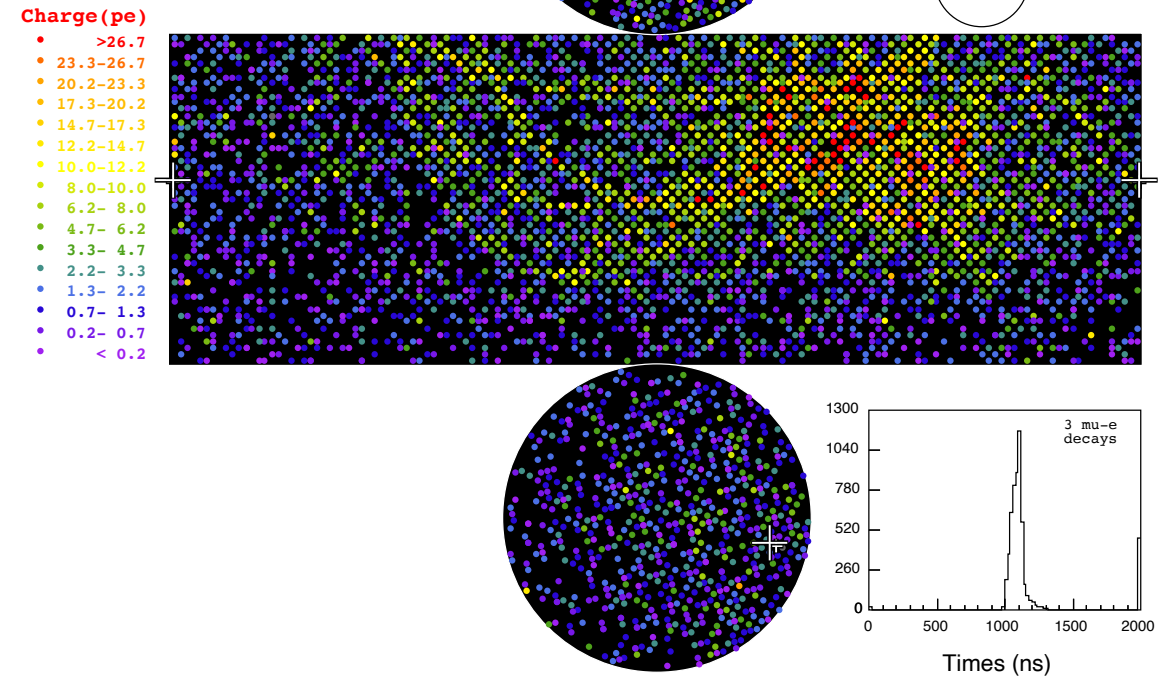
Super-K
CC ν_τ Monte Carlo



Roger Wendell



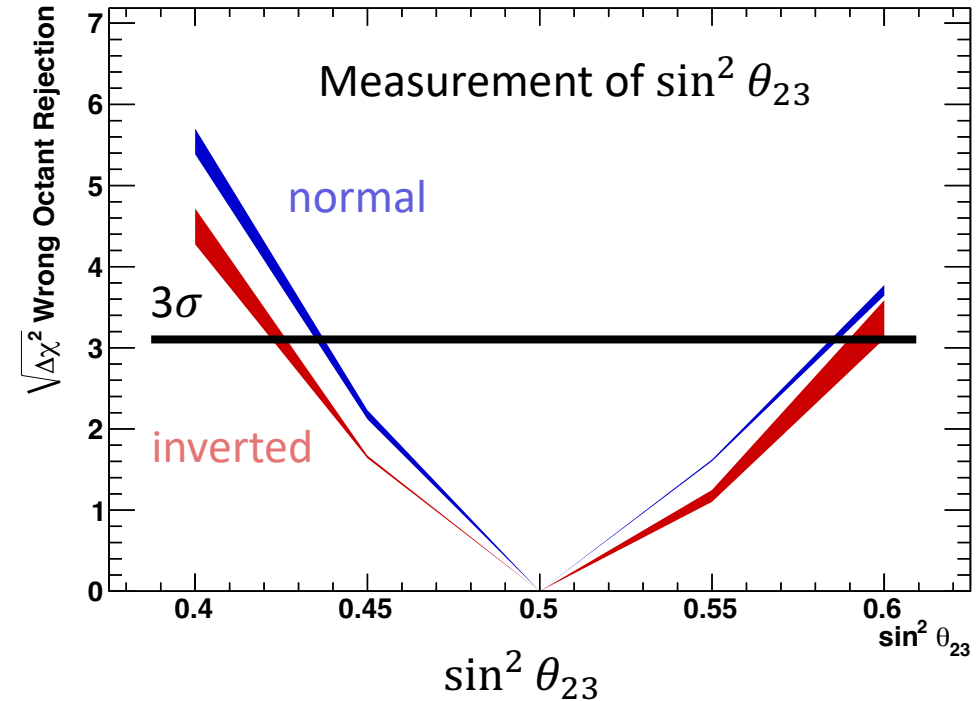
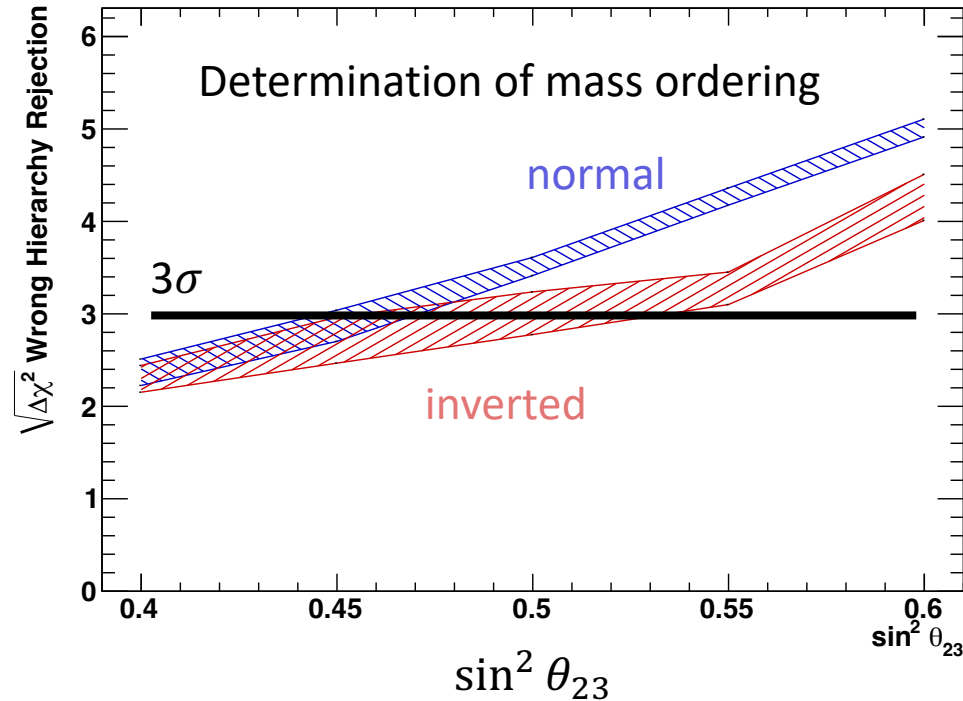
Same event
simulated appearance
in Hyper-K



20% B&L PMT coverage
+ equivalent light collection from mPMT

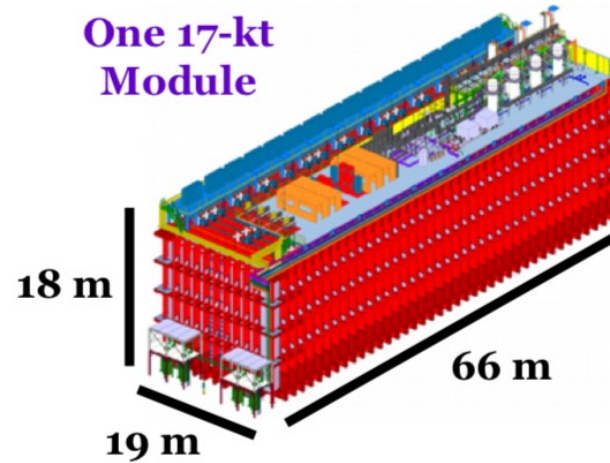
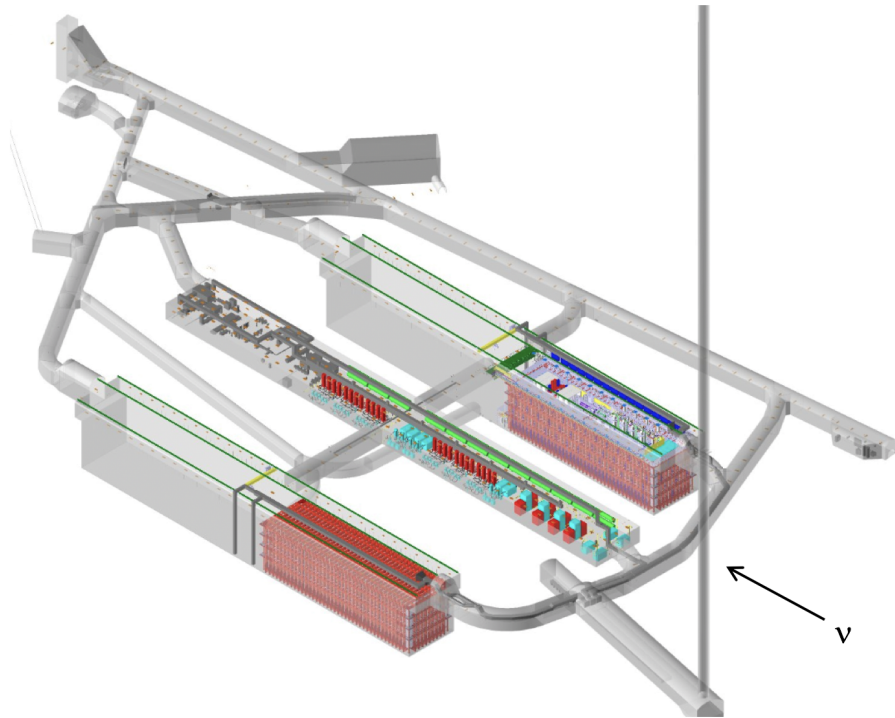
Sensitivity: 10-year Hyper-K atmospheric neutrinos

<https://arxiv.org/pdf/1805.04163.pdf>



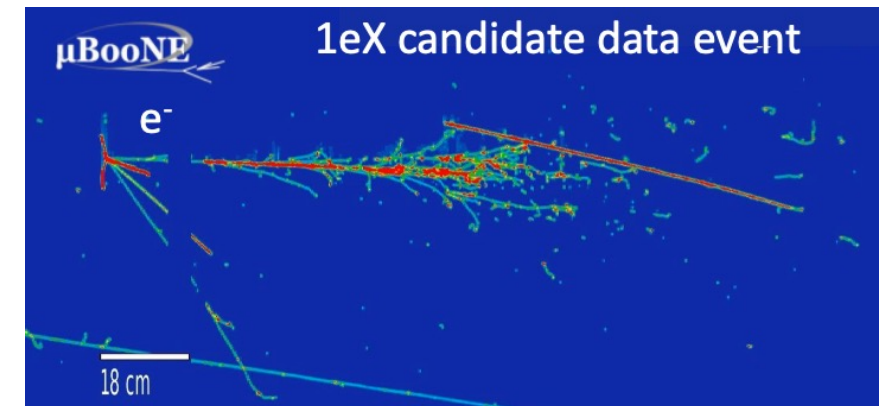
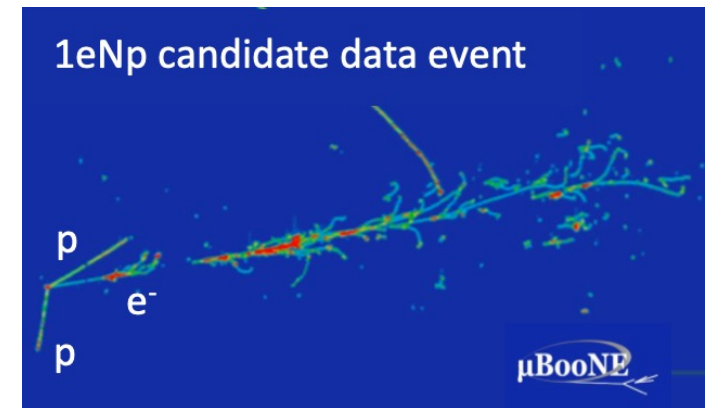
Width of bands reflects unknown δ_{CP}

DUNE (Deep Underground Neutrino Experiment)

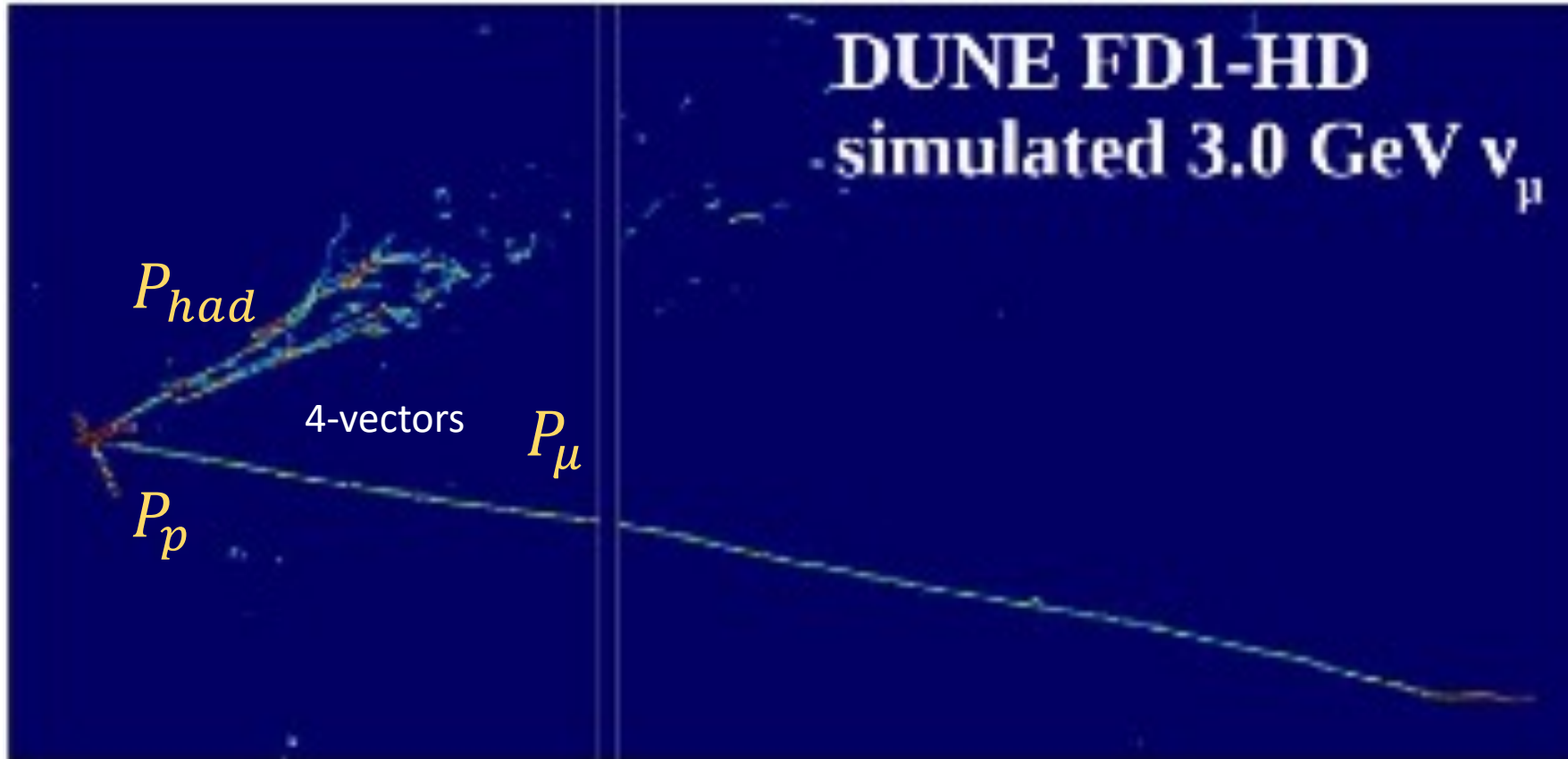


**Liquid Argon Time
Projection Chamber
(LArTPC)**

1.5 km deep in SURF (South Dakota)
modular ... up to 4 x 10 kt total fiducial mass
Neutrino beam from Fermilab
Sensitive to ν_e from supernova



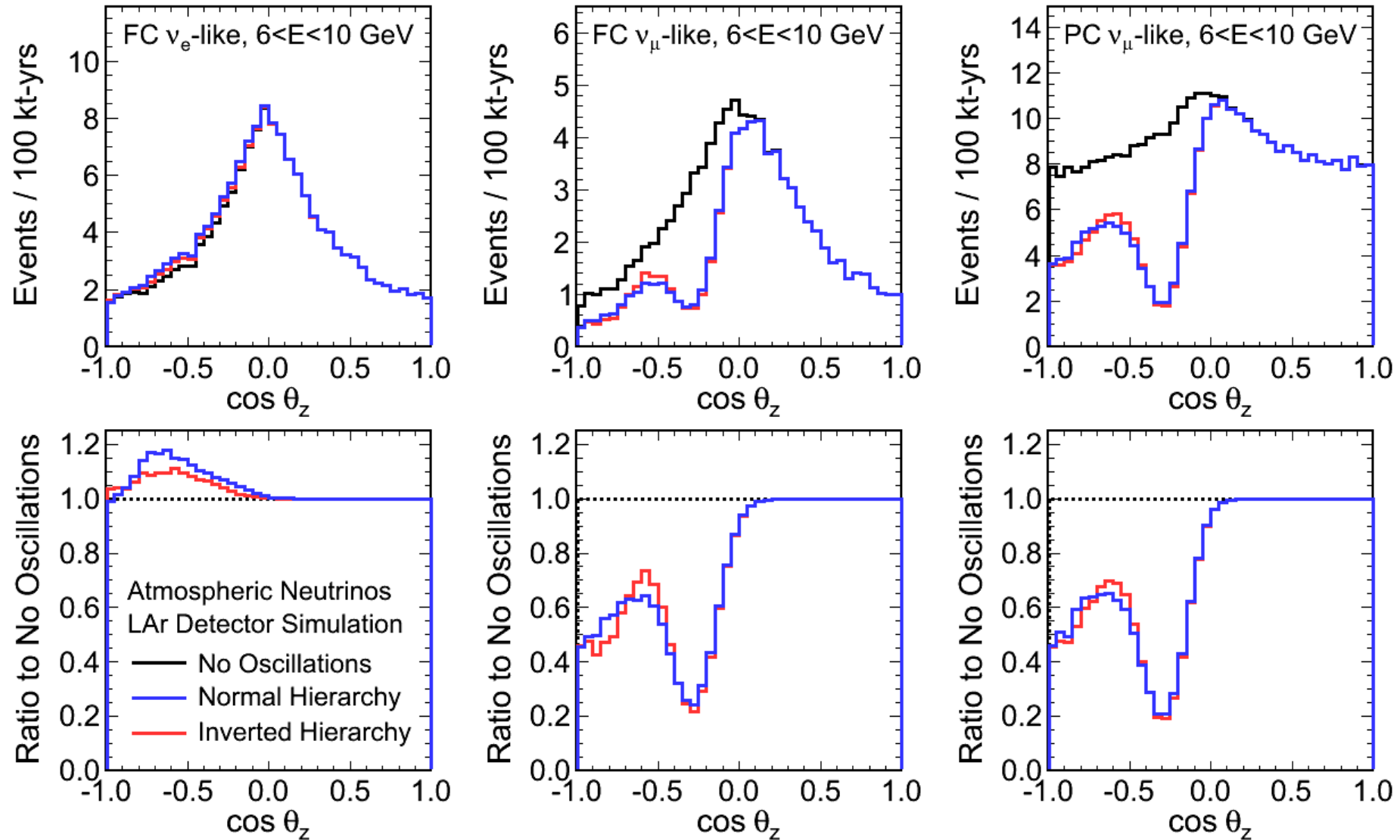
Event displays courtesy S. Zeller



Tarak Thakore

$$P_\nu = P_p + P_{had} + P_\mu = (E_\nu, \vec{p}_\nu)$$

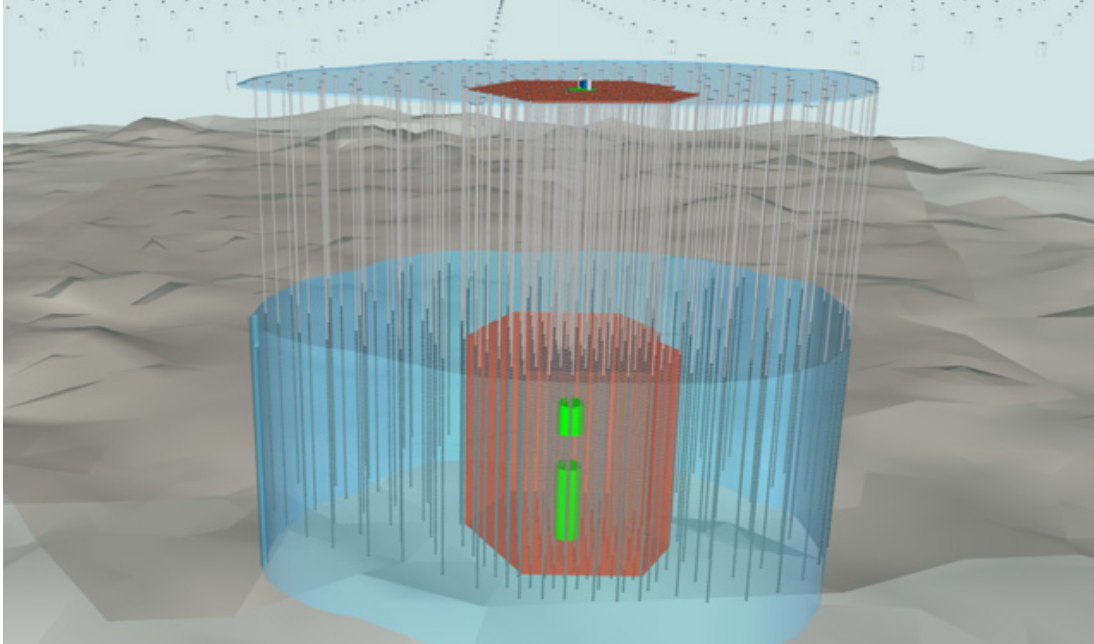
DUNE: Resolution of Oscillation Pattern



Binned quantity is reconstructed neutrino direction (not lepton direction as in SK/HK)

Kilometer-scale arrays

IceCube & DeepCore & upcoming Gen2



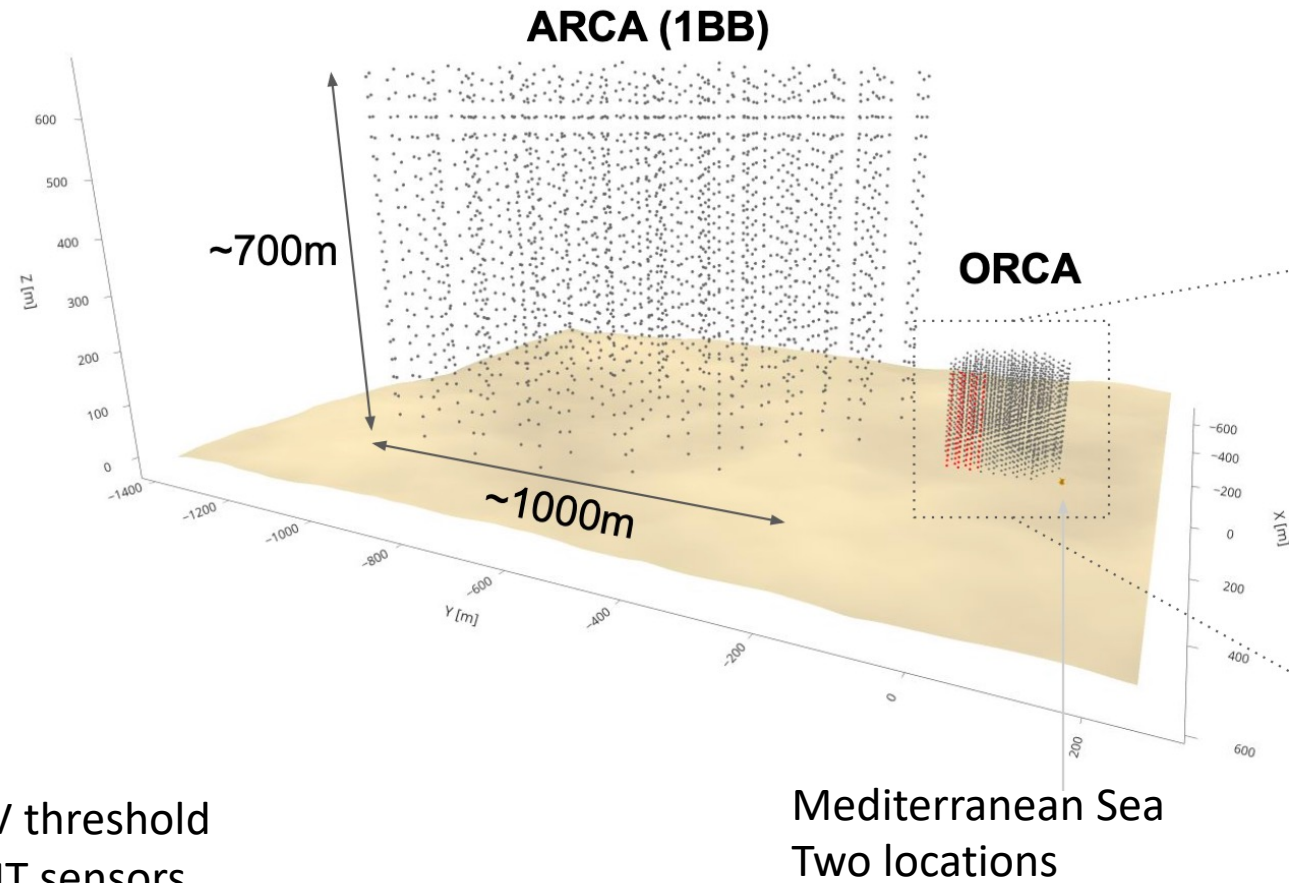
kilometer-scale ice/water Cherenkov detectors

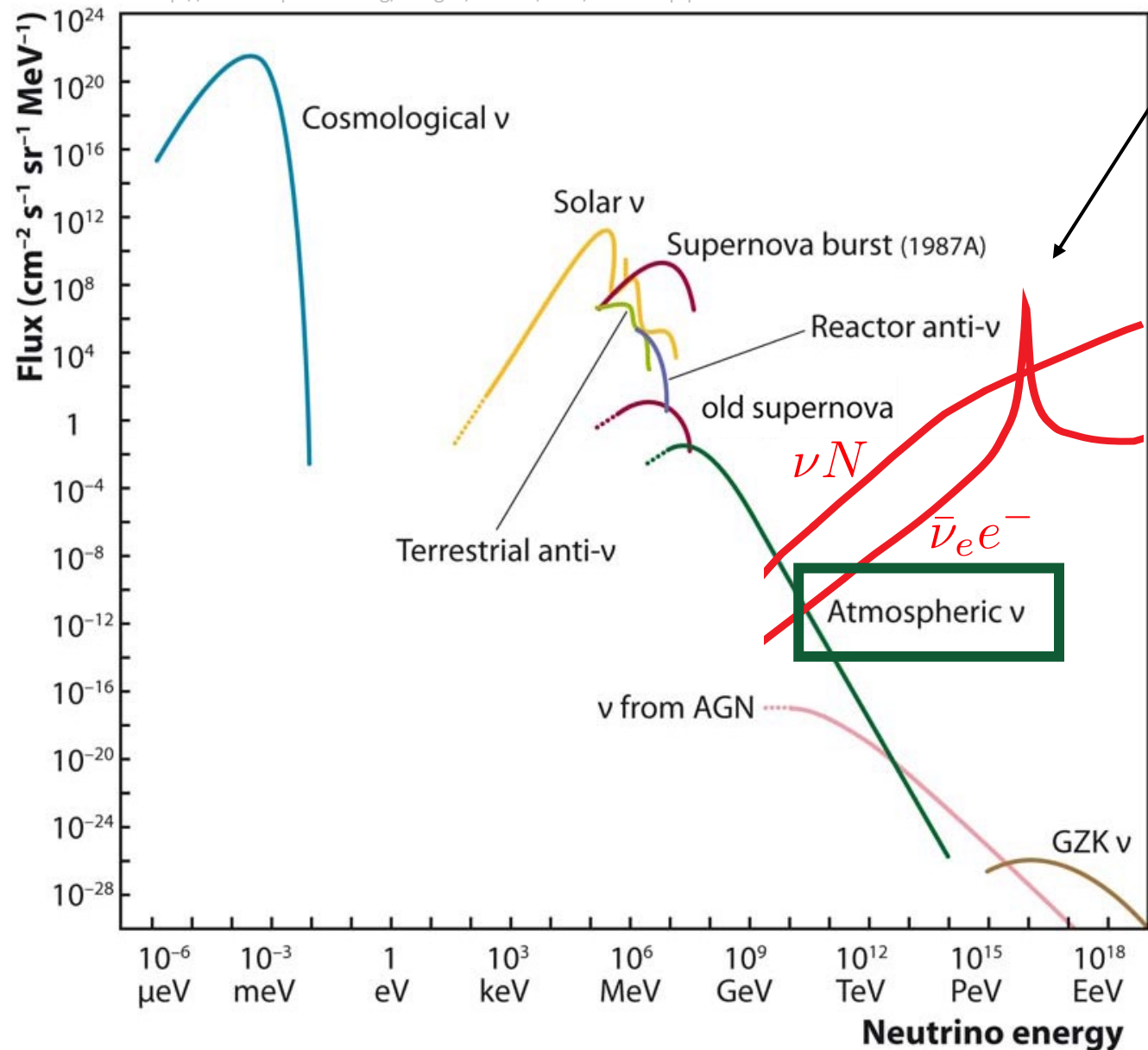
Huge statistics, specializing in **highest energy neutrinos**

Deep Core (10 Mton): high density infill to achieve 10 GeV threshold

Gen2 Upgrade (2 Mton): seven more strings with new PMT sensors
achieve 1 GeV threshold

KM3Net: ARCA and ORCA





One event DETECTED!

<https://doi.org/10.1038/s41586-021-03256-1>

Cross section

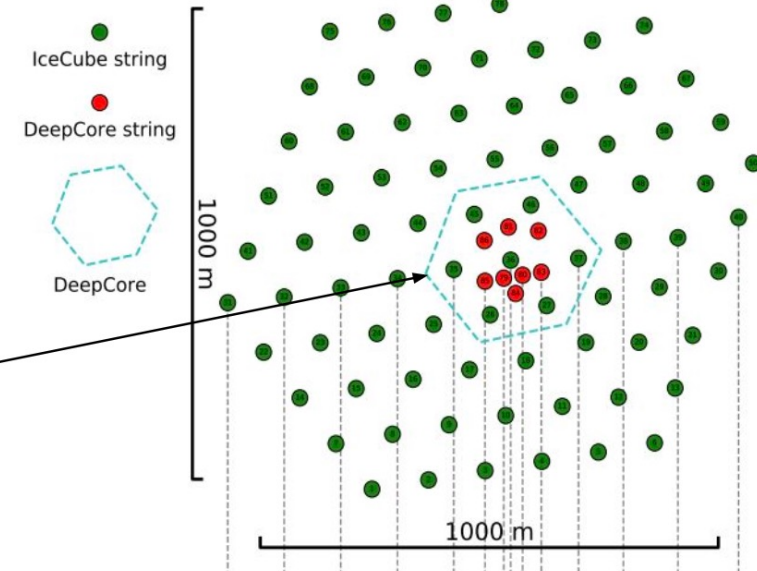
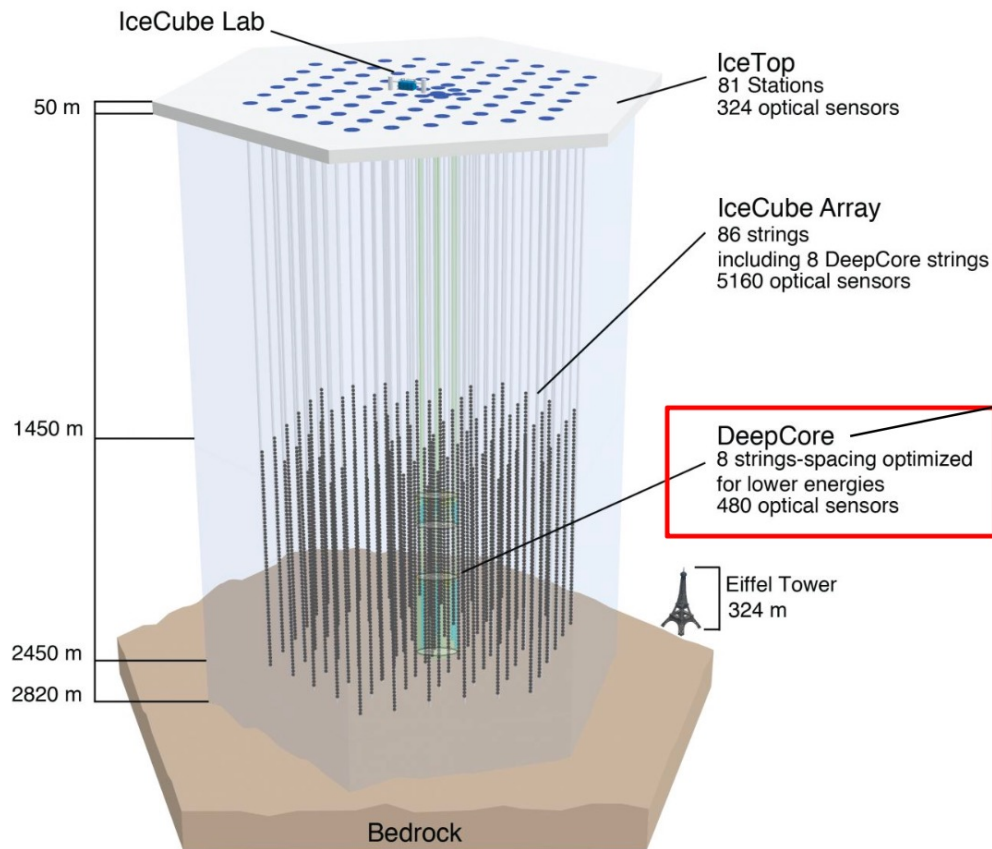
σ

millibarn (mb)

(1 mb = 10^{-27}cm^2)

probability of
interaction increases
with energy

IceCube-DeepCore Neutrino Telescope

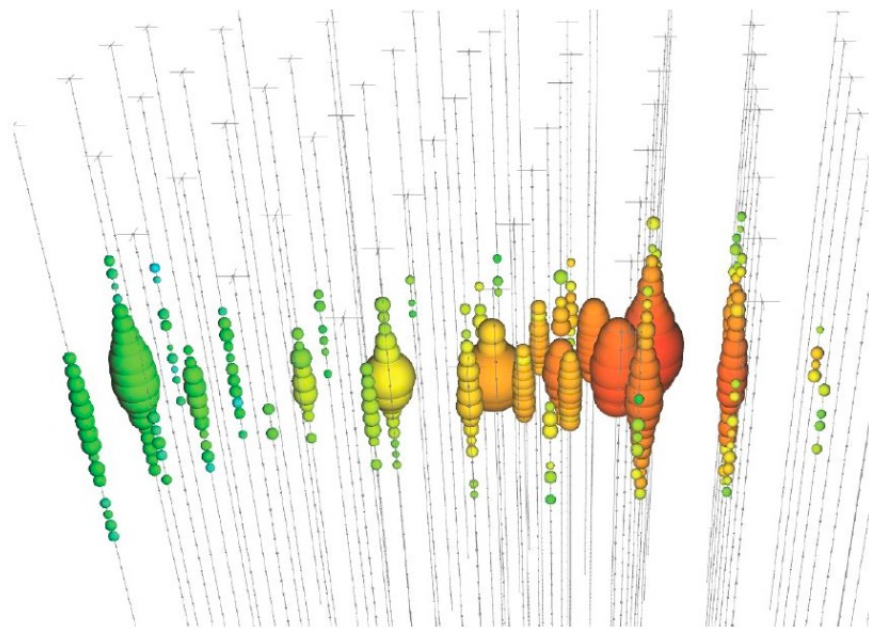


DeepCore

- 8 dedicated strings with denser spacing
- Optimized for GeV scale neutrinos
- Uses IceCube as VETO
- Fiducial volume ~ 10 Mton

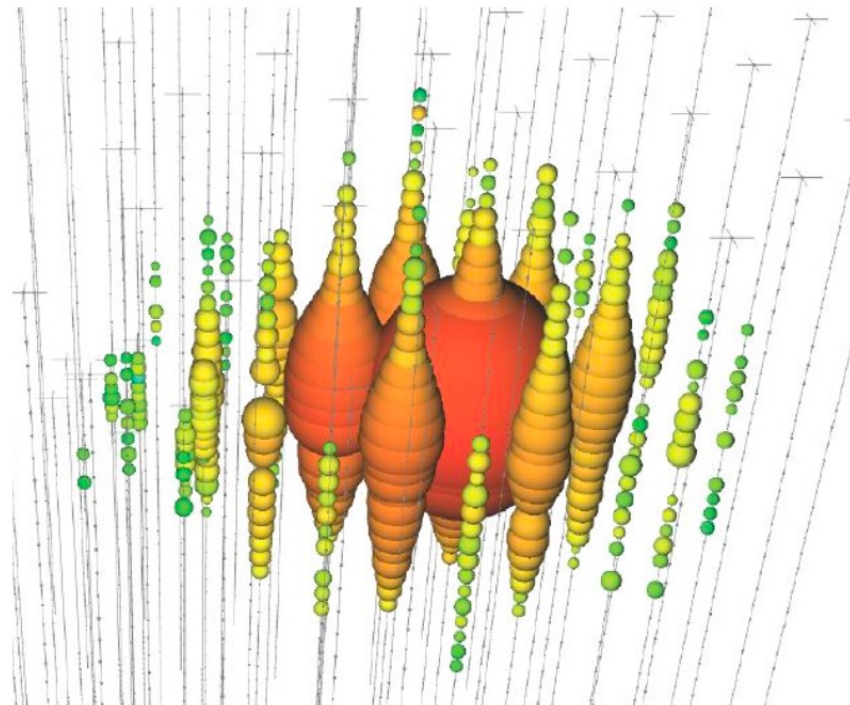
Ref. : The design and performance of IceCube DeepCore (2012) [Astroparticle Physics, 35\(10\), 615-624 \(2012\)](#)

Track-like (muon neutrino)



late ← early

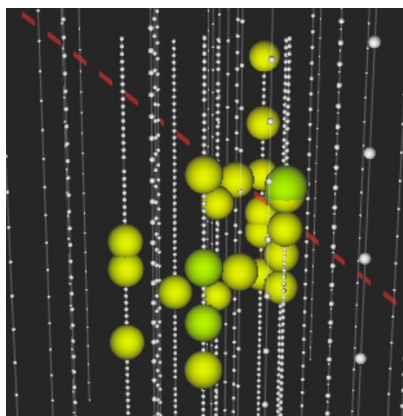
Cascade-like (electron, tau neutrino, NC)



IceCube

Agarwal, Koskinen

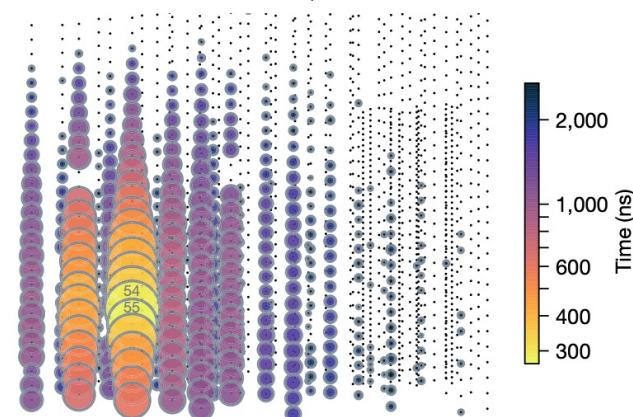
4 GeV upgoing ν_μ



Deep Core
with Upgrade

b

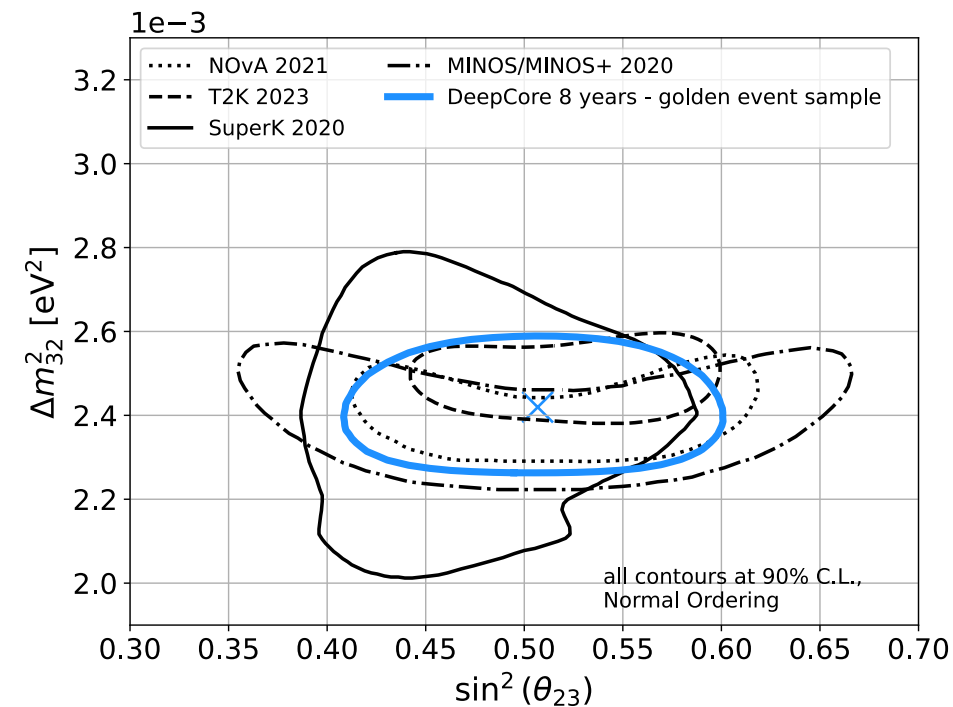
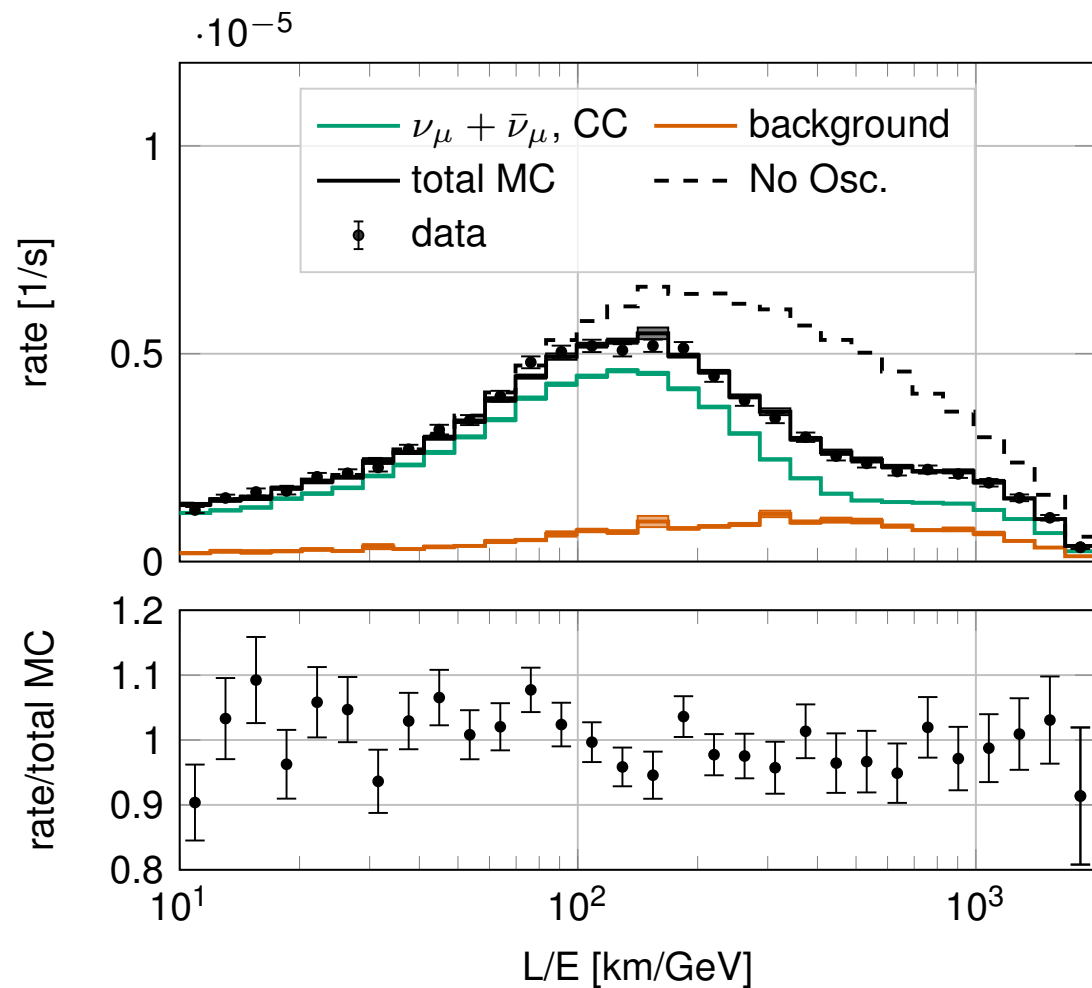
3 ms after t_1



Glashow
resonance
event

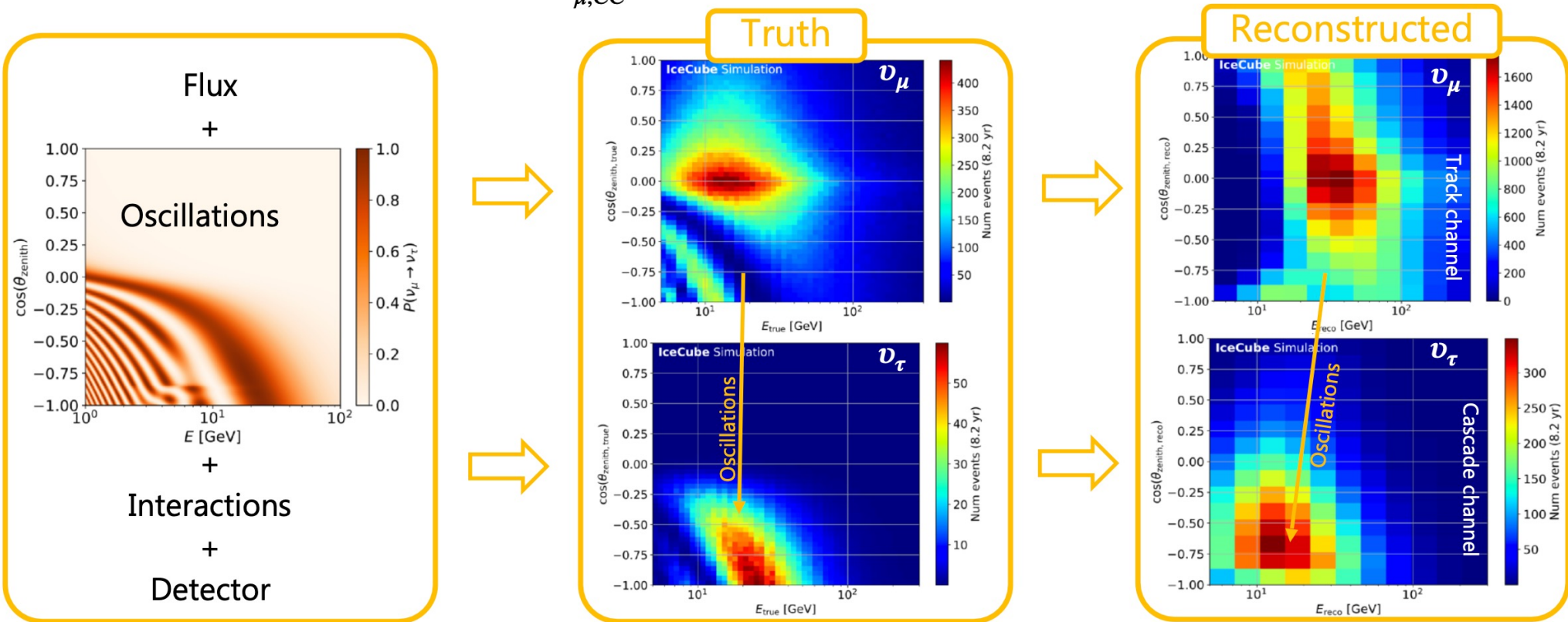
IceCube DeepCore 2023 Golden Sample

23000 events (10% of full data set)



Enormous statistics: hope to take real oscillogram

- Measure 3D distortions in reconstructed [energy, zenith, particle type]
 - Robust against systematic uncertainties
 - Particle identification discriminates $\nu_{\mu,CC}$ interactions vs all other flavors/channels



Thanks for all your attention and questions!