For the IceCube Collaboration

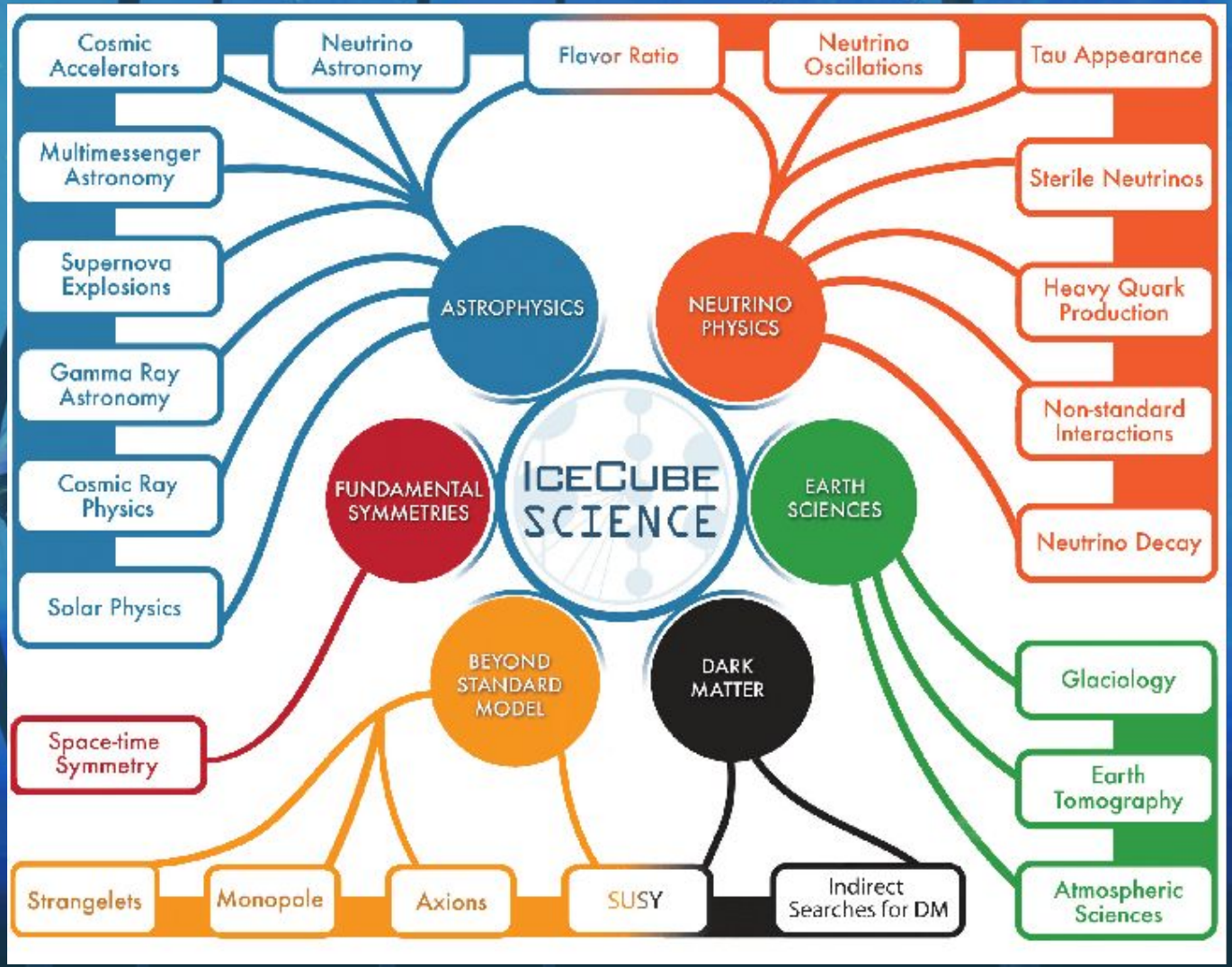
IceCube
South Pole Neutrino Observatory

Latest neutrino oscillation results and prospect from IceCube

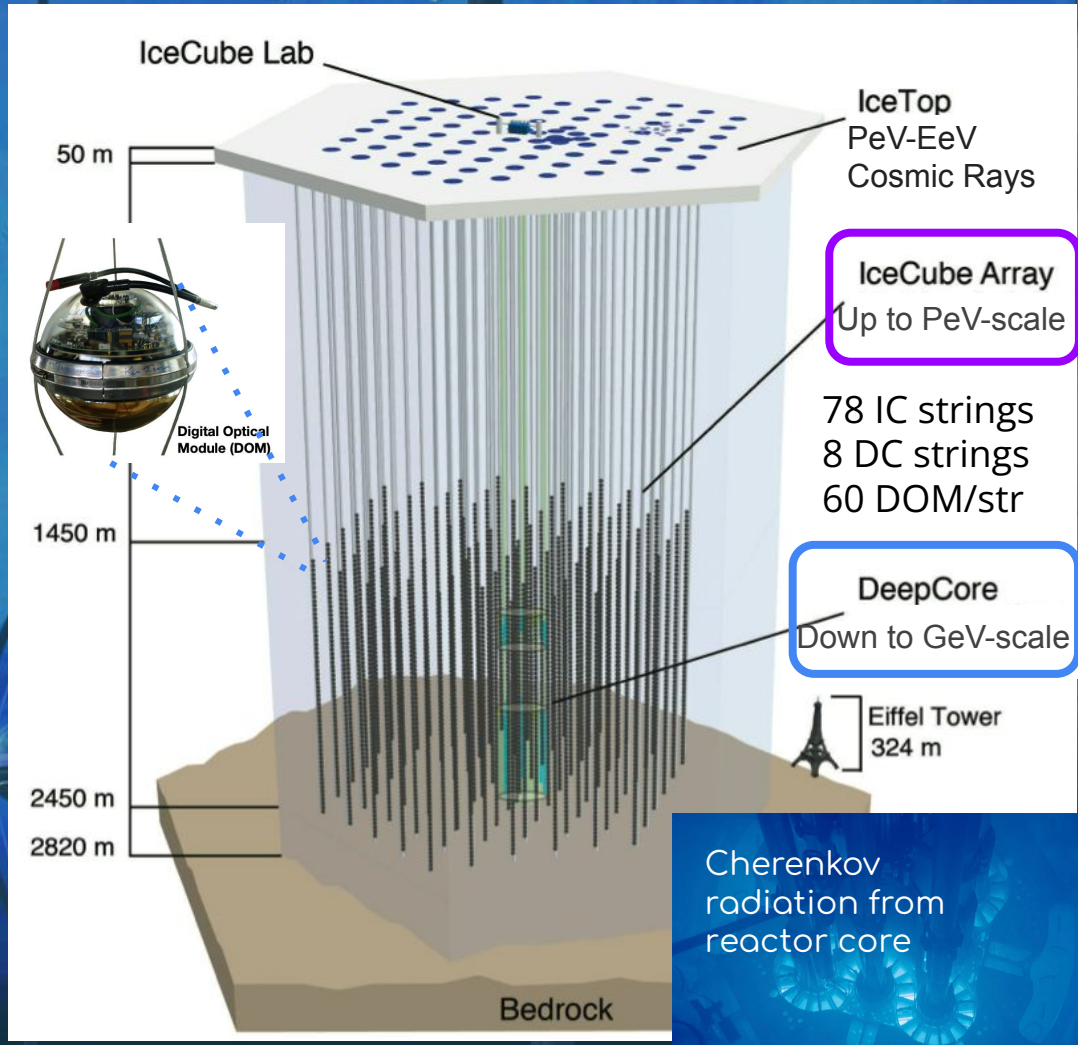
Shiqi Yu

Michigan State University

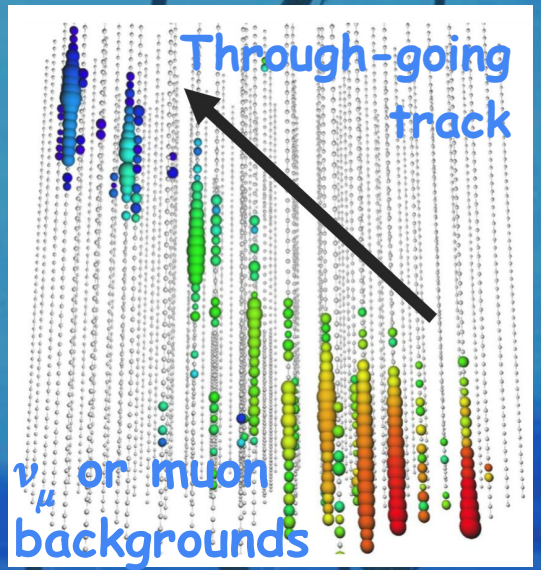
Neutrino Workshop 2023, Quy Nhon, Vietnam

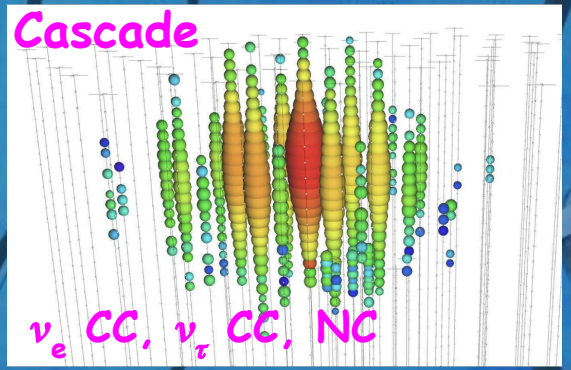

ICECUBE SCIENCE
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
Neutrino Decay
Solar Physics
Space-time Symmetry
Glaciology
Earth Tomography
Atmospheric Sciences
Strangelets
Monopole
Axions
SUSY
Indirect Searches for DM

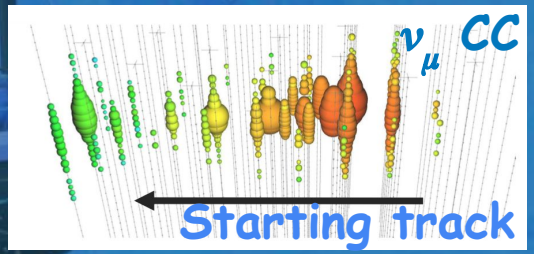
- 1 km^3 deep under antarctic ice;
- 5160 digital optical modules (DOMs) detect Cherenkov photons;
- DOMs record pulse charges & times;
- Can see up to PeV-scale neutrinos.
- **DeepCore**: denser configured sub-detector, can observe GeV-scale neutrinos.

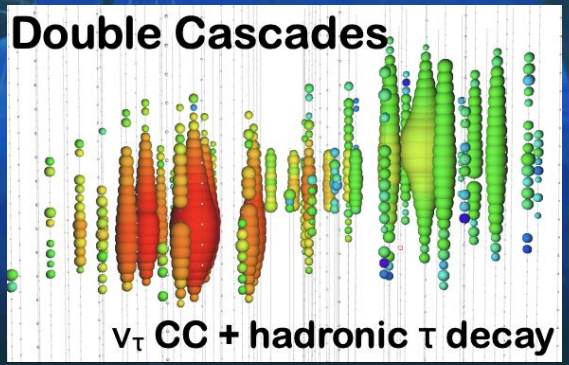


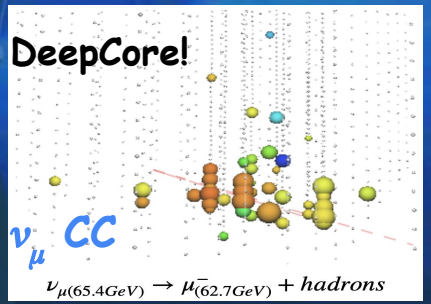
Typical Events in IceCube

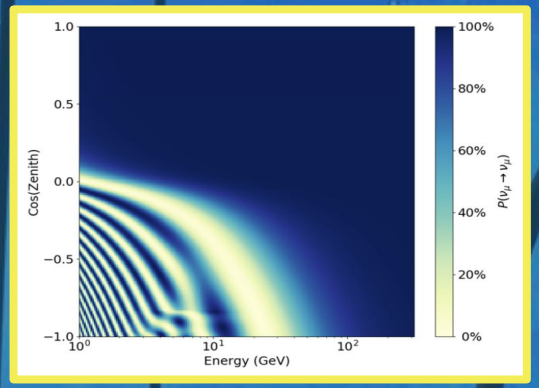


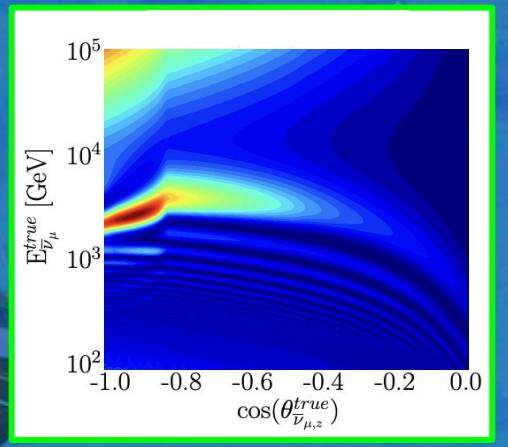


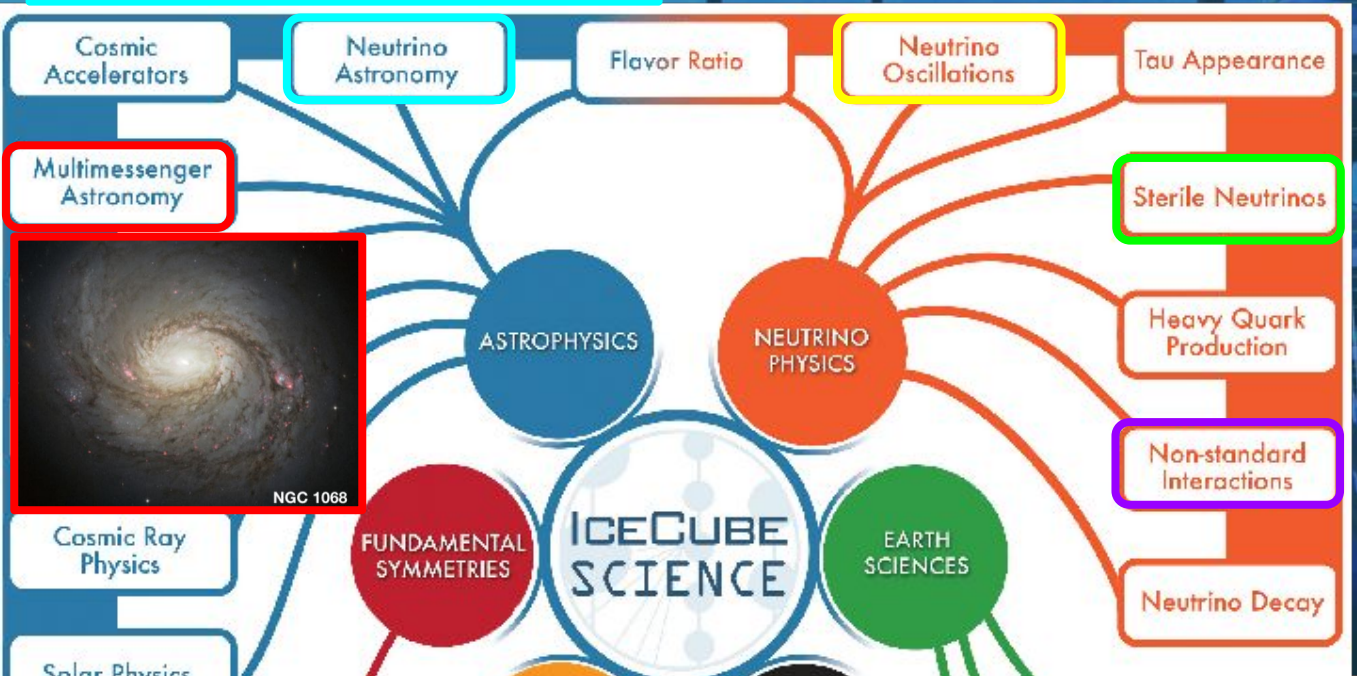


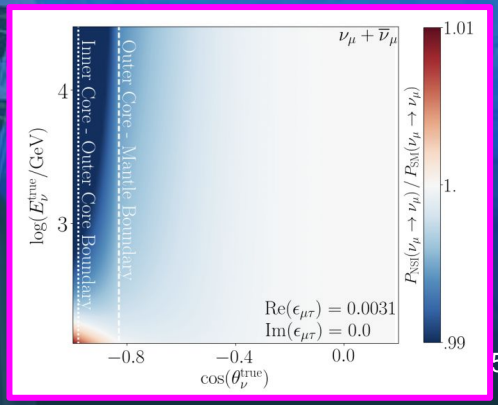




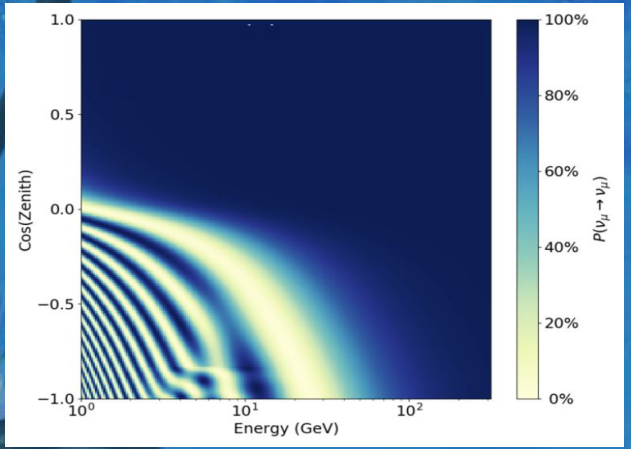

1.0
0.5
0.0
−0.5
−1.0
Cos(Zenith)
10^0
10^1
10^2
Energy (GeV)
100%
80%
60%
40%
20%
0%
$P(\nu_\mu \to \nu_\mu)$


10^5
10^4
10^3
10^2
$E^{true}_{\overline{\nu}_\mu}$ [GeV]
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
$\cos(\theta^{true}_{\overline{\nu}_{\mu,z}})$


Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
NGC 1068
ASTROPHYSICS
NEUTRINO PHYSICS
Heavy Quark Production
Non-standard Interactions
Cosmic Ray Physics
FUNDAMENTAL SYMMETRIES
ICECUBE SCIENCE
EARTH SCIENCES
Neutrino Decay
Solar Physics


$\nu_\mu + \overline{\nu}_\mu$
Inner Core
Outer Core
Mantle
Outer Core Boundary
4
3
$\log(E^{true}_\nu / \mathrm{GeV})$
$\mathrm{Re}(\epsilon_{\mu\tau}) = 0.0031$
$\mathrm{Im}(\epsilon_{\mu\tau}) = 0.0$
−0.8
−0.4
0.0
$\cos(\theta^{true}_\nu)$
1.01
1.
.99
$P_{\mathrm{Osc}}(\nu_\mu \to \nu_\mu) / P_{\mathrm{Std}}(\nu_\mu \to \nu_\mu)$

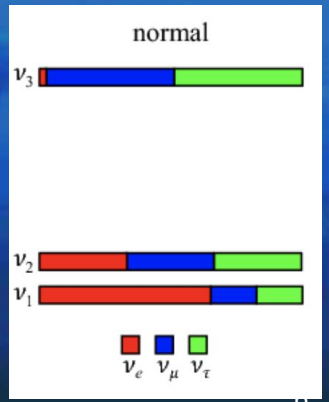
ν_μ Disappearance



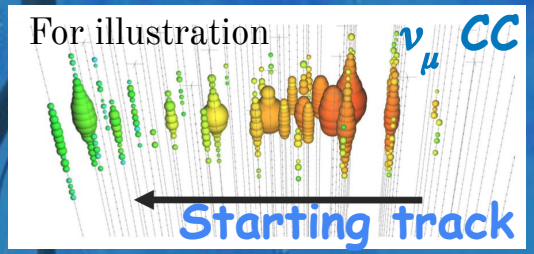
Each flavor (e, μ, τ) is a superposition of masses (1, 2, 3)

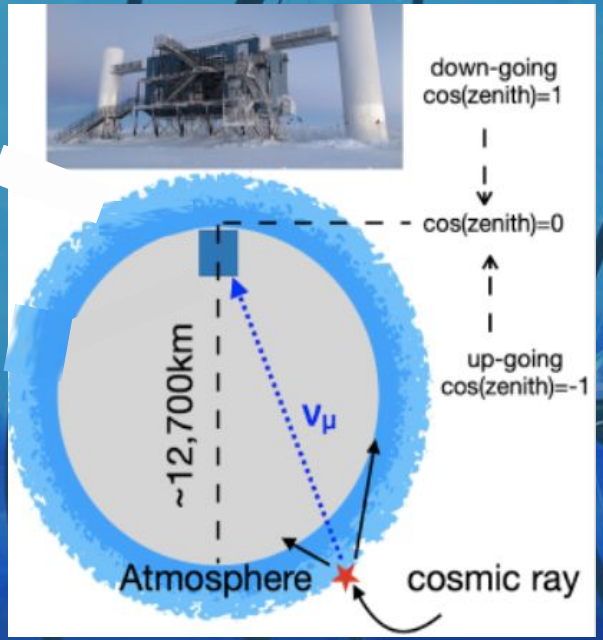
Oscillations are described by:

- Mixing angles (θ_{23}, θ_{13}, θ_{12}), δ_{CP}
- Squared mass differences: Δm^2_{32}, Δm^2_{21}

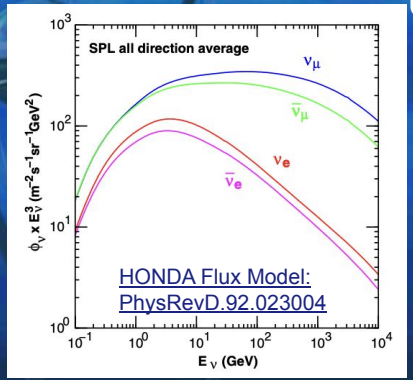


ν_μ Disappearance with IceCube

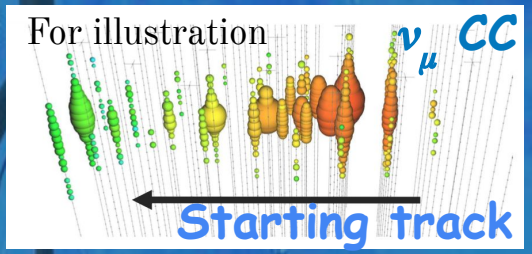


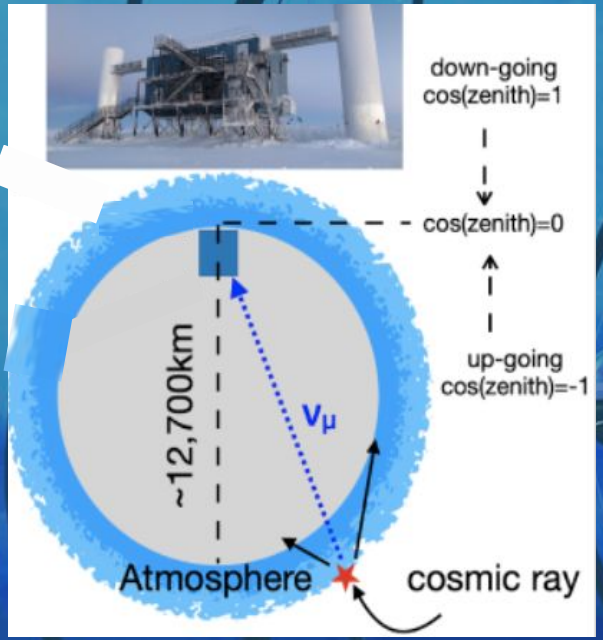


- **Atmospheric muon neutrinos** from cosmic ray interactions:
  - Wide ranges of both energy (E) and baseline (L), and largest values.



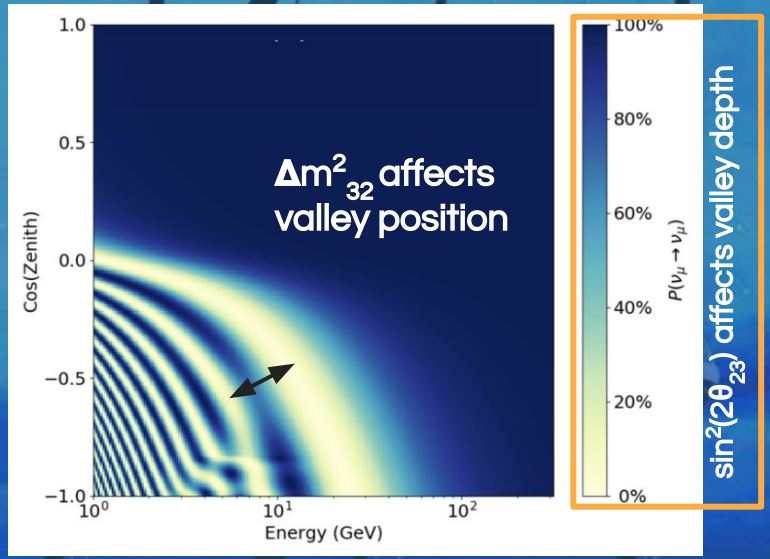
ν_μ Disappearance with IceCube





- **Atmospheric muon neutrinos** from cosmic ray interactions:
  - Wide ranges of both energy (E) and baseline (L), and largest values.
- Neutrino **distance of travel** (L) calculated using **arrival direction (zenith).**

ν_μ Disappearance with IceCube



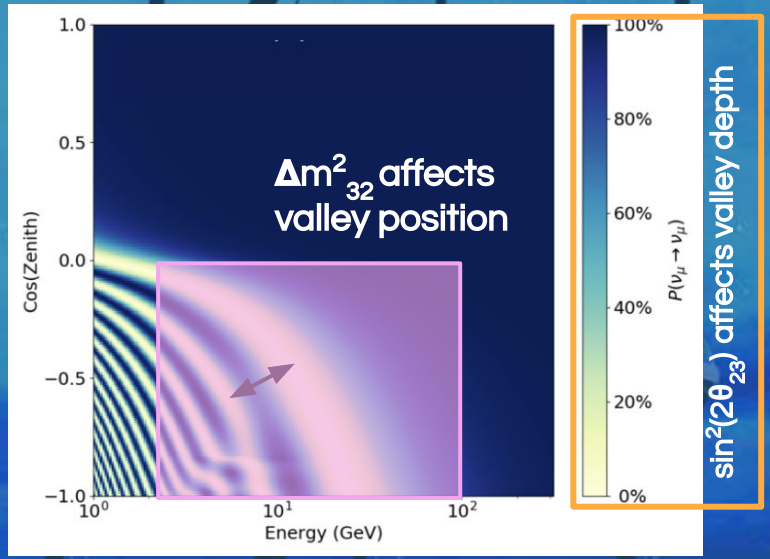
DOI: 10.1016/j.nima.2020.164332

- **Atmospheric muon neutrinos** from cosmic ray interactions:
  - Wide ranges of both energy (E) and baseline (L), and largest values.
- Neutrino **distance of travel** (L) calculated using **arrival direction (zenith).**

ν_μ survival probability (two flavor approx.):

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27 \Delta m^2_{32} L}{E}\right)$$

ν_μ Disappearance with IceCube



DOI: 10.1016/j.nima.2020.164332

- Low-energy (< 100 GeV) reconstruction is critical to oscillation analysis

- **Atmospheric muon neutrinos** from cosmic ray interactions:
  - Wide ranges of both energy (E) and baseline (L), and largest values.
- Neutrino **distance of travel** (L) calculated using **arrival direction (zenith).**

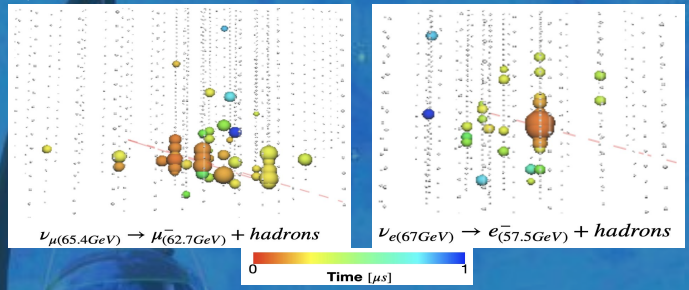
ν_μ survival probability (two flavor approx.):

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27 \Delta m^2_{32} L}{E}\right)$$

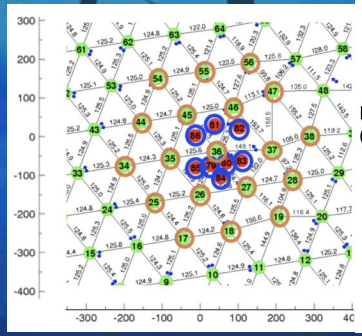
Convolutional Neural Networks

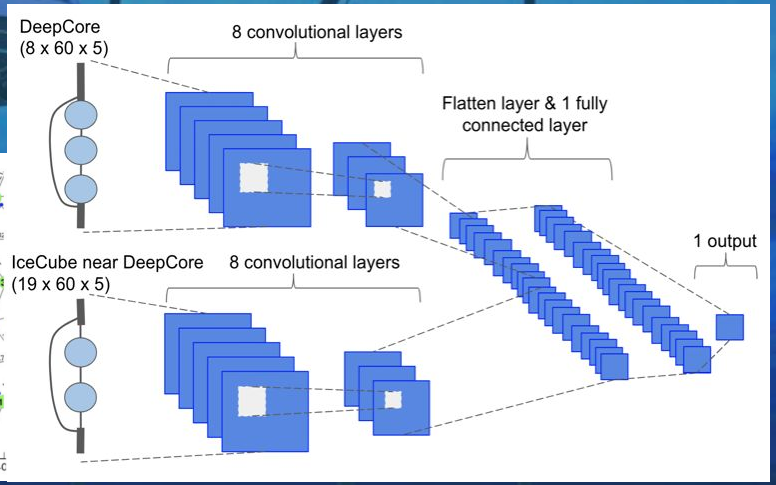
Track-like events: ν_μ CC, 17% ν_τ CC

Cascade-like events: ν_e CC, NC, ν_τ CC



- Only use DeepCore & nearby IceCube strings;
- Five CNNs trained on balanced MC samples: optimized for different variables.





Reconstruct variables at final level

- Neutrino Energy
- Direction (L)
- PID: ν_μ CC vs. others

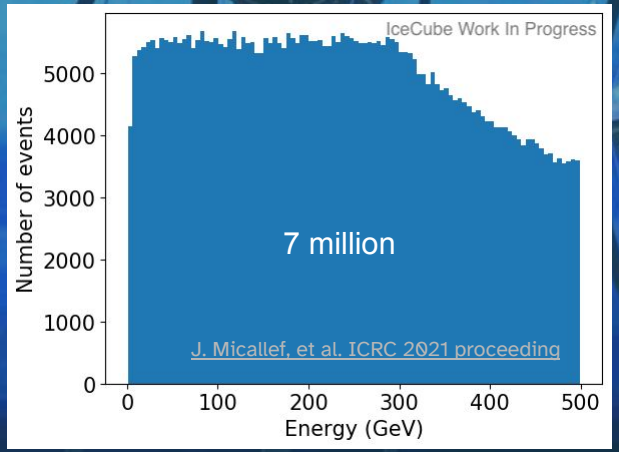
} Analysis binning

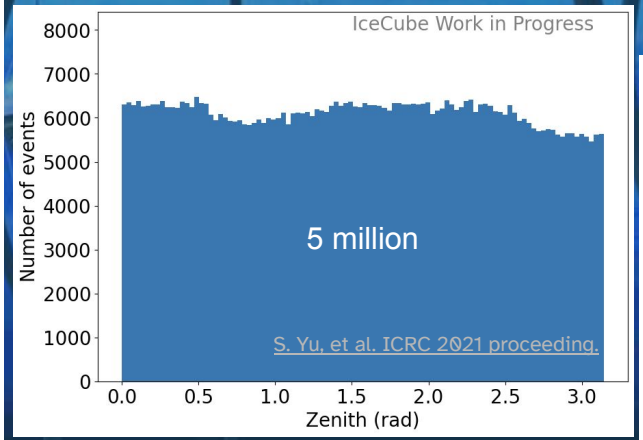
- Interaction vertex
- Atm. muon classifier

} Selections

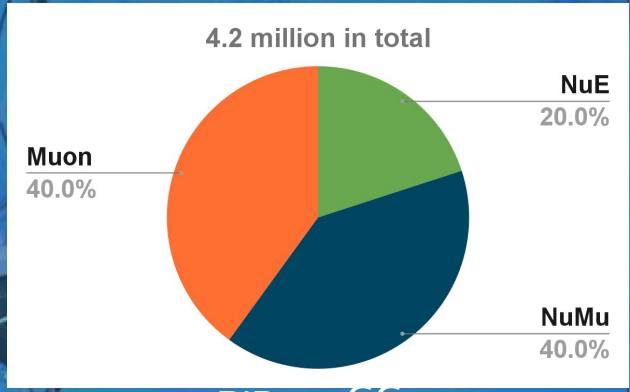
Training Samples

- Balanced MC samples;
- Energy, direction, interaction vertex are trained on ν_μ CC events (signal).

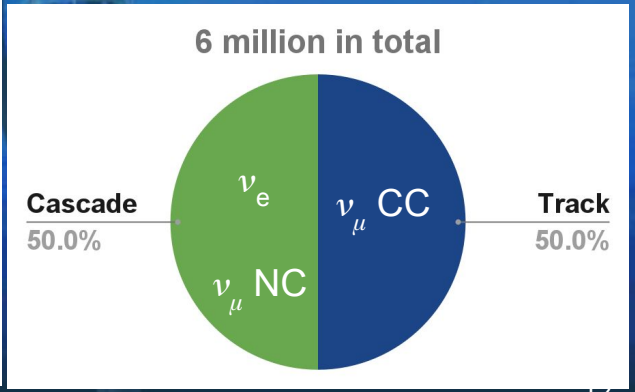




Muon Classifier

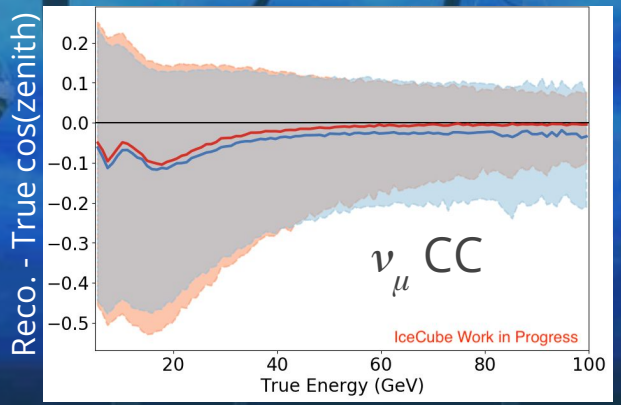


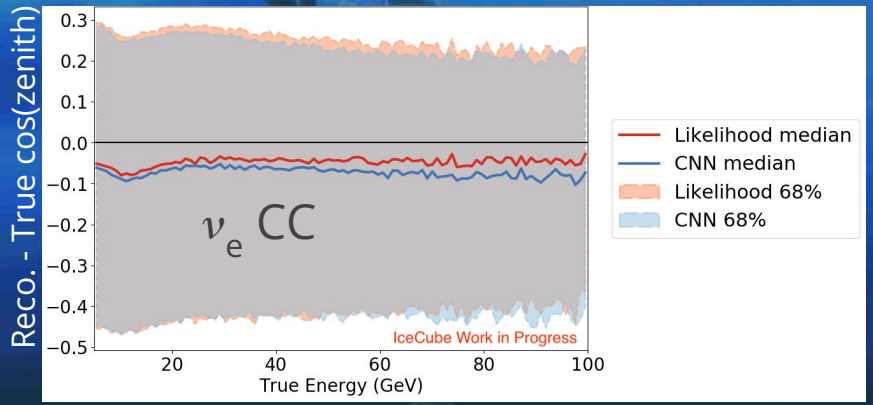
PID: ν_μ CC



Reconstruction Performance

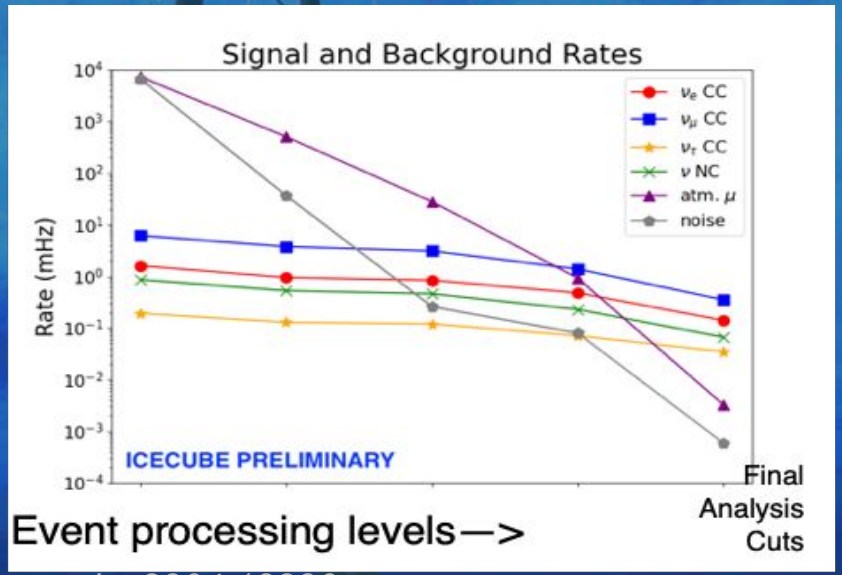
- Nominal MC with analysis cuts and flux, xsec, and oscillation weights applied;
- Comparable resolution to current (likelihood-based) method;
- *~3,000 times faster in runtime*: big advantage for full MC production of atmospheric neutrino datasets.





Preliminary Analysis Sample

- Data taken over ~3,390 days between 2012-2021;
- Total of 150,257 candidates;
- High signal (ν_μ CC) and low background (noise and atm. muon) rates (~0.6%):
  - Several levels of selection are applied to eliminate the primary atm. muons and noise backgrounds.

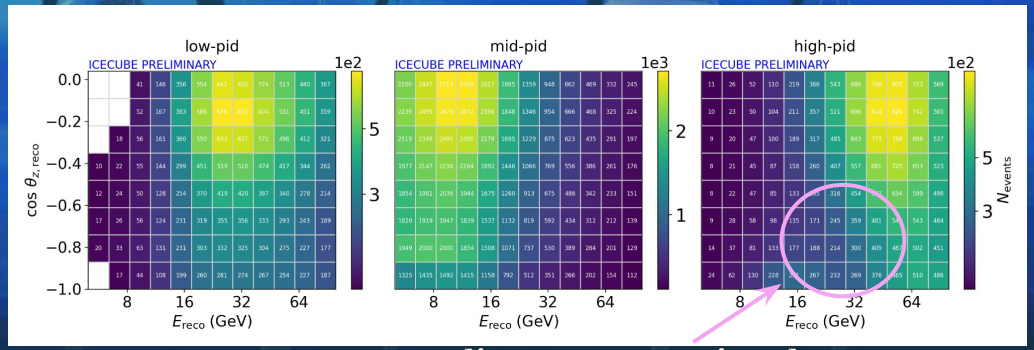


arxiv: 2304.12236

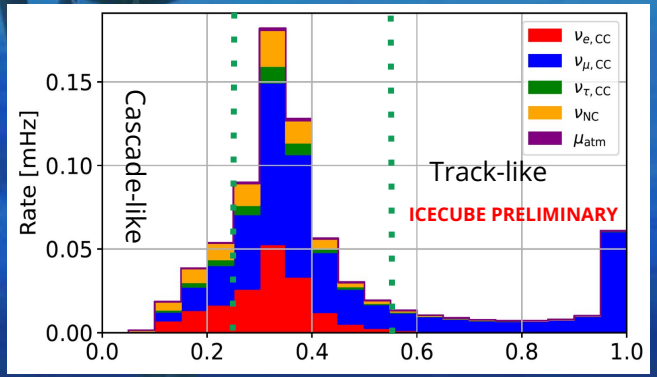
3D Binned Analysis Sample

Measure 3D distortions in reconstructed [energy, cos(zenith), PID]:

- PID discriminates ν_μ CC vs. neutrino backgrounds;
  - 27,352 tracks; 22,963 cascades.



ν_μ disappearance signal

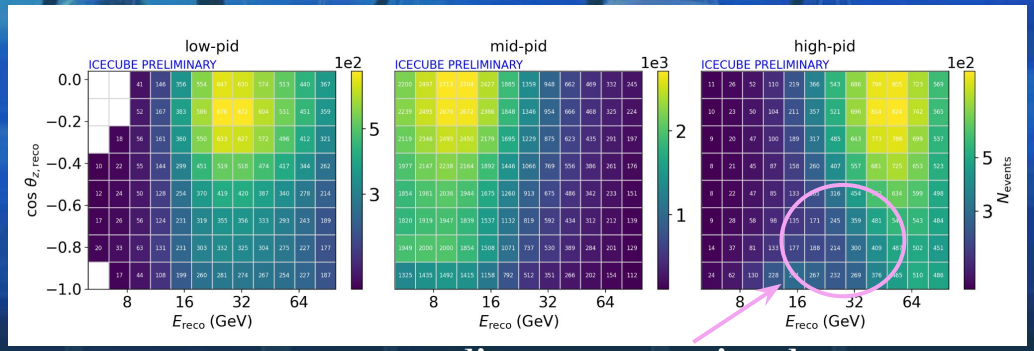


ν_μ CC ID

3D Binned Analysis Sample

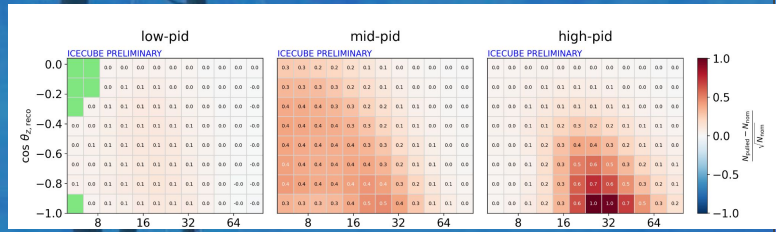
Measure 3D distortions in reconstructed [energy, cos(zenith), PID]:

- PID discriminates ν_μ CC vs. neutrino bkgs;
  - 27,352 tracks; 22,963 cascades.
- Robust against systematic uncertainties.

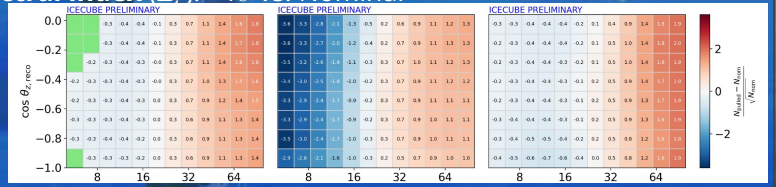


ν_μ disappearance signal

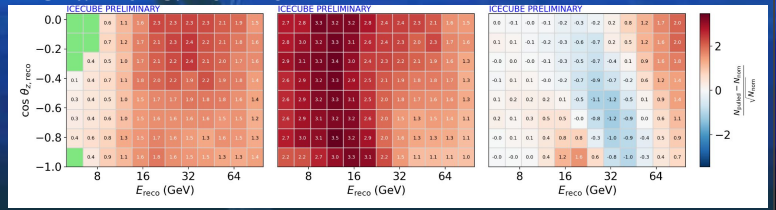
θ_{23}: +5° vs. Nominal



Spectral index ($\Delta\gamma$): +1σ vs. Nominal

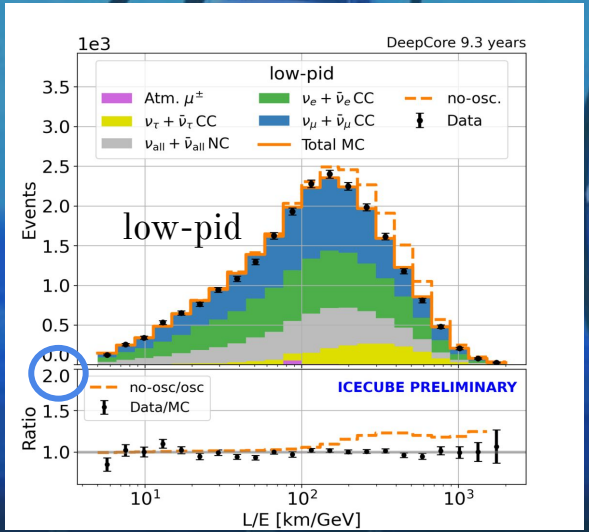


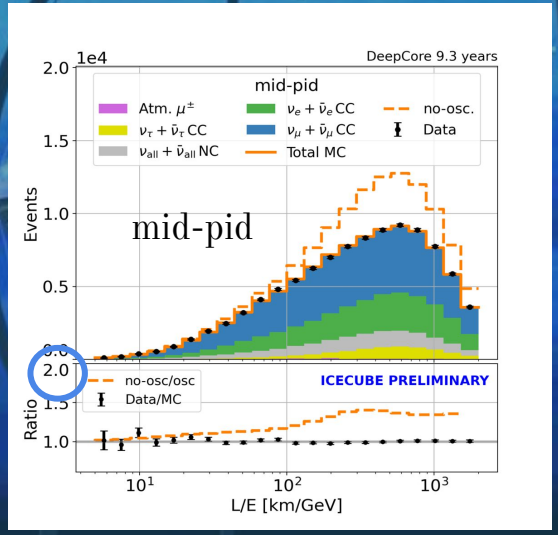
DOM eff.: +1σ vs. Nominal

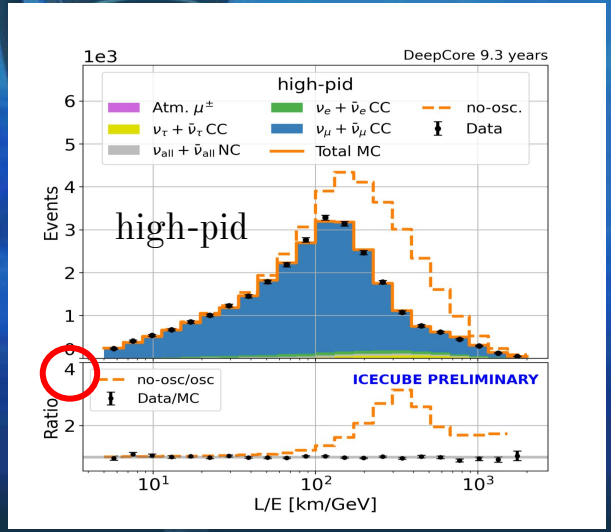


Oscillation Result: L/E

- Good overall data/mc agreement;
- Outstand oscillation signature in high-pid bin.

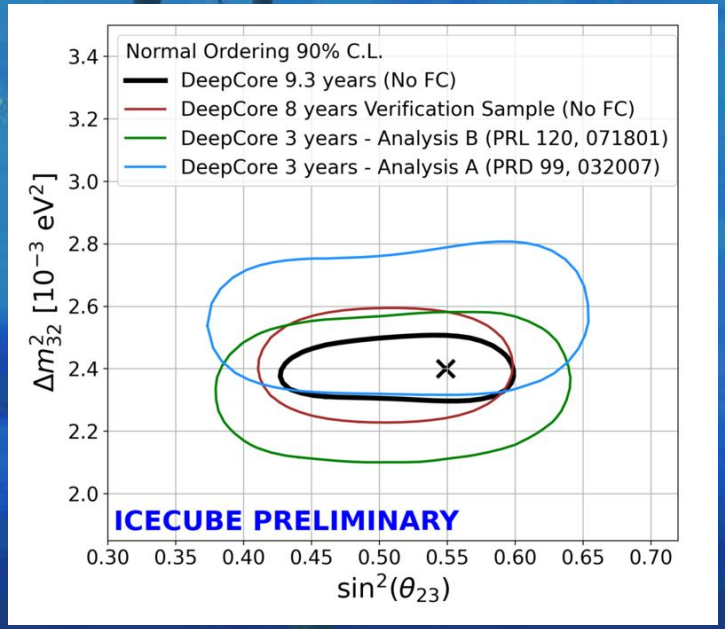






Oscillation Result: Contours

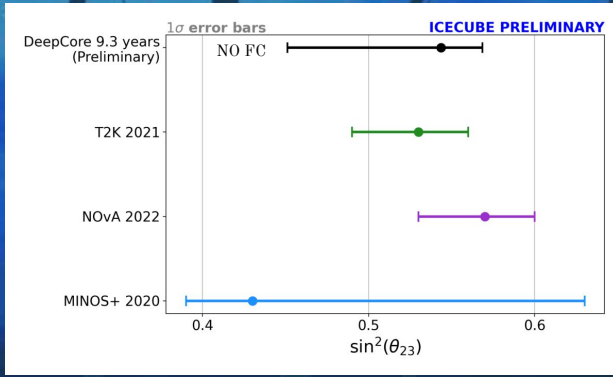
- Consistent with the previous IceCube results.
- Big updates on MC models and calibration since last publication (DeepCore 3-year).
- Compared to DeepCore 8-year result: New reconstruction, including mixed- and low-pid bins into analysis, more statistics.

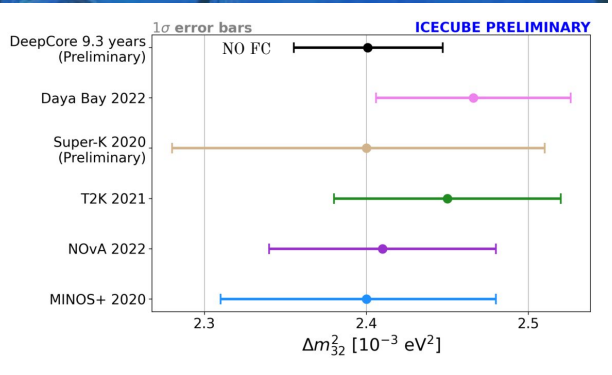


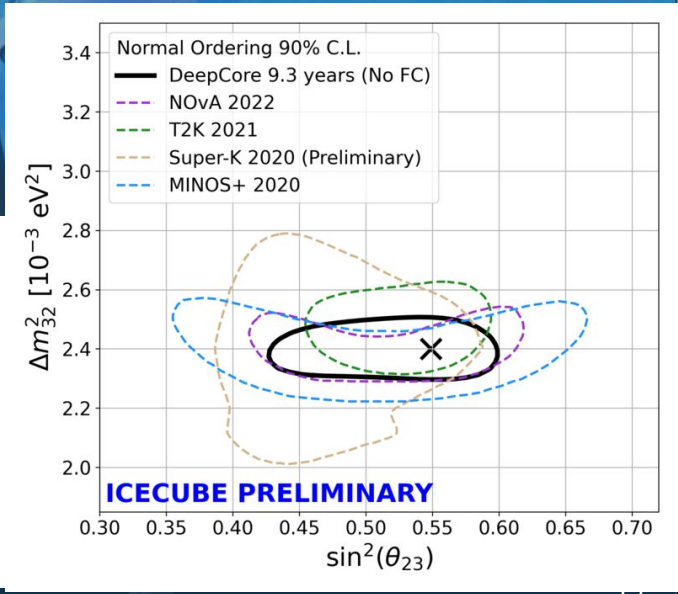
8 years result: arxiv: 2304.12236

Oscillation Results: Contours

- The new result is compatible and complementary with the existing measurements:
  - Very high energy sample (5–100 GeV) and very different systematic uncertainties → strong validation of the standard 3-flavor oscillation

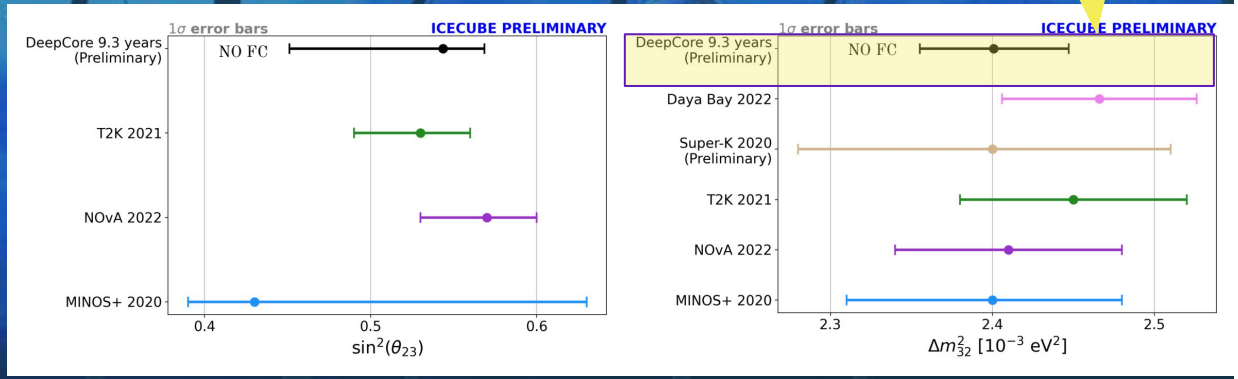


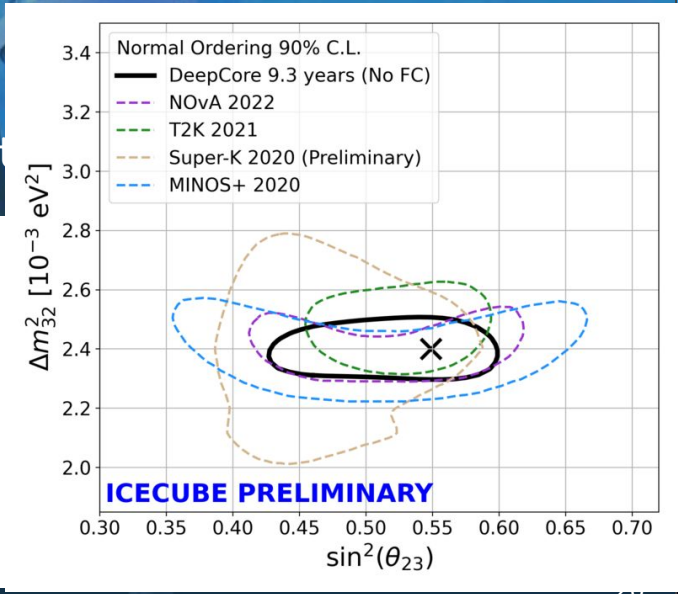




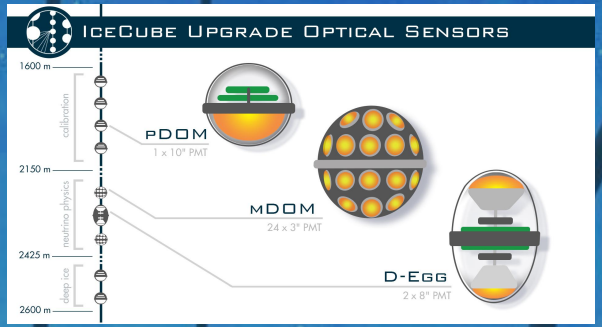
Oscillation Results: Contours

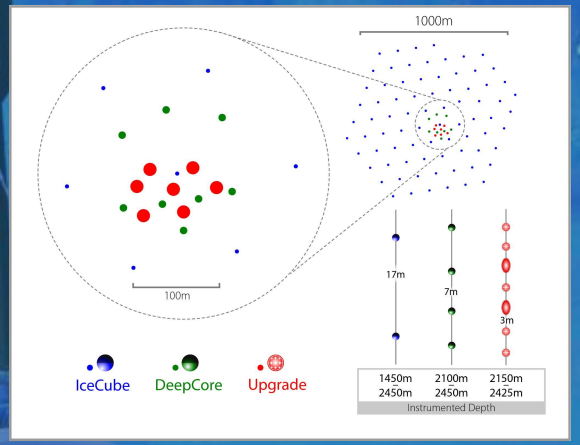
- The new result is compatible and complementary with the existing measurements.
- Competitive on Δm^2_{32} measurement.
- Room for future improvements!
  - Flux model; particle modeling; calibration, et





Future



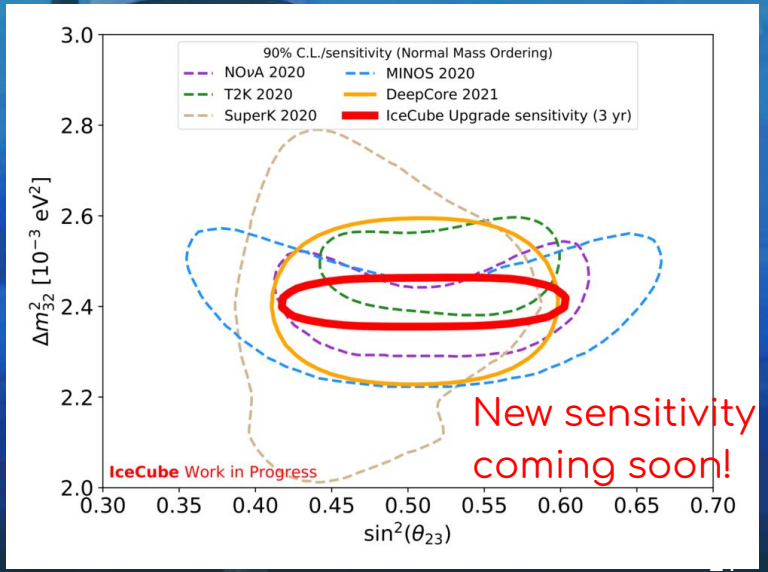


Upcoming results of neutrino physics:

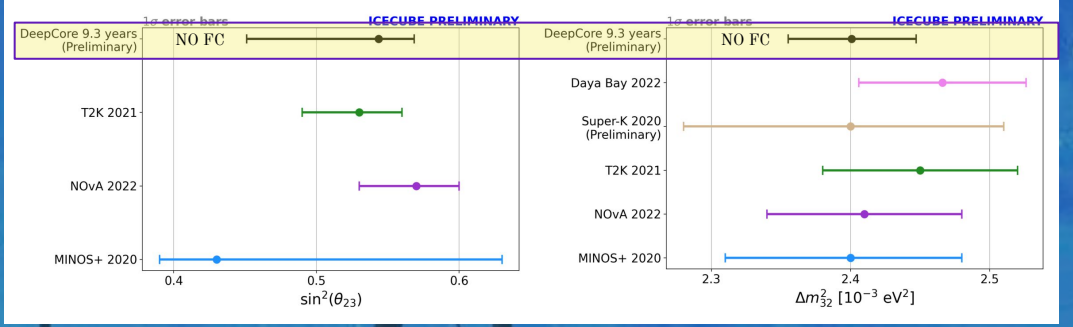
- mass ordering, non-standard interaction, etc...

<u>The Upgrade detector:</u>

- More densely instrumented strings in the center
  - Better event resolution!
- DOM: multiple PMT designs
  - Great for calibration studies!
- Target deploying 2024/25



Conclusions



- First-time using the highest-statistic (9.3yr) DeepCore atmospheric neutrino dataset for oscillation measurements:
  - Machine learning tools (including CNNs) are used for multi-purpose reconstruction.
- Compatible, complementary result with the existing measurements;
  - Competitive constraint on Δm^2_{32}.
- A lot of room for future improvements!
- More oscillation results using this new sample on the way!
  - Neutrino mass ordering, NSI analysis, etc...

Stay tuned!

Thank you for your attention!

Overflow Slides

PhysRevLett.129.011804 (2022)

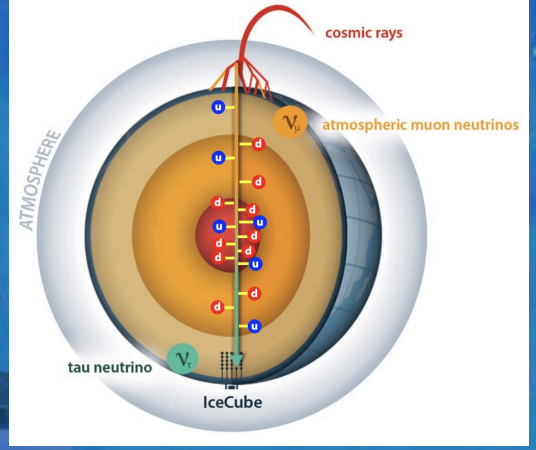
Non-standard Interactions (NSI)

New neutrino-quark interactions could result in additional matter effects

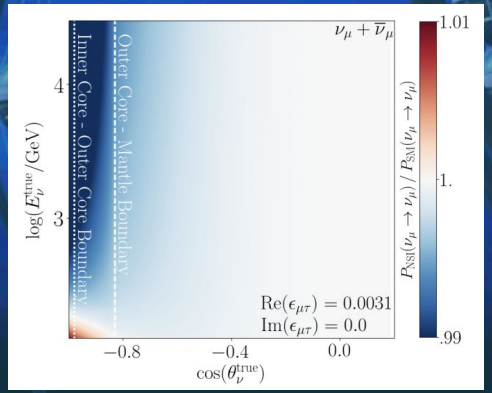
- ~300,000 ν_μ candidates in 0.5 – 10 TeV energy range
- Results consistent with no NSI
- Strong limits set on $\varepsilon_{\mu\tau}$ (benefited from including TeV-scale sample)

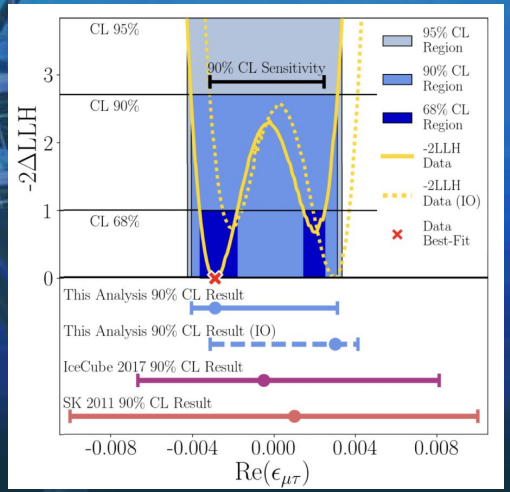
parameterise via a generic matter potential matrix

$$H_{\text{mat+NSI}} = V_{CC}(x) \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix}$$



Strong effects for neutrinos crossing Earth's core

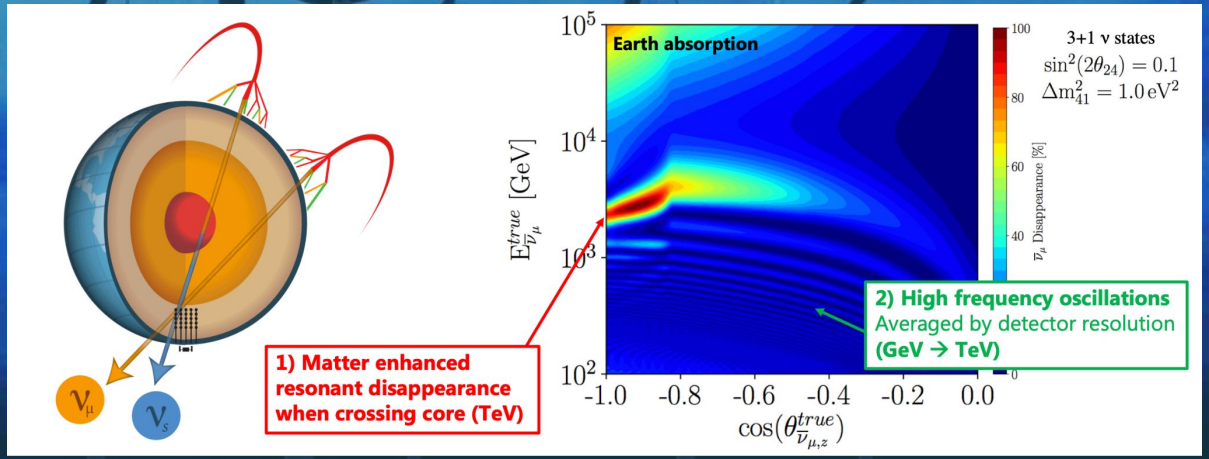


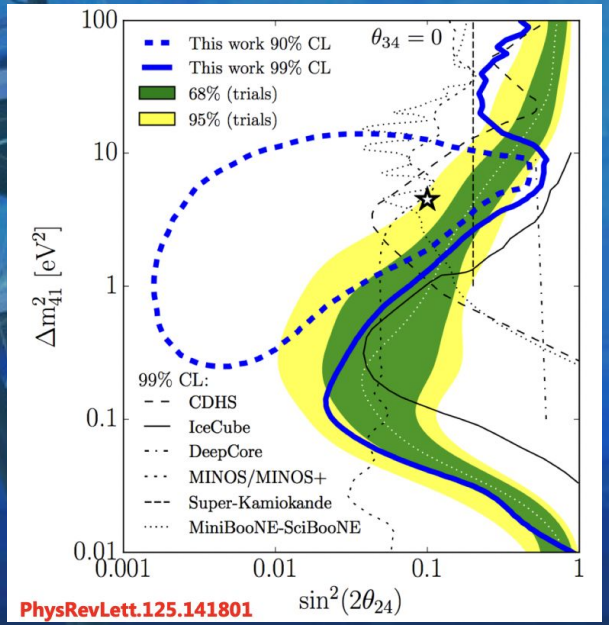


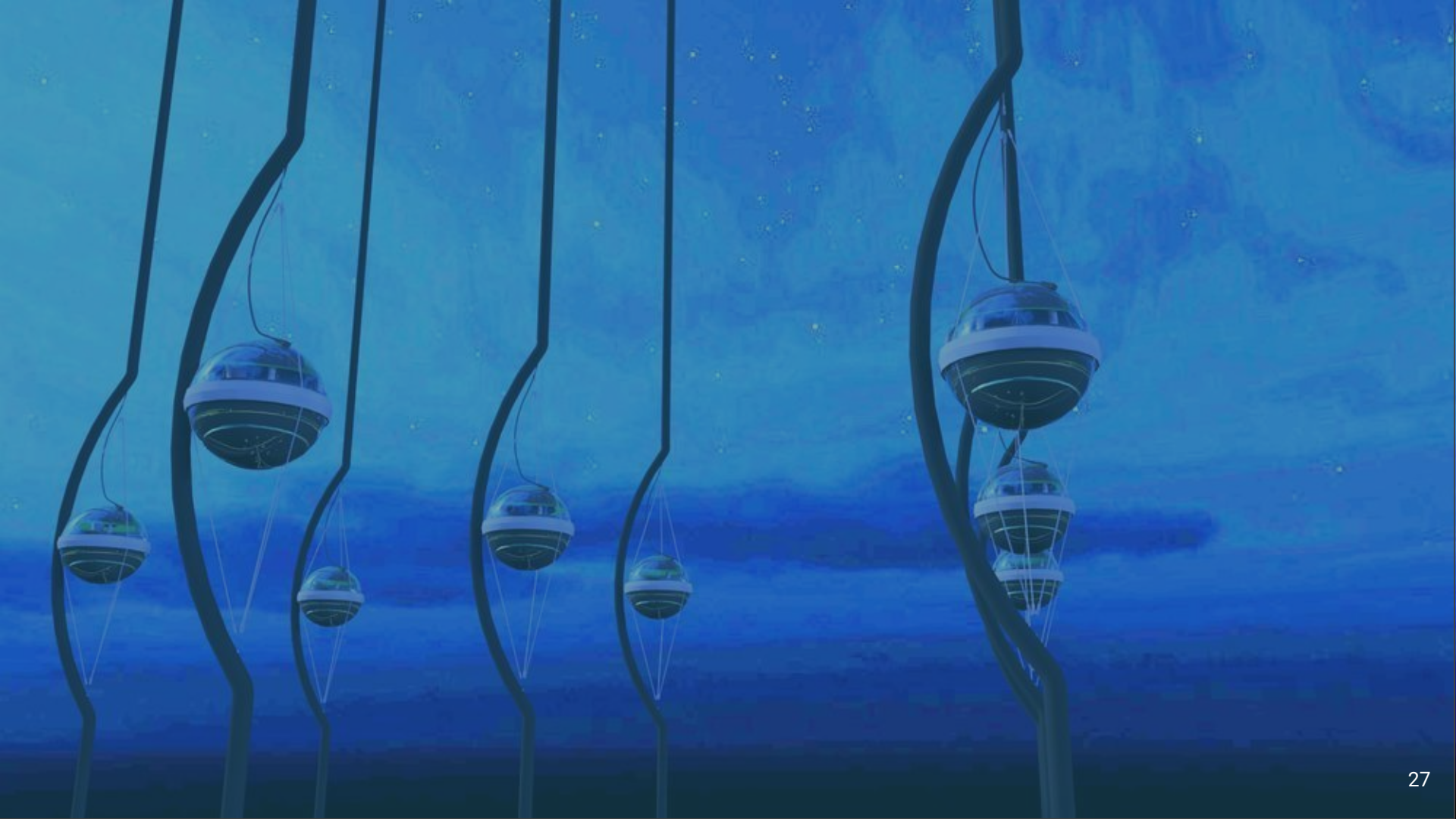
Phys. Rev. D 102, 052009 (2020)

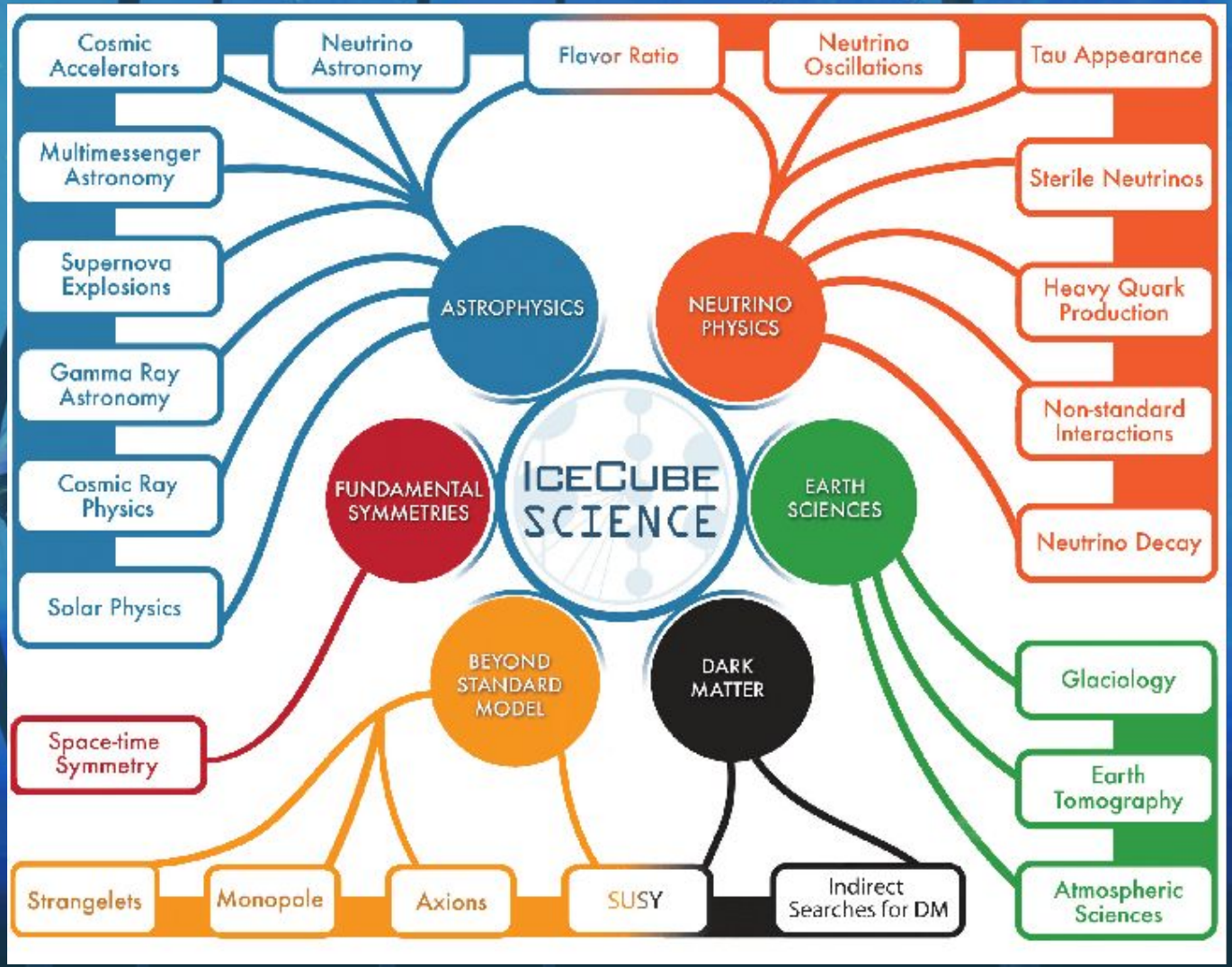
Sterile Neutrino Result

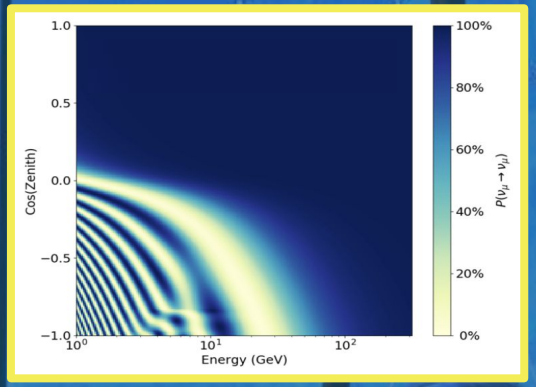
- 8 yr IceCube data → 300,000 **ν** candidates (GeV – TeV)
- Result suggests consistent with standard 3ν paradigm
- New results are coming!

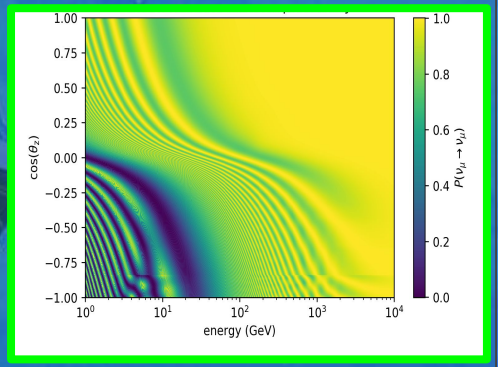


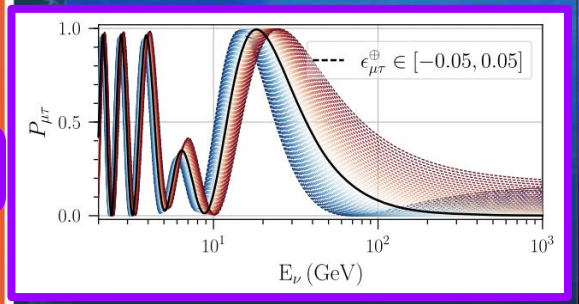





ICECUBE SCIENCE
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
EARTH SCIENCES
BEYOND STANDARD MODEL
DARK MATTER
Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
Neutrino Decay
Solar Physics
Space-time Symmetry
Glaciology
Earth Tomography
Atmospheric Sciences
Strangelets
Monopole
Axions
SUSY
Indirect Searches for DM





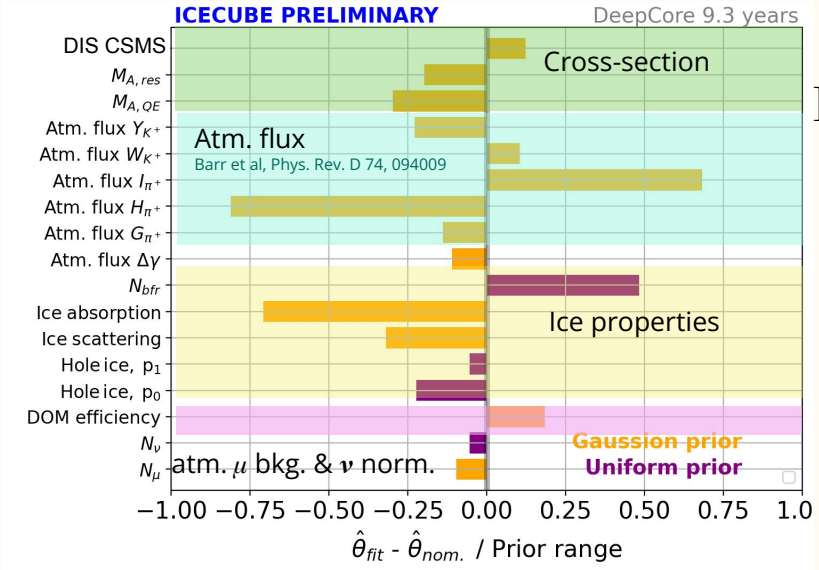


Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
Neutrino Decay
Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
ASTROPHYSICS
NEUTRINO PHYSICS
FUNDAMENTAL SYMMETRIES
EARTH SCIENCES
ICECUBE SCIENCE

Phys. Rev. D104 (2021) 072006

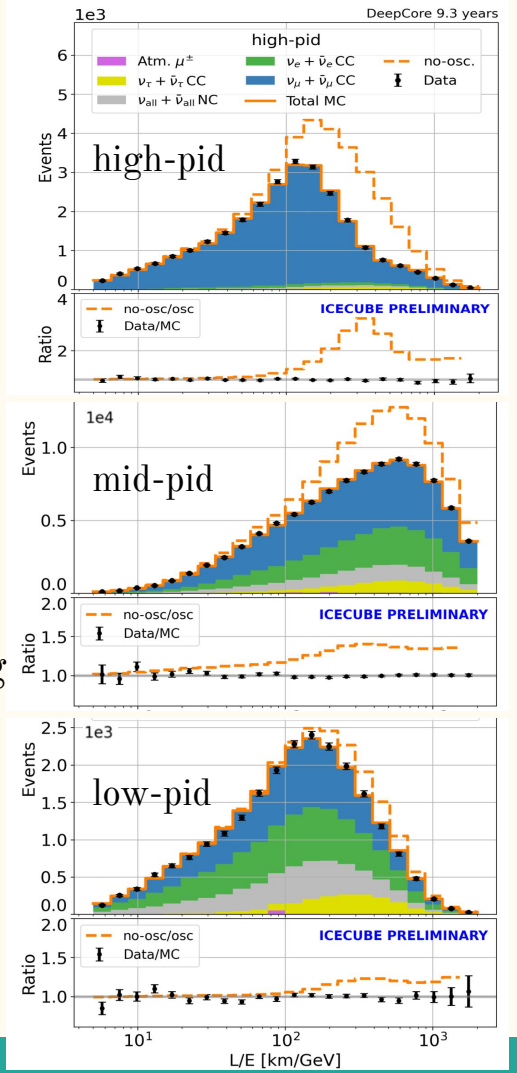
ν_μ Disappearance Analysis

- Systematic uncertainty pulls within expectations;
- Same treatments with DeepCore 8-year results:
  - A publication with details coming soon.



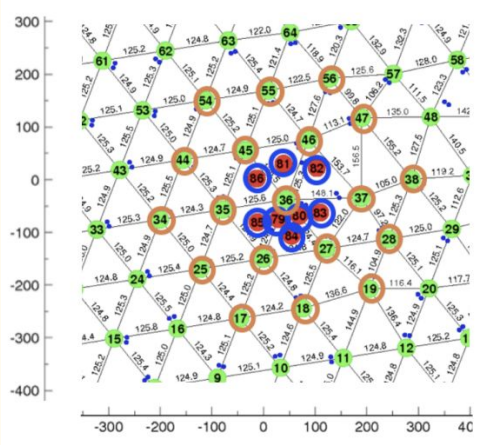
Future improvements:

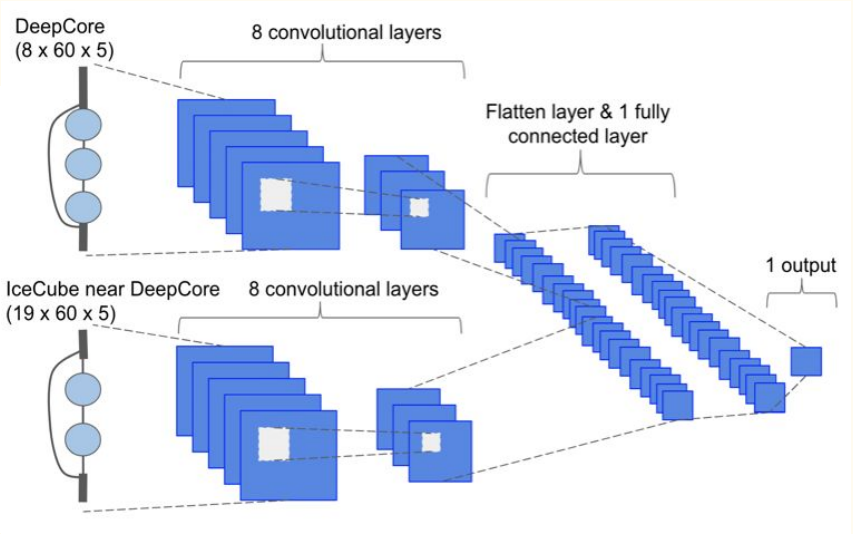
- Reduce correlations among flux uncertainties: PCA;
- Further MC improvements underway.



Convolutional Neural Networks (CNNs)

- Only use DeepCore & nearby IceCube strings;
- Five CNNs trained on balanced MC samples: optimized for different variables.



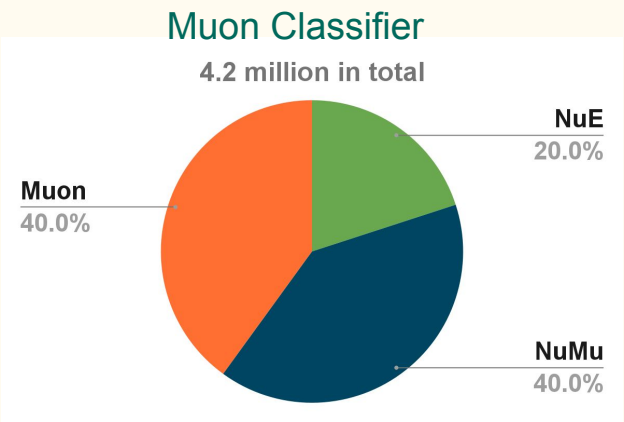


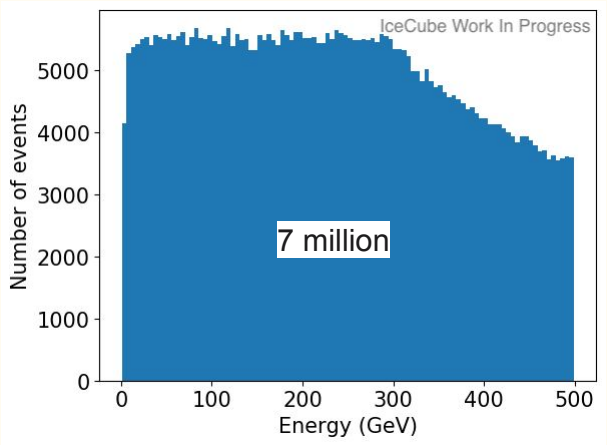
5 summarized variables per DOM:

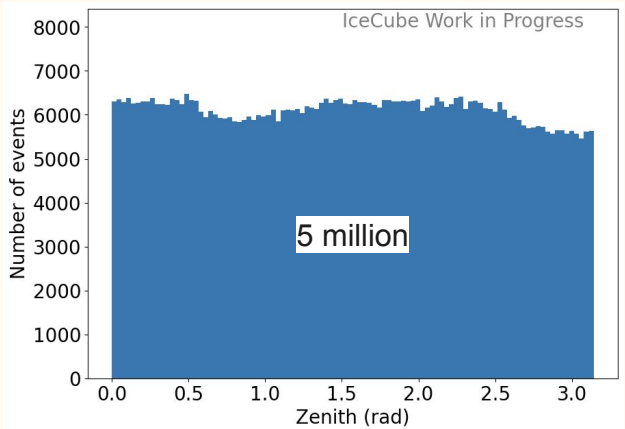
- sum of charges
- time of first (last) pulse
- charge weighted mean (std.) of times of pulses

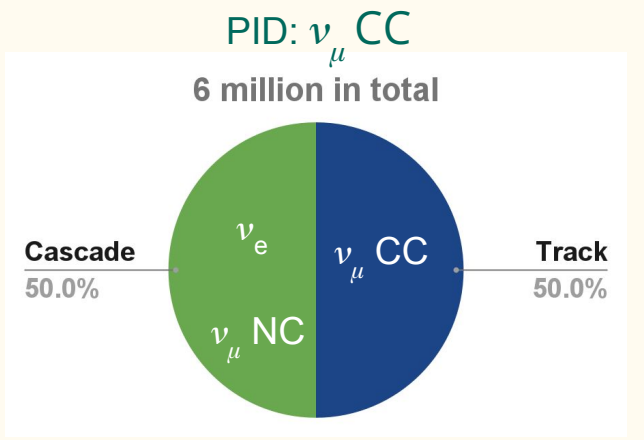
Training Samples

- Balanced MC samples;
- Energy, direction, interaction vertex are trained on ν_μ CC events (signal).









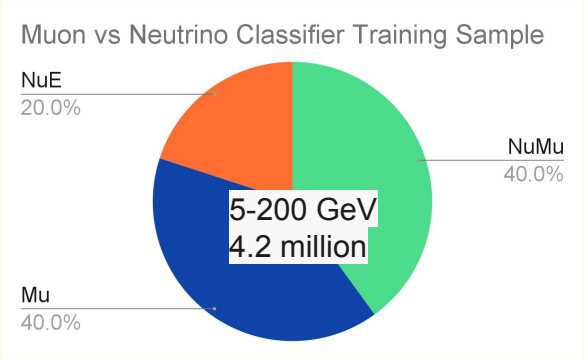
Training Samples

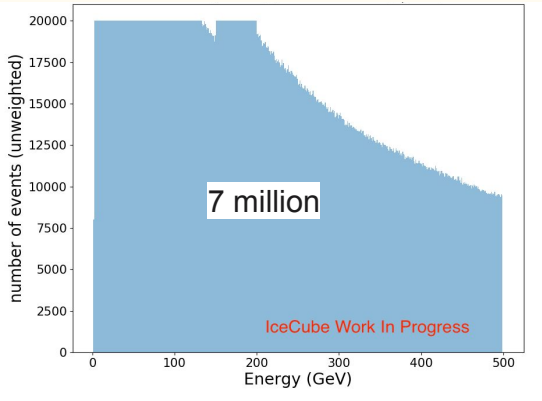
Energy: nDOM >= 7

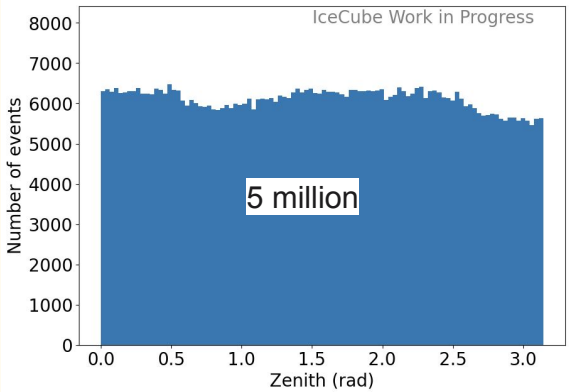
Muon : nDOM >= 4; 5–200 GeV

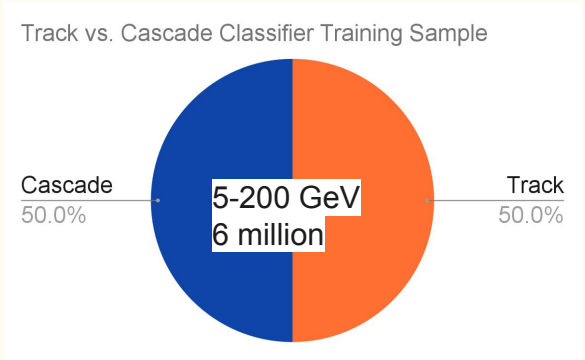
Muon, PID, Vertex: nhits >= 8 hit 5-200 GeV

Zenith: full containment cut on true vertexes, 5-300GeV









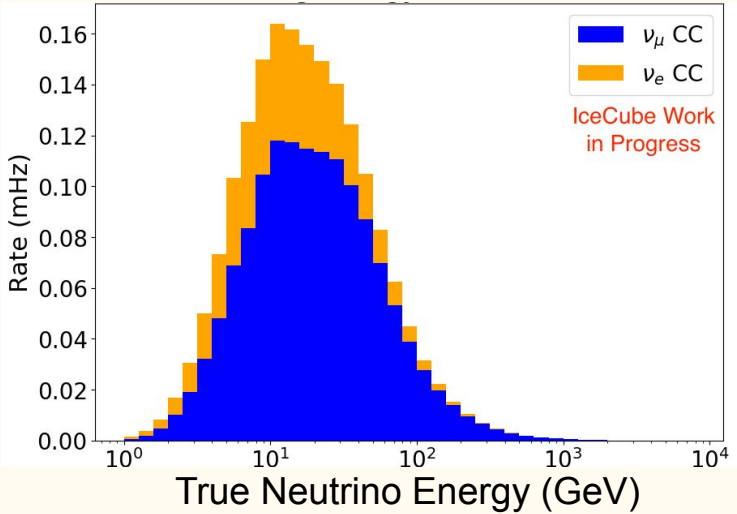
Performance: Speed

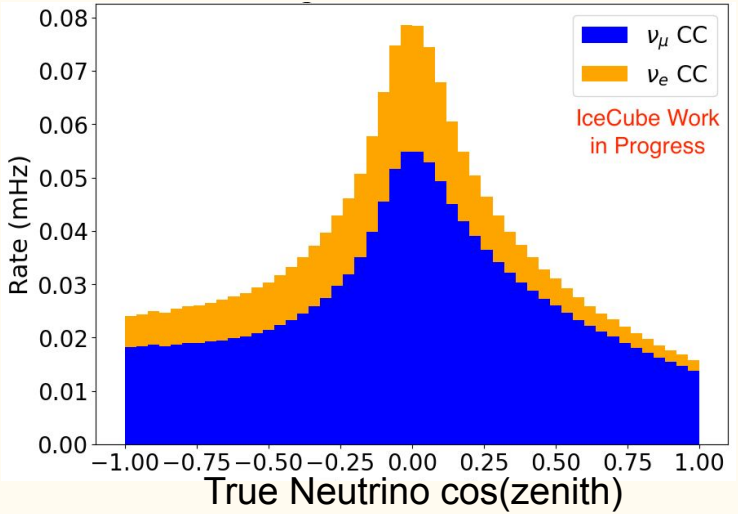
	Second per file (~3k events)	Time for full sample assuming 1000 cores
CNN on GPU	21	~ 13 minutes
CNN on CPU	45	~ 7.5 hours
Current Likelihood-based method (CPU only)	120,000	~ 46 days

- CNN runtime improvement: ~3,000 times faster;
  - CNNs are able to process in parallelize with clusters → can be even faster!
- Big advantage: large production of full Monte Carlo simulations ~O(10^8).

Testing Samples

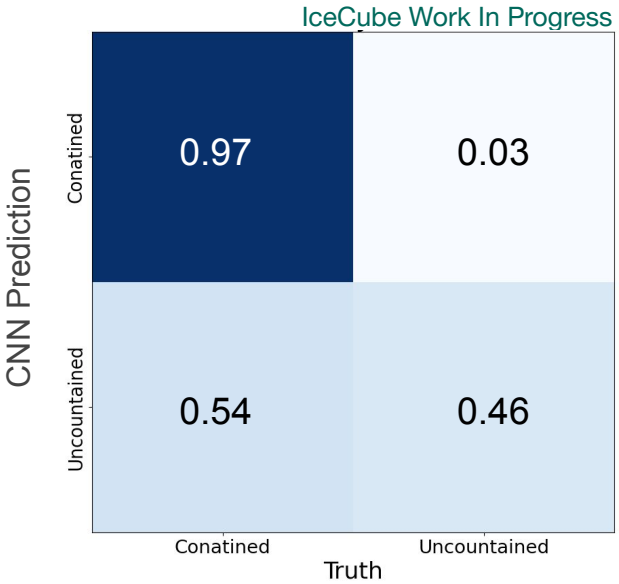
- Nominal MC sample with flux, xsec, and oscillation weights applied;
- Testing on signal (ν_μ CC) and major background (ν_e CC);
- Baseline: current reconstruction method (likelihood-based)

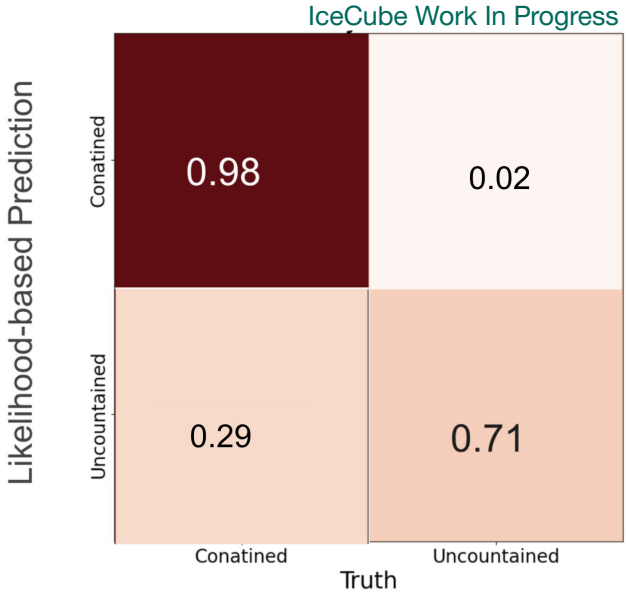




Performance: Vertex

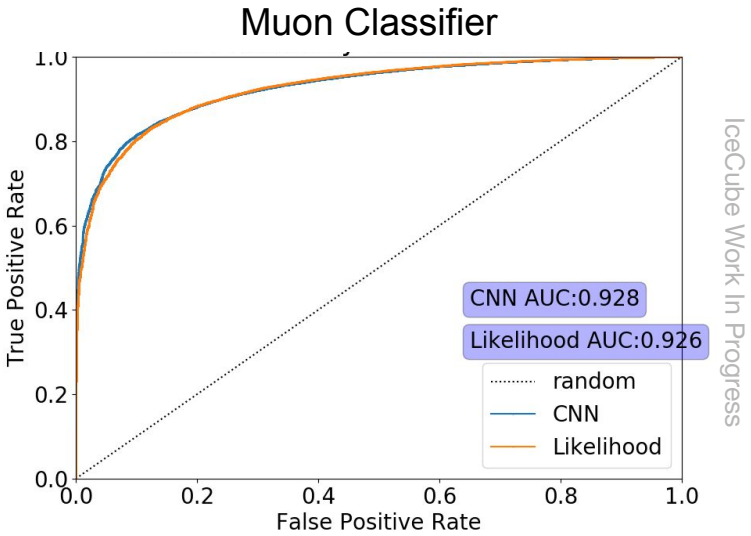
- Selecting events starting near DeepCore;
- Comparable purities in selected ν_μ CC samples.

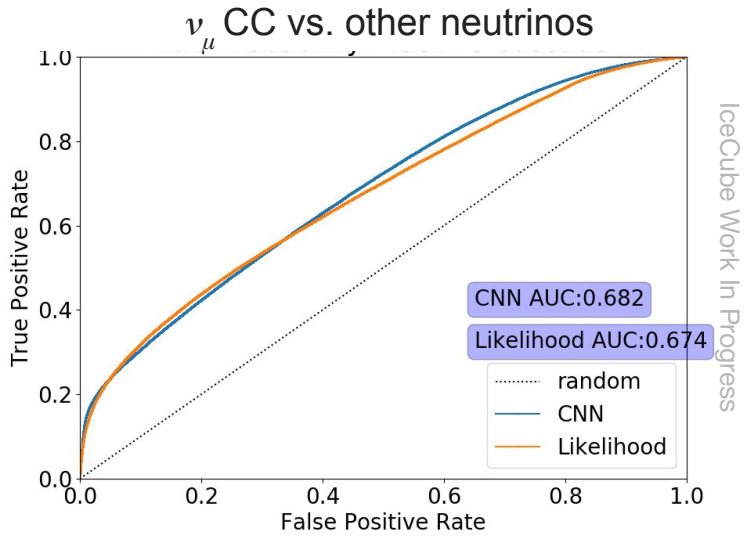




Performance: Muon and PID Classifiers

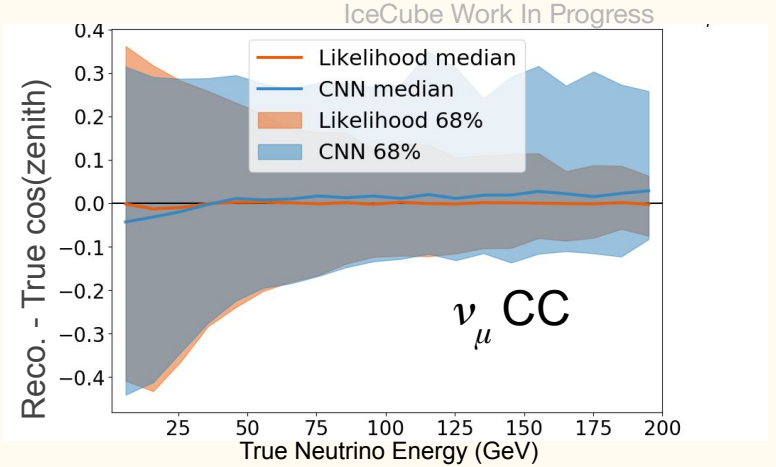
- Comparable performance to the current methods:
  - Similar AUC values.
- Hard to identify track from cascades at low energy → less DOMs see photons.

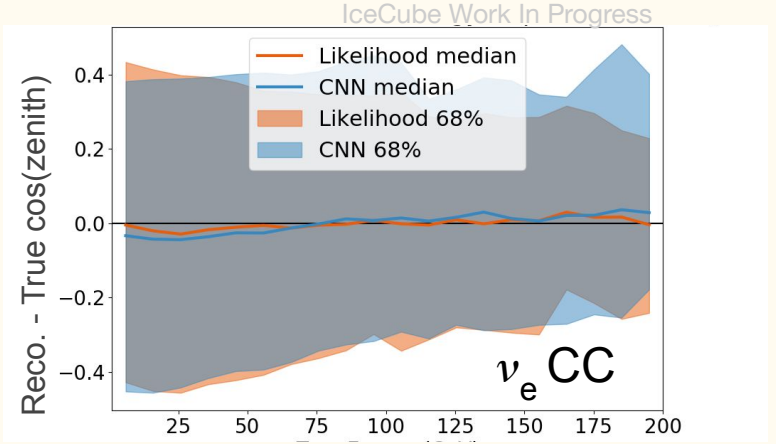




Performance: Direction

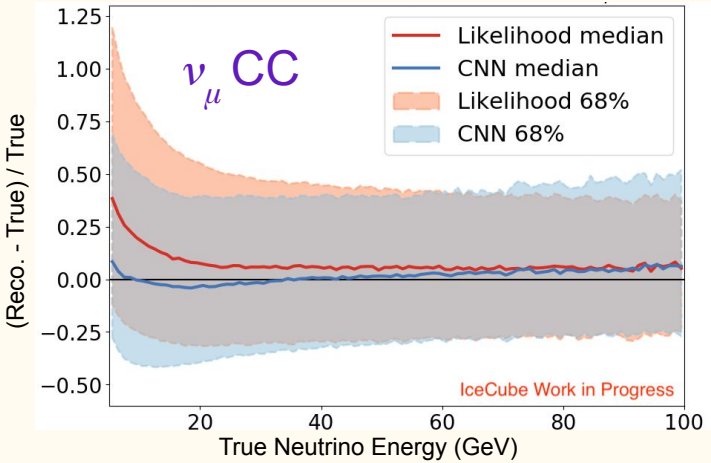
- Direction bias flat against true energy;
- Comparable to current method;
- Better resolution for ν_μ CC (signal);
- High energy (>100 GeV) neutrinos leaving DeepCore
  - Need containment cut: interaction vertex reconstruction.

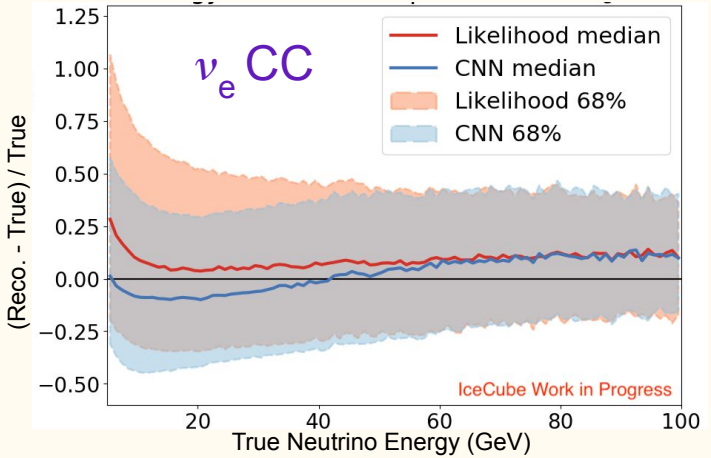




Performance: Energy

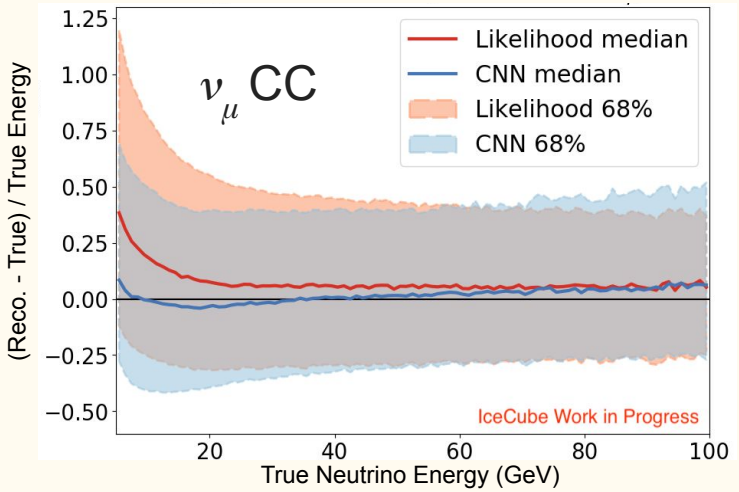
- Flat median against true neutrino energy;
  - CNN has better resolution at low energy (majority of sample)
- Comparable performance to current method at higher energy and in background;

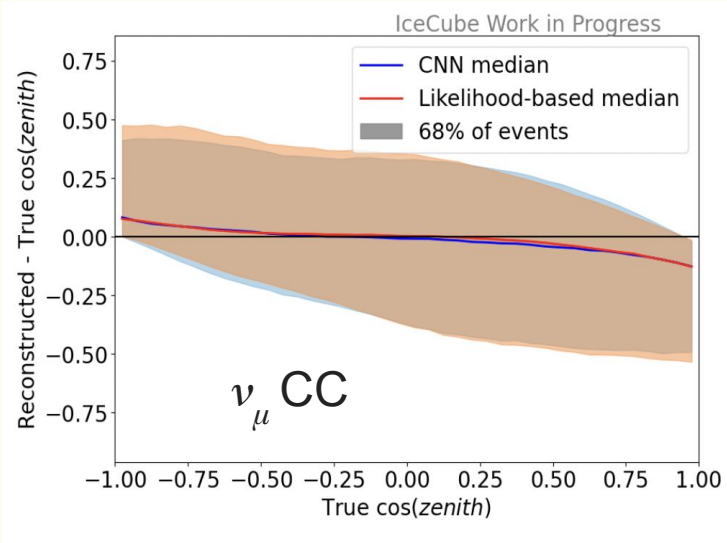




Reconstruction Performance

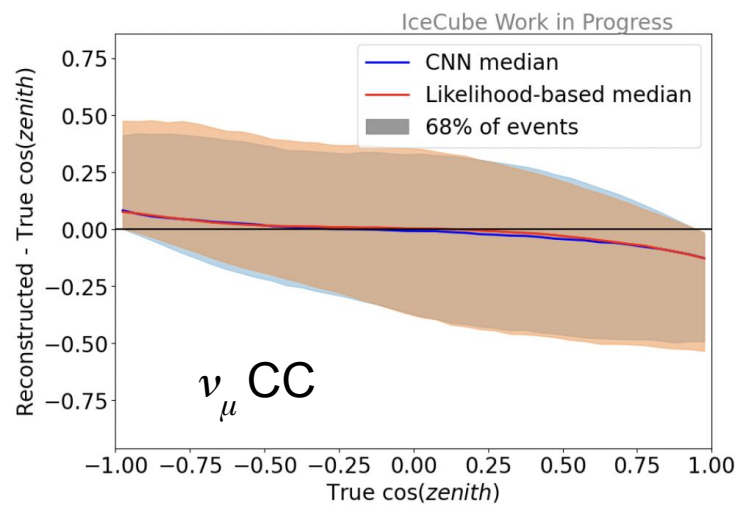
- Flat median against true neutrino energy and zenith;
- CNN has comparable resolution to current method, and better at low energy (majority of sample)

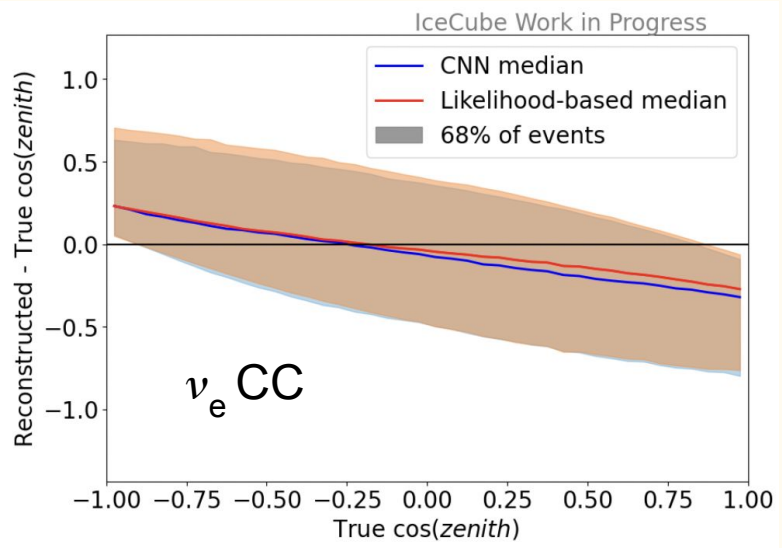




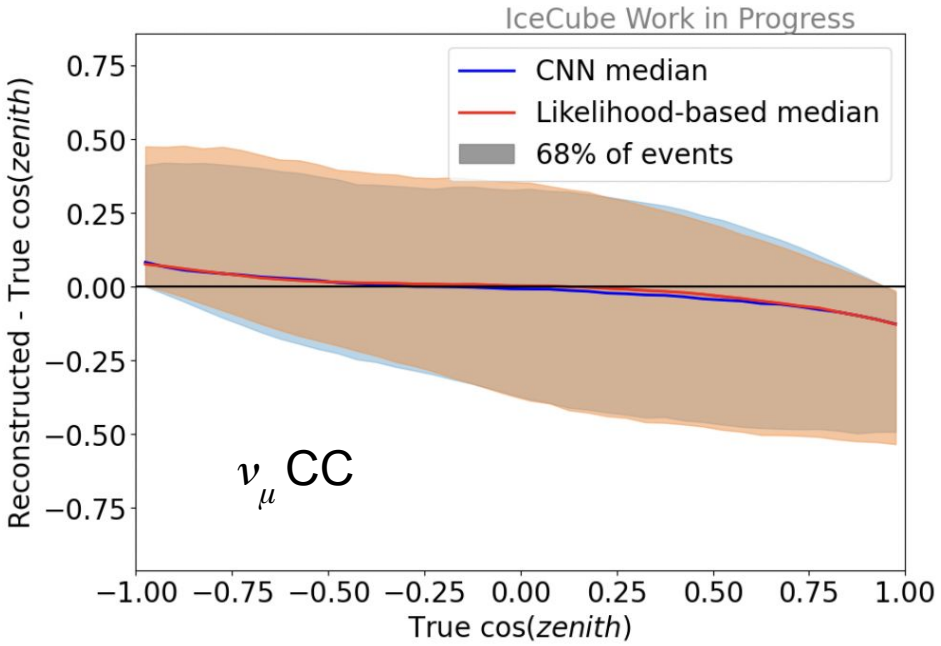
Performance: Zenith

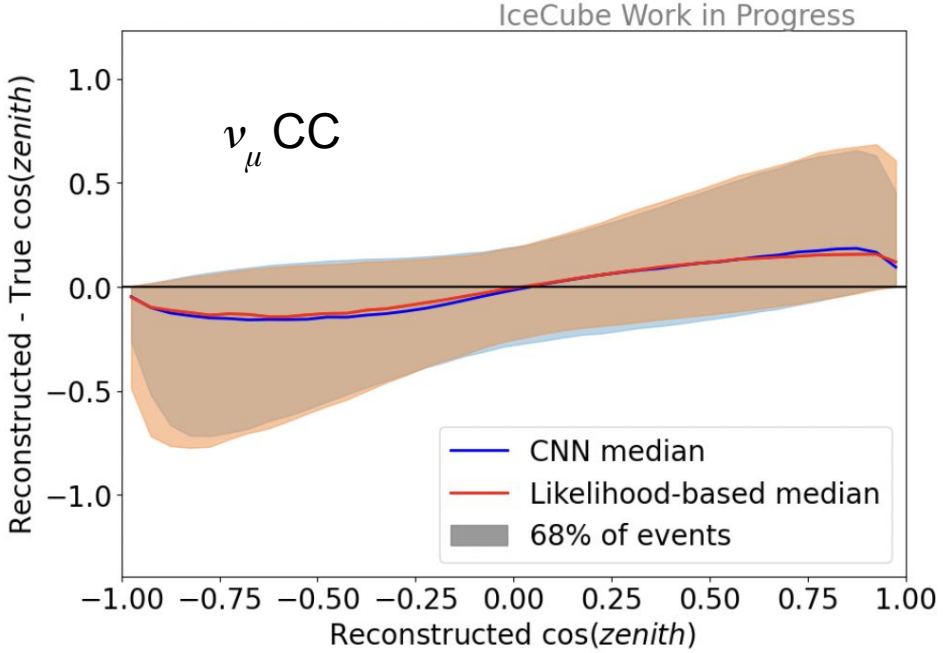
- Flat median against true direction;
- Comparable to current method in both signal and background.





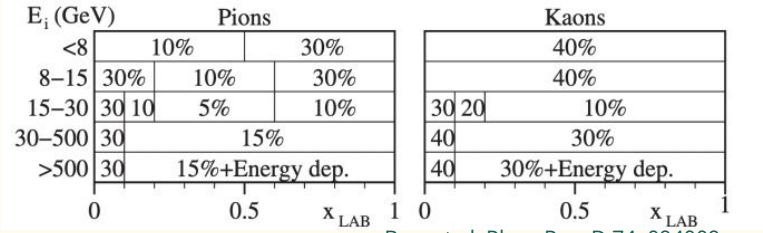
Performance: Zenith (Contained, 5-300 GeV Sample)





Systematic Uncertainty Consideration

- Flux uncertainty
  - Pion & Kaon production uncertainties



Barr et al, Phys. Rev. D 74, 094009