For the IceCube Collaboration

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

New Measurement of Muon Neutrino Disappearance from the IceCube Experiment

Shiqi Yu

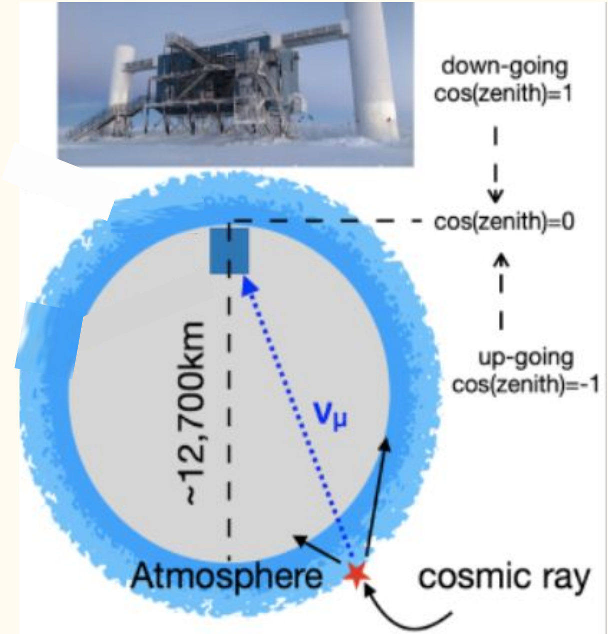
Michigan State University

MORIOND EW, March 19th, 2023

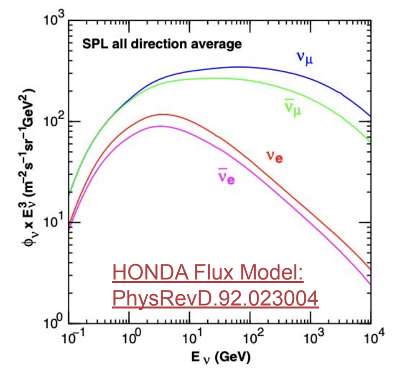
Presentation Outline

- Introduction
- Reconstruction: Convolutional neural networks
- Atmospheric ν_μ disappearance measurements

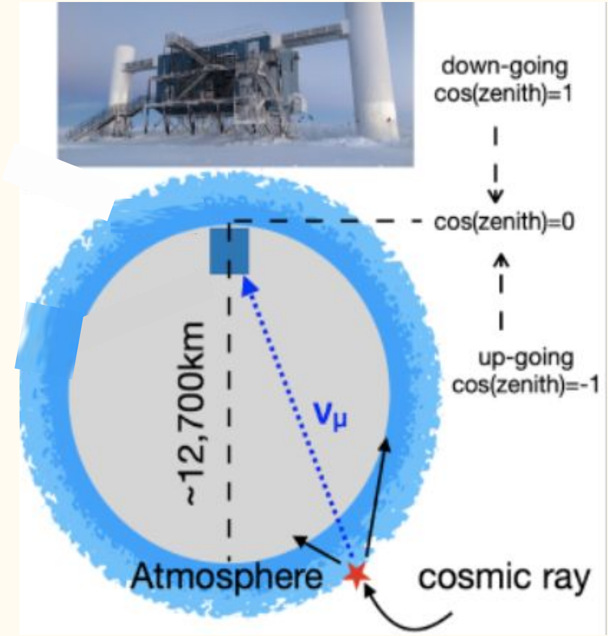
ν_μ Disappearance with IceCube



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

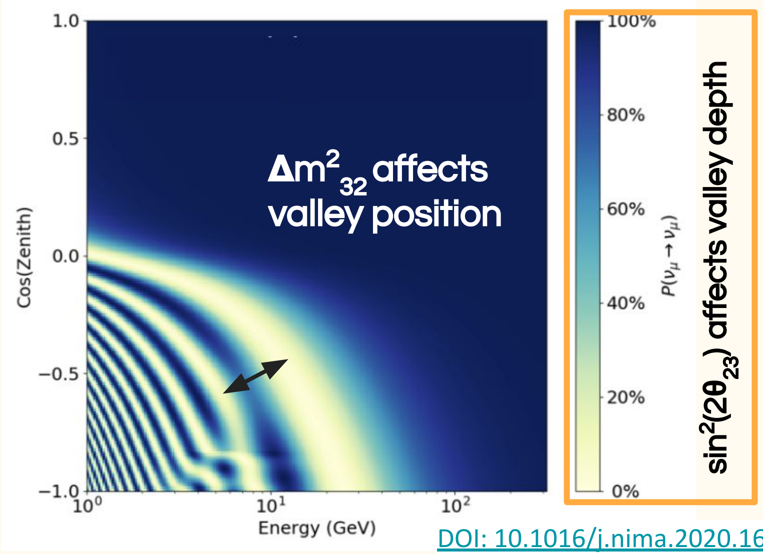


ν_μ Disappearance with IceCube



- **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



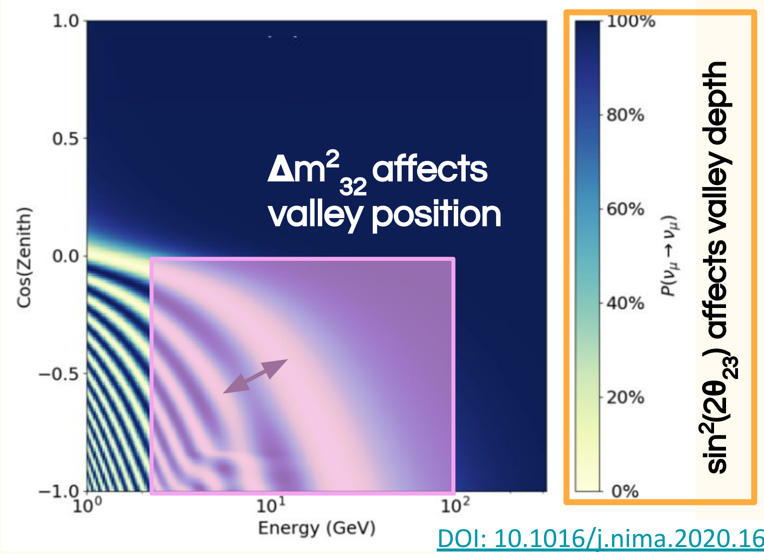
DOI: 10.1016/j.nima.2020.164332

- **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

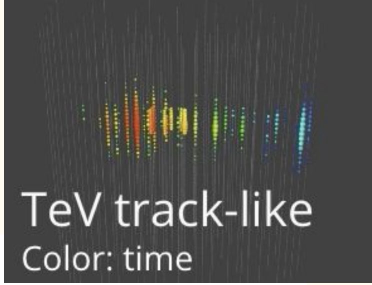
- **Atmospheric muon neutrinos** from cosmic ray interactions:
  - Wide ranges of both energy (E) and baseline (L), and largest values.
- Neutrino **distance of travel** (L) calculated using **arrival direction (zenith).**

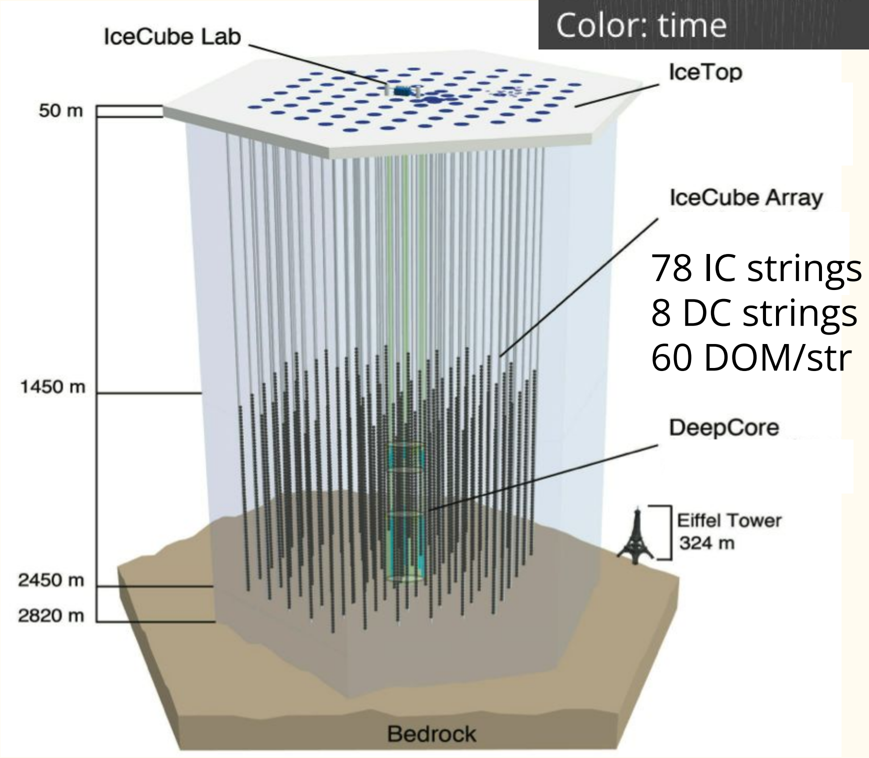
ν_μ survival probability (two flavor approx.):

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

IceCube Neutrino Observatory

- 1 km^3 neutrino detector deep under South Pole ice;
- 5160 digital optical modules (DOMs) detect Cherenkov photons emitted during neutrino interactions;
- DOMs record pulse charges & times;
- **DeepCore**: denser configured sub-detector, can observe **GeV-scale neutrinos**.





Reconstruction

Machine learning techniques reconstruct:

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

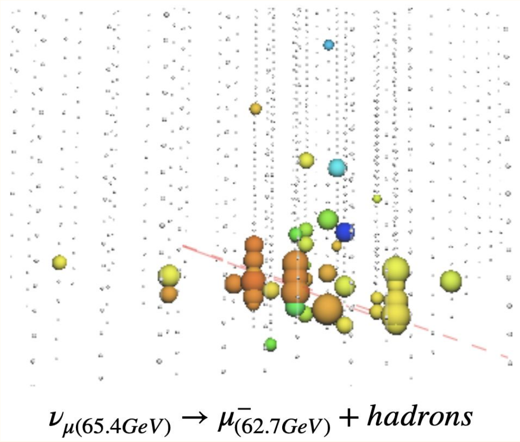
} Analysis binning

- Interaction vertex
- Atm. muon classifier

} Selections

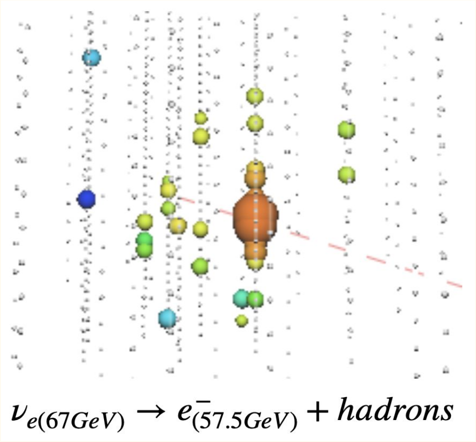
Track-like events:

ν_μ CC, 17% ν_τ CC



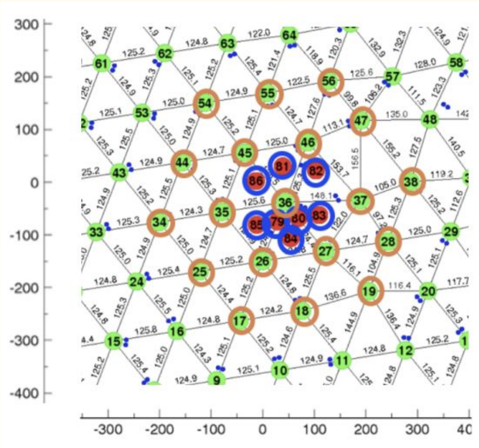
Cascade-like events:

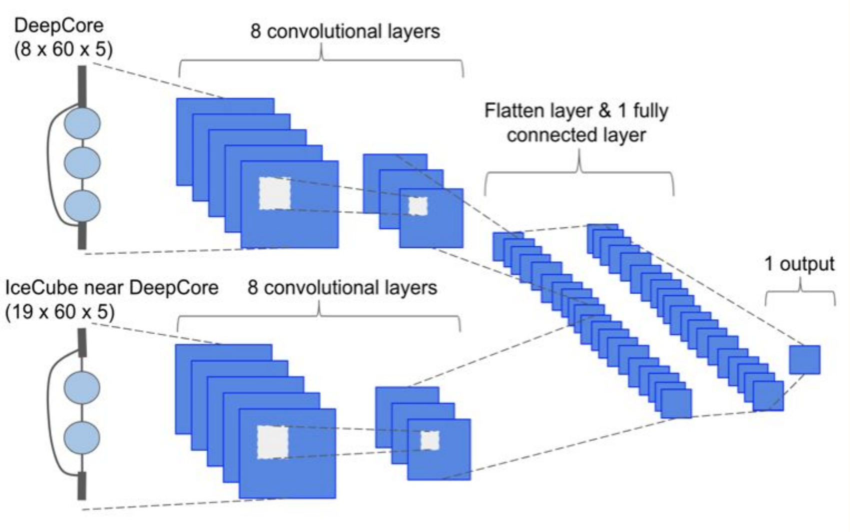
ν_e CC, NC, ν_τ CC



Convolutional Neural Networks (CNNs)

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



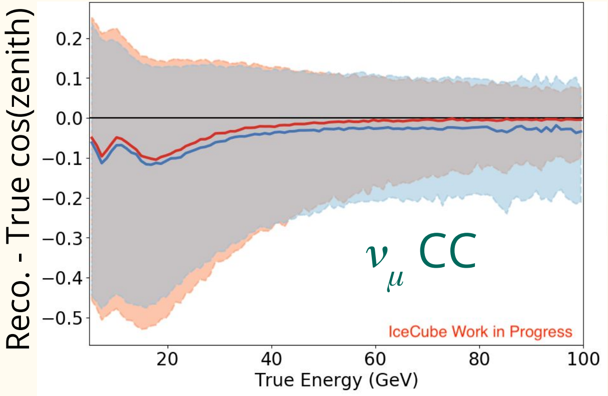


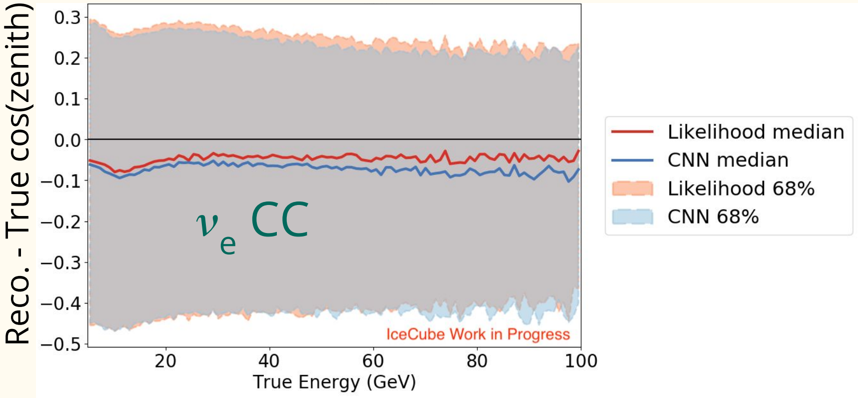
5 summarized variables per DOM:

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

Reconstruction Performance

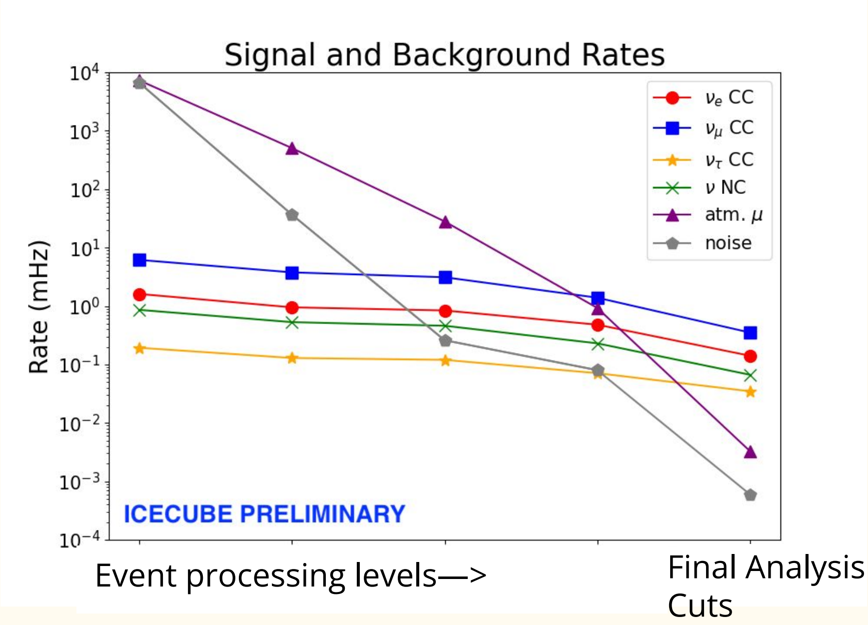
- Nominal MC with analysis cuts and flux, xsec, and oscillation weights applied;
- Comparable resolution to current (likelihood-based) method;
- *~3,000 times faster in runtime*: big advantage for full MC production of atmospheric neutrino datasets.





Preliminary Analysis Sample

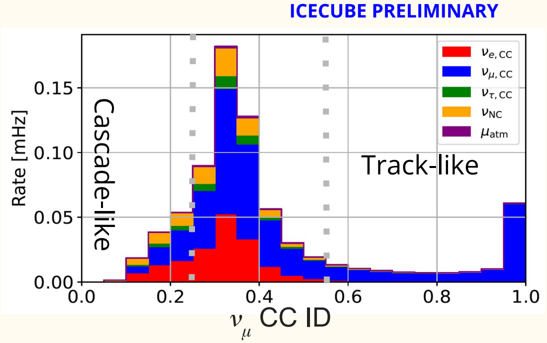
- Data taken over 3,390 days between 2012-2021;
- Total of 150,257 events;
- High signal (ν_μ CC) and low background (noise and atm. muon) rates (~0.6%):
    - Several levels of selection are applied to eliminate the primary atm. muons and noise backgrounds.

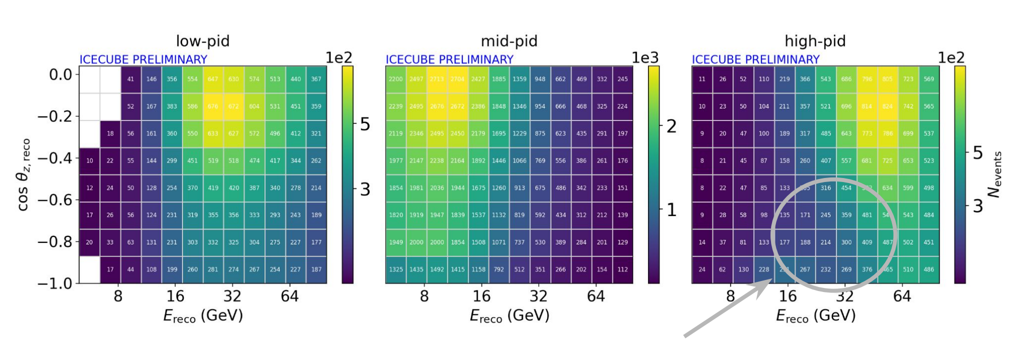


3D Binned Analysis Sample

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.



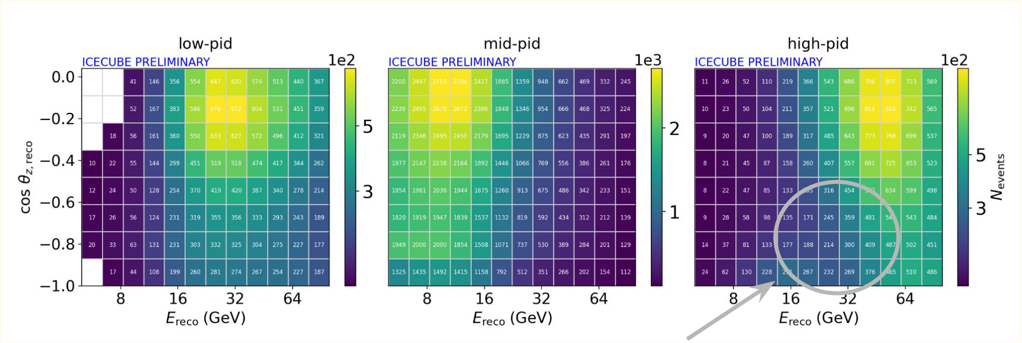


ν_μ disappearance signal

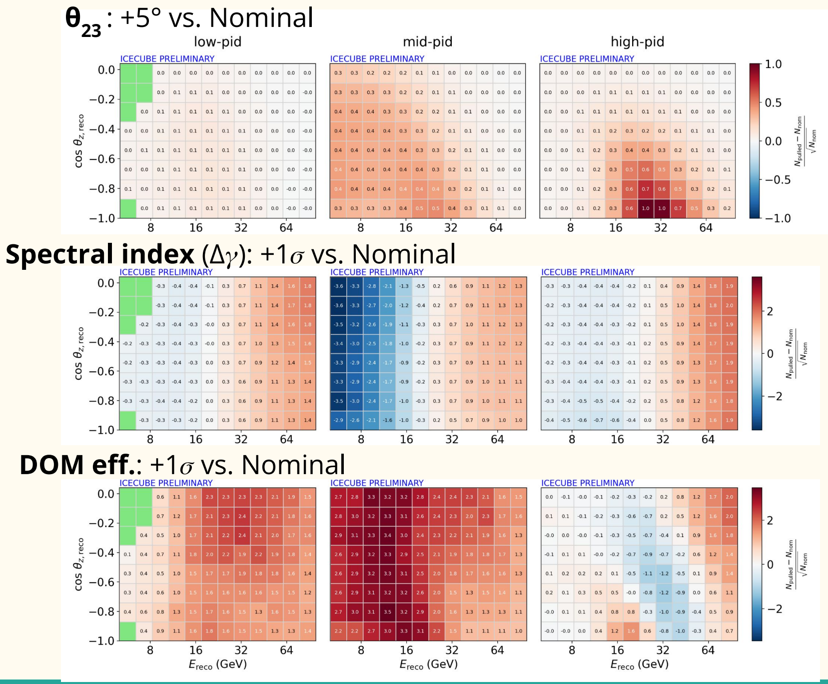
3D Binned Analysis Sample

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.

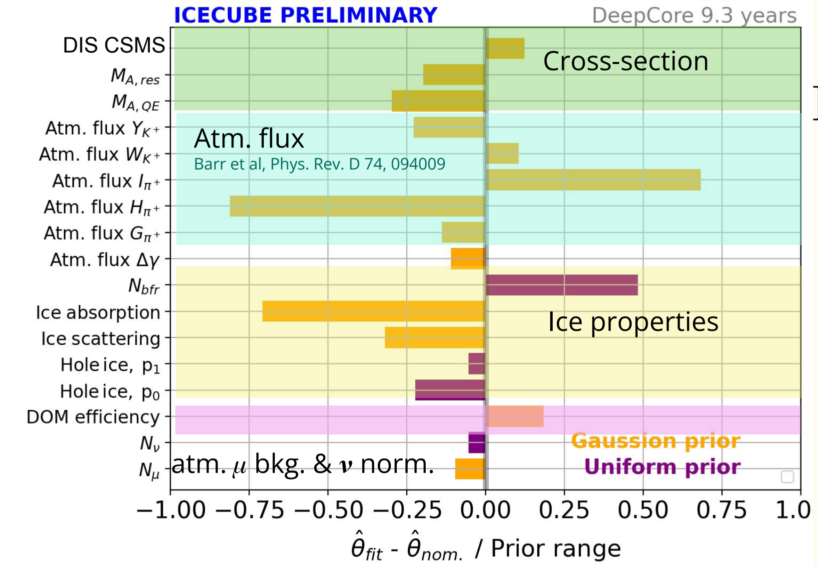


ν_μ disappearance signal



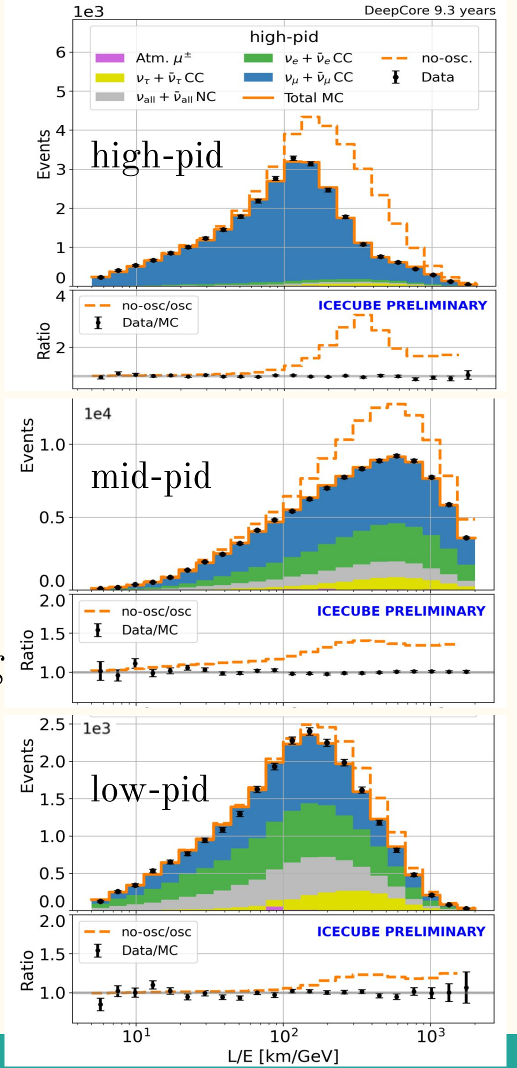
ν_μ Disappearance Analysis

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



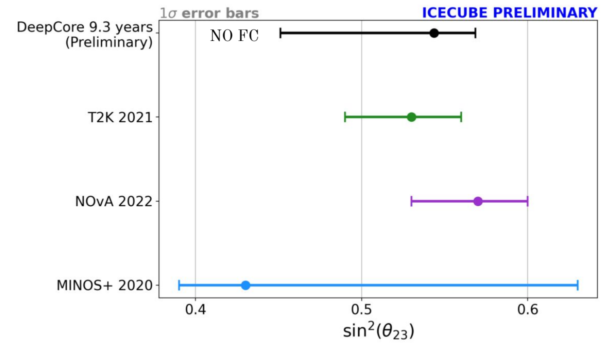
Future improvements:

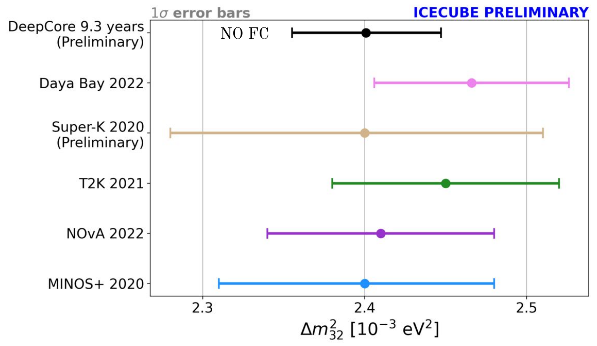
- Reduce correlations among flux uncertainties: PCA;
- Further MC improvements underway.

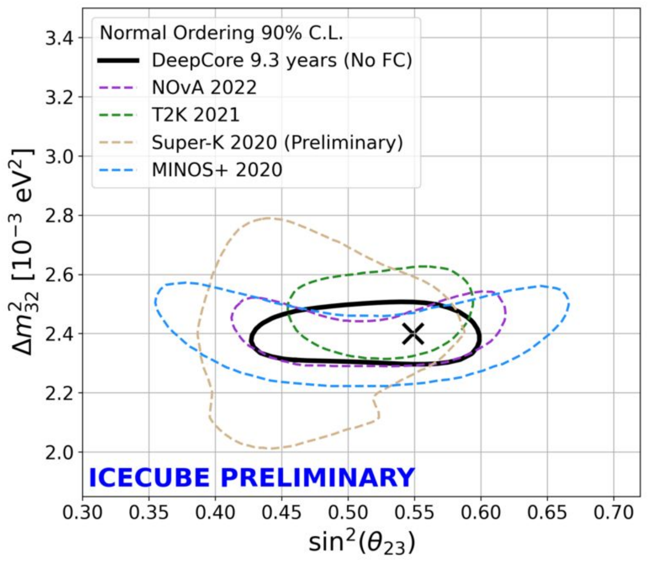


Oscillation Results

- The new result is compatible and complementary with the existing measurements:
  - Different sample and facing different systematics.
- Big updates on MC models and calibration since last publications (DeepCore 3-year).

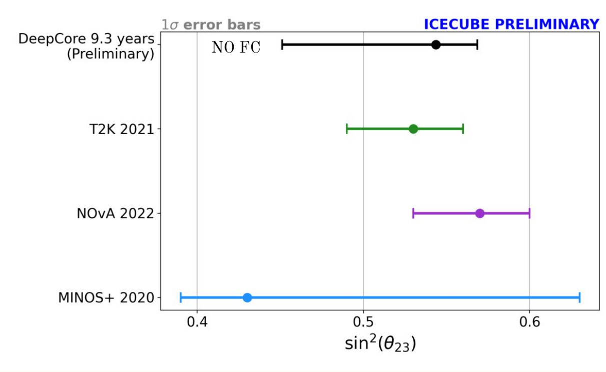


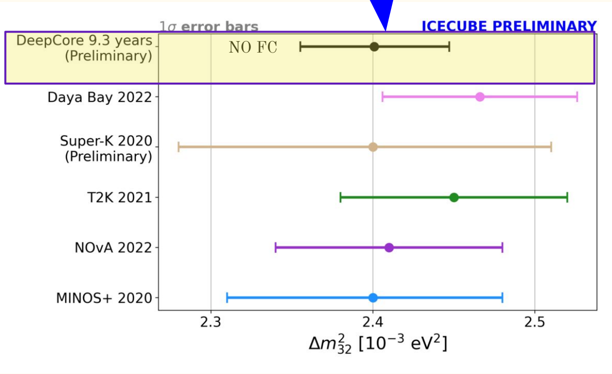


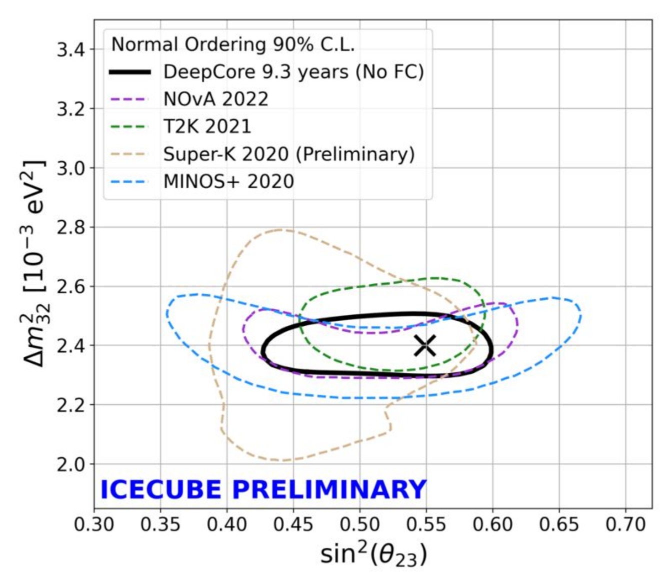


Oscillation Results

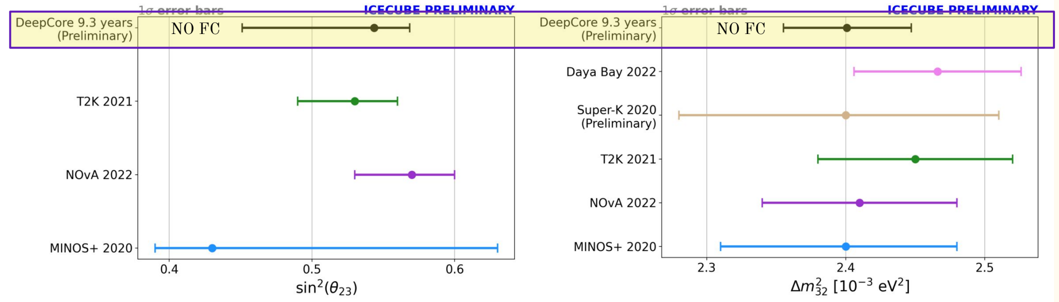
- The new result is compatible and complementary with the existing measurements.
- Competitive on Δm^2_{32} measurement.
- Room for future improvements!
  - Flux model; particle modeling; calibration, etc







Conclusion



- 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 results with the existing measurements:
  - Different sample and facing different systematics;
  - Competitive constraint on Δm^2_{32} .
- A lot of room for future improvements!
  - MC models, detector calibration, reconstruction, uncertainty modeling...
- More oscillation results using this new sample on the way!
  - Neutrino mass ordering, non-standard interactions...

Stay tuned!

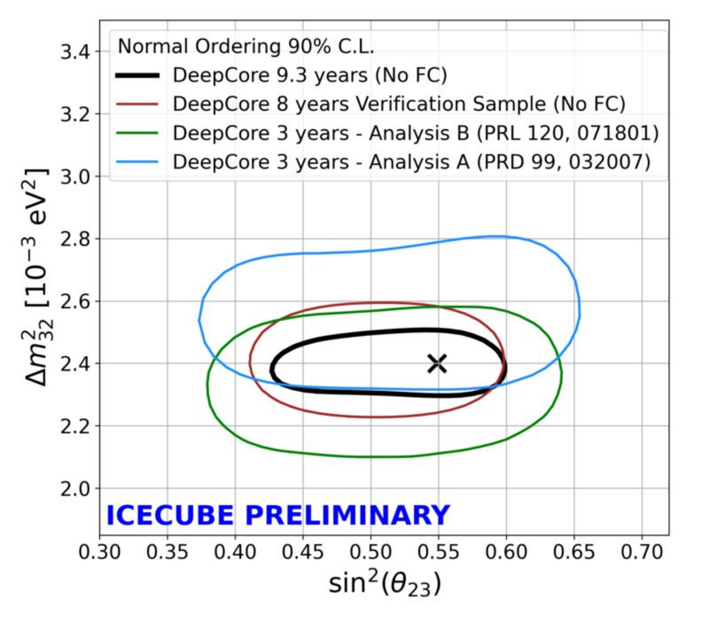
Thank you for your attention!

Hey I'm a D-Egg

Backup

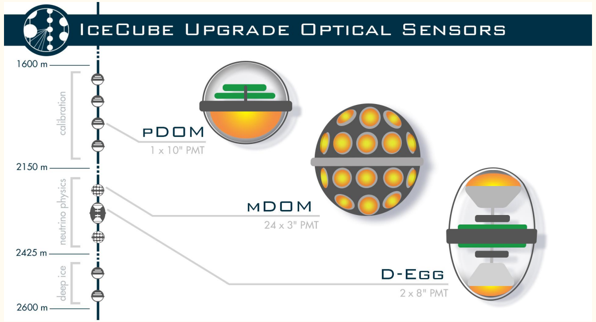
Oscillation Results

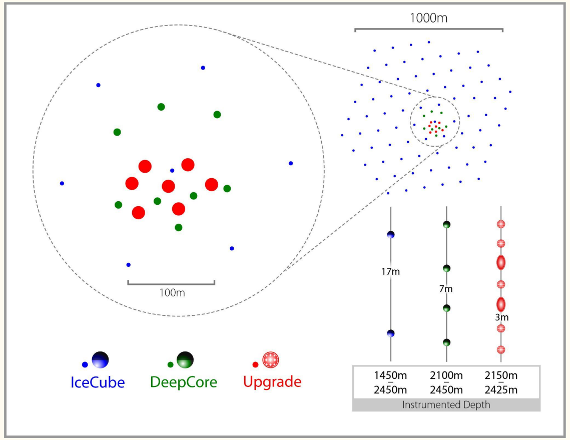
- Consistent with the previous IceCube results.
- Big updates on MC models and calibration since last publication (DeepCore 3-year).
- Compared to DeepCore 8-year result: New reconstruction, including mixed- and low-pid bins into analysis.



Future

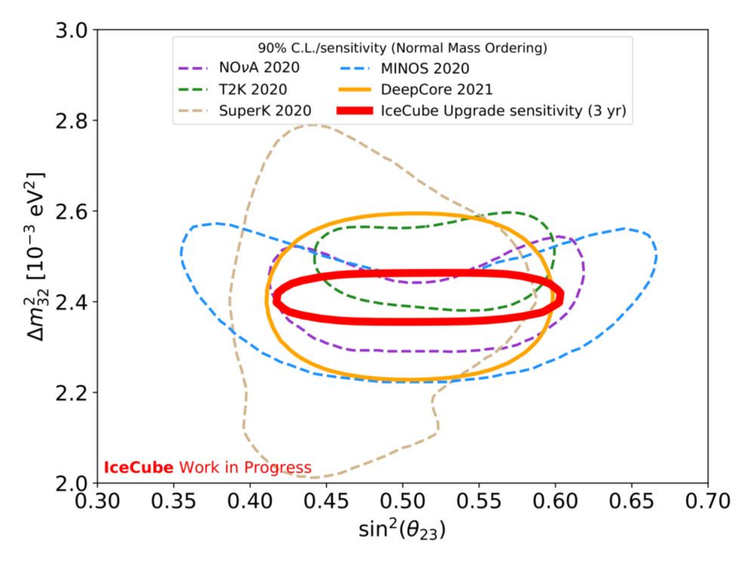
The Upgrade detector:





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

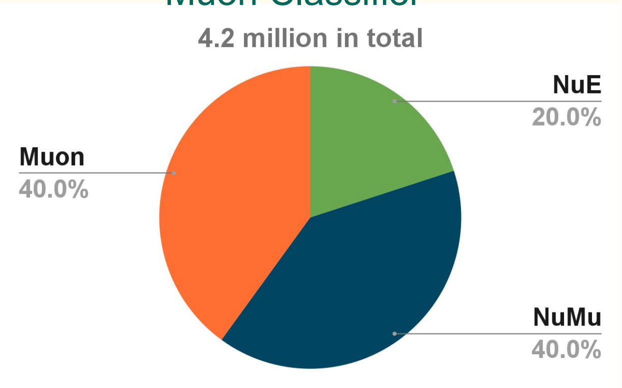
New sensitivity of Upgrade expected in summer!

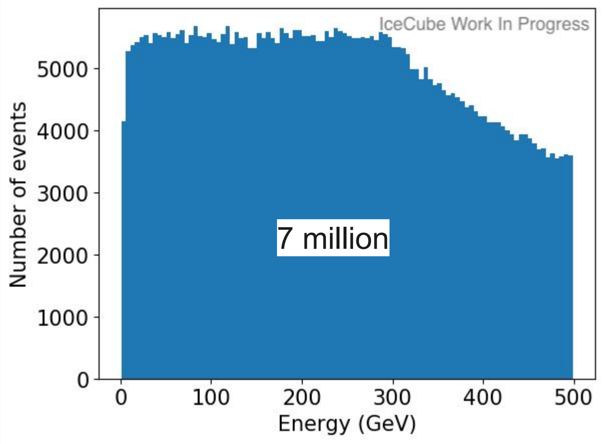


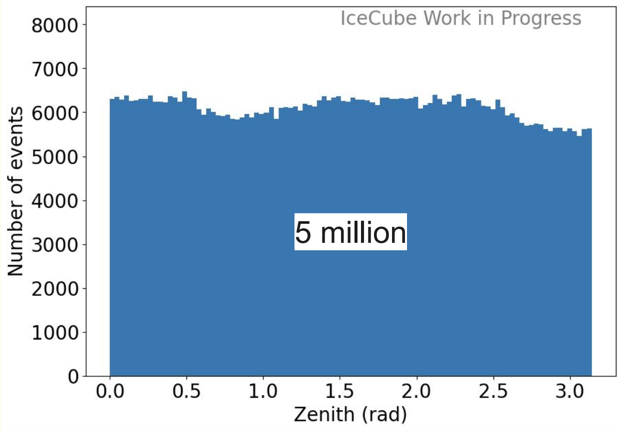
Training Samples

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

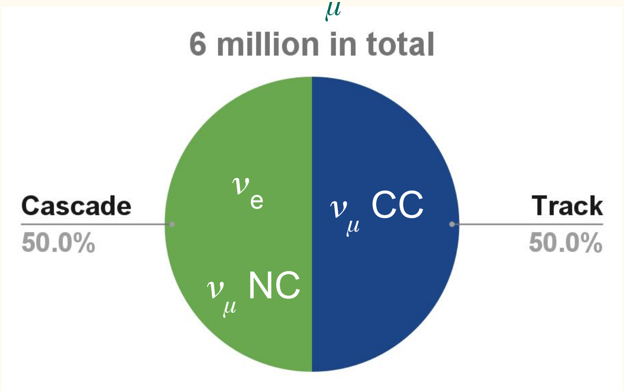
Muon Classifier







PID: ν_μ CC



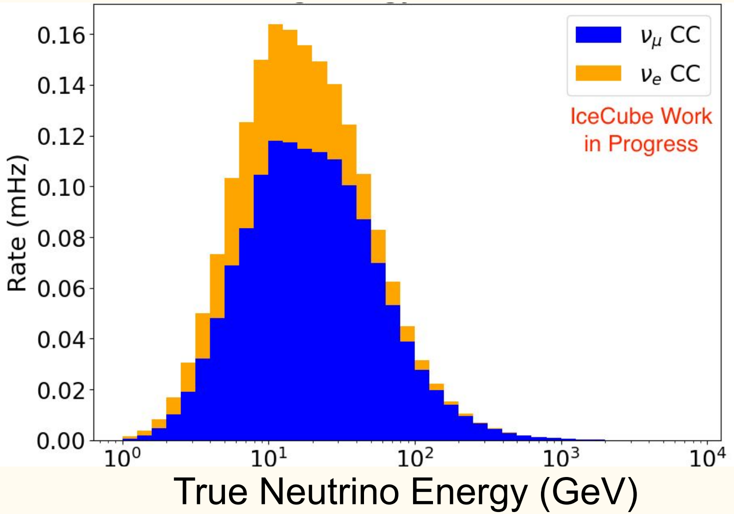
Performance: Speed

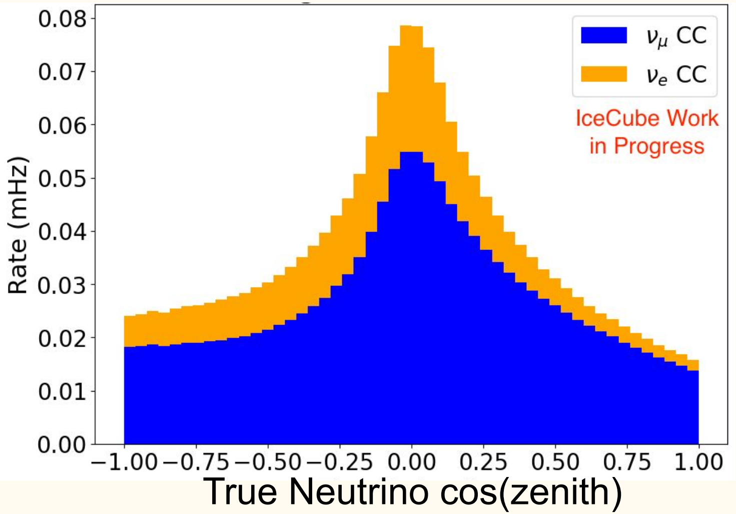
	Second per file (~3k events)	Time for full sample assuming 1000 cores
CNN on GPU	21	~ 13 minutes
CNN on CPU	45	~ 7.5 hours
Current Likelihood-based method (CPU only)	120,000	~ 46 days

- 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

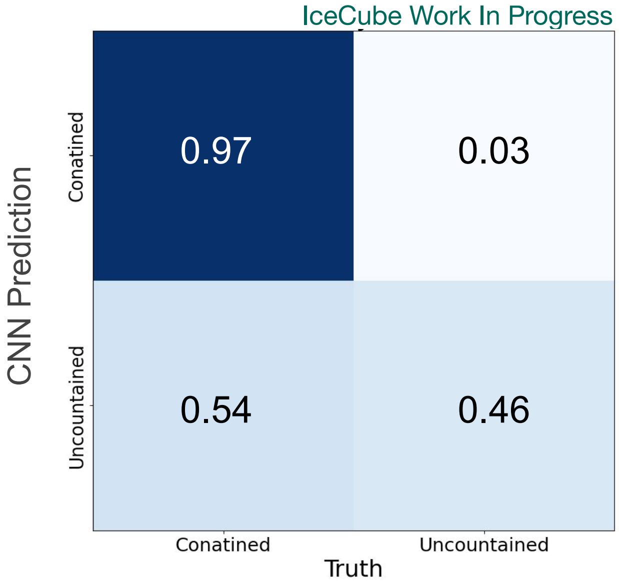
- Nominal MC sample with flux, xsec, and oscillation weights applied;
- Testing on signal (ν_μ CC) and major background (ν_e CC);
- Baseline: current reconstruction method (likelihood-based)

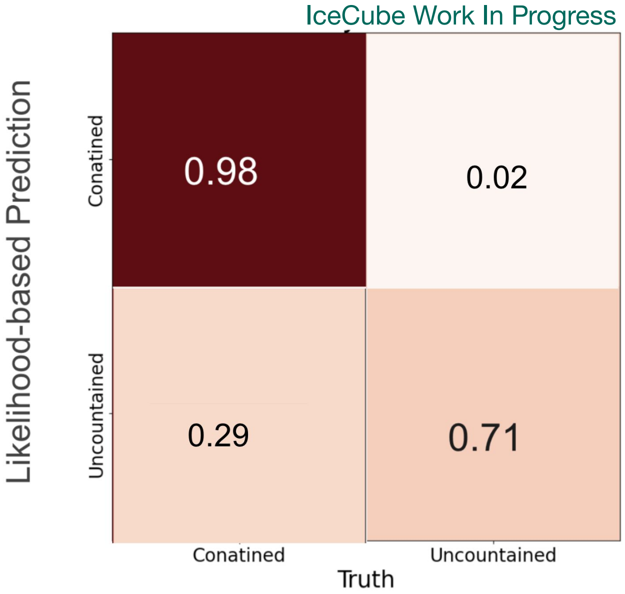




Performance: Vertex

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

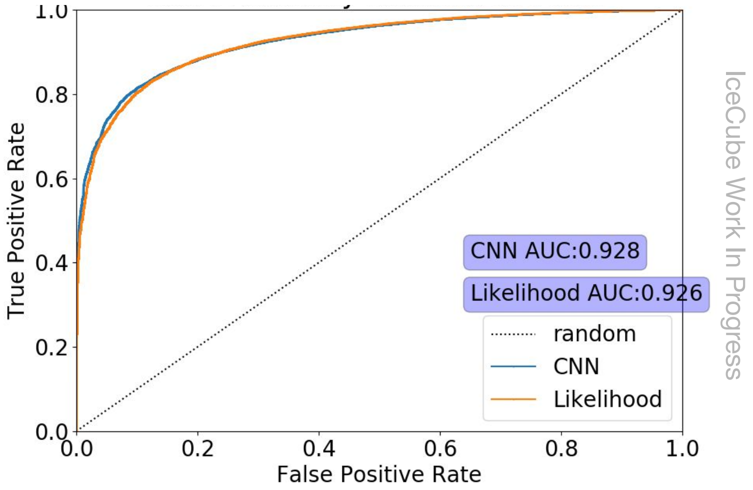




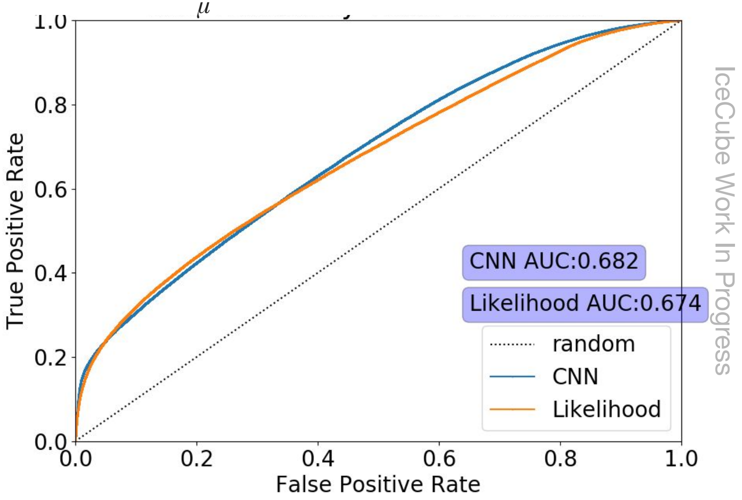
Performance: Muon and PID Classifiers

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

Muon Classifier



ν_μ CC vs. other neutrinos



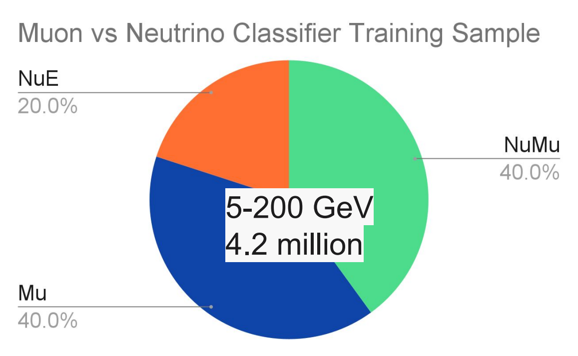
Training Samples

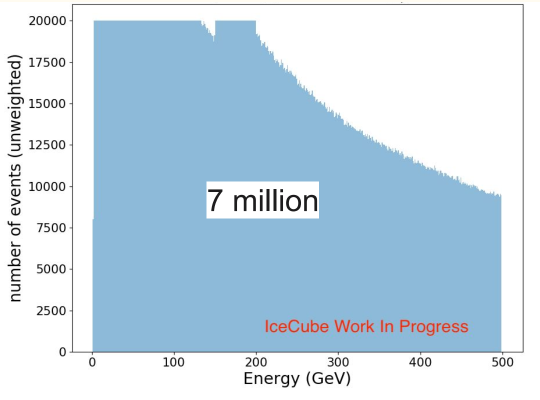
Energy: nDOM >= 7

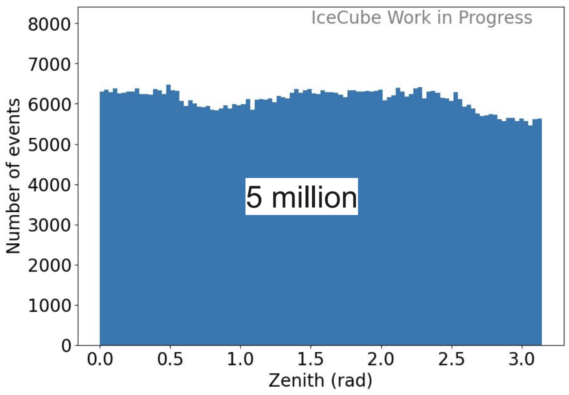
Muon : nDOM >= 4; 5–200 GeV

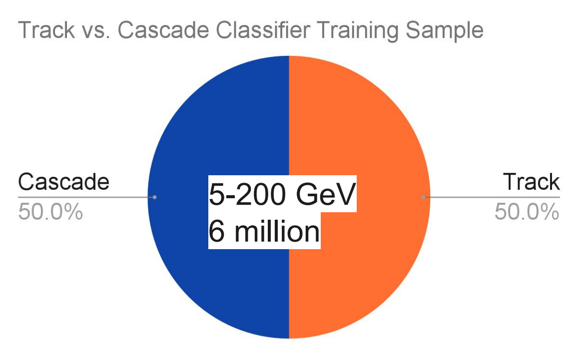
Muon, PID, Vertex: nhits >= 8 hit 5-200 GeV

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



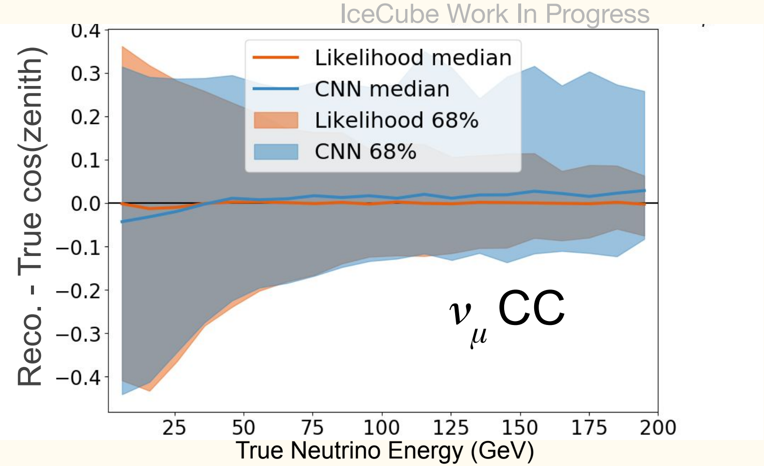


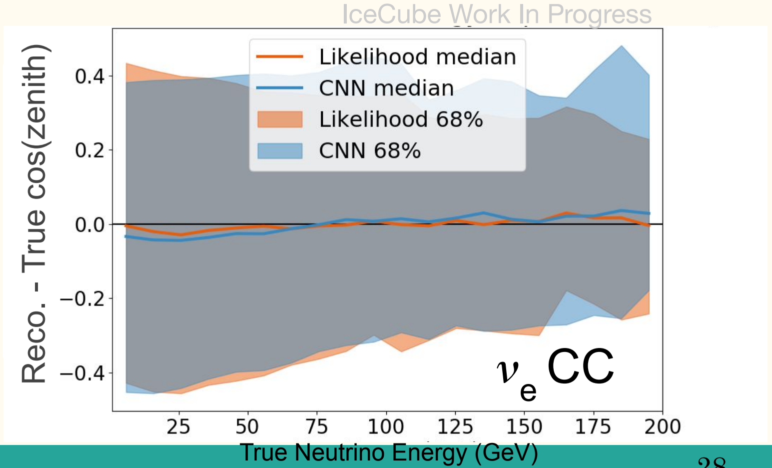




Performance: Direction

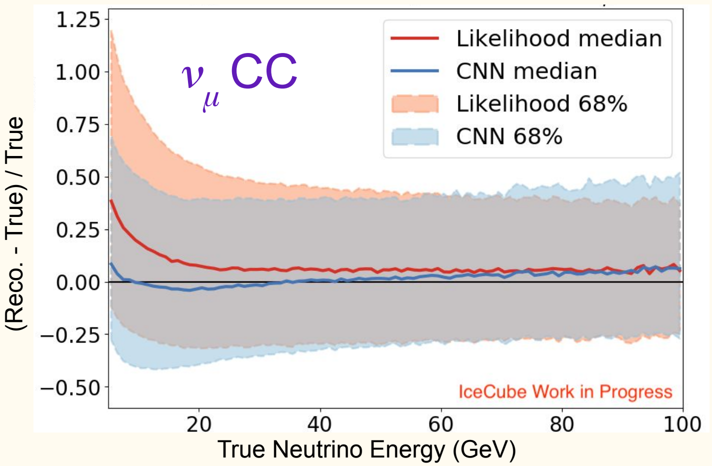
- Direction bias flat against true energy;
- Comparable to current method;
- Better resolution for ν_μ CC (signal);
- High energy (>100 GeV) neutrinos leaving DeepCore
  - Need containment cut: interaction vertex reconstruction.

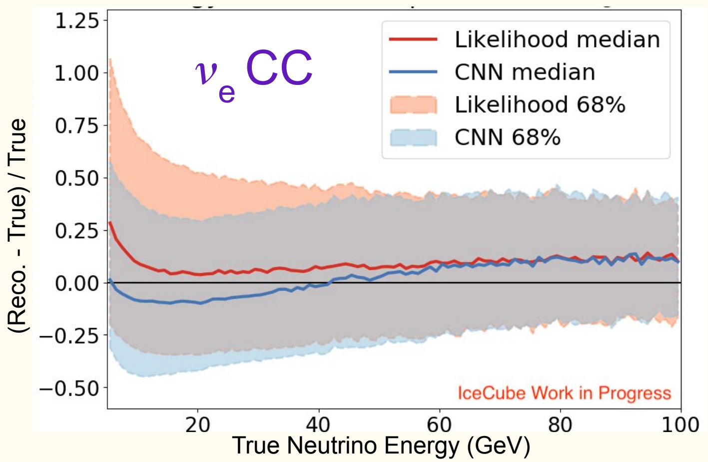




Performance: Energy

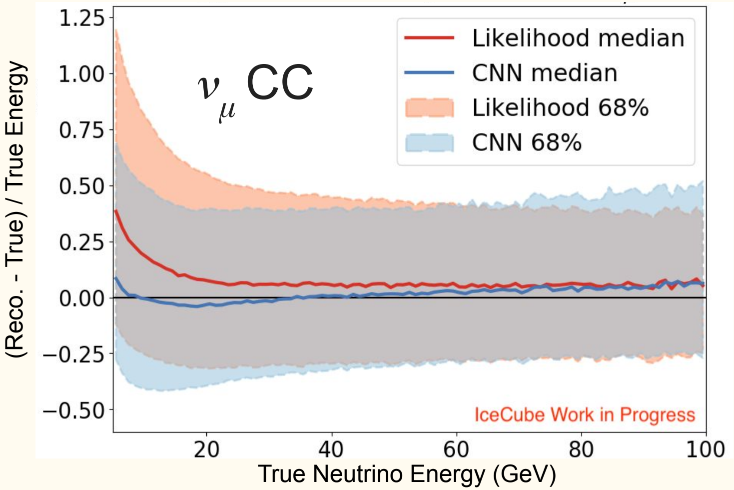
- Flat median against true neutrino energy;
  - CNN has better resolution at low energy (majority of sample)
- Comparable performance to current method at higher energy and in background;

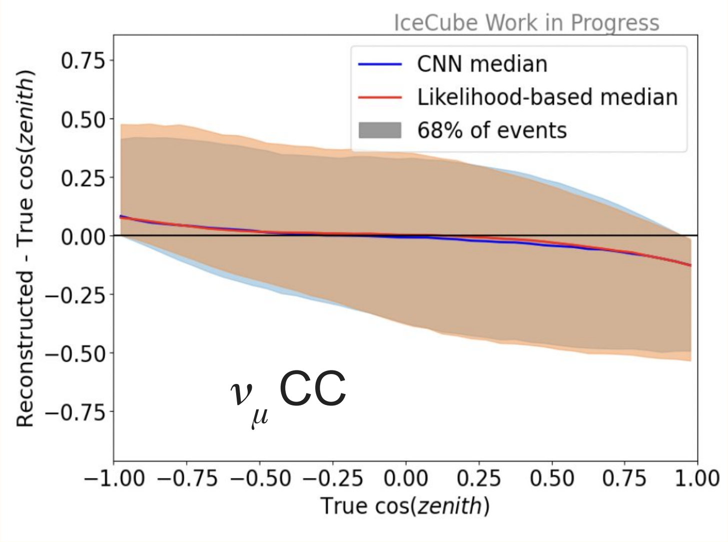




Reconstruction Performance

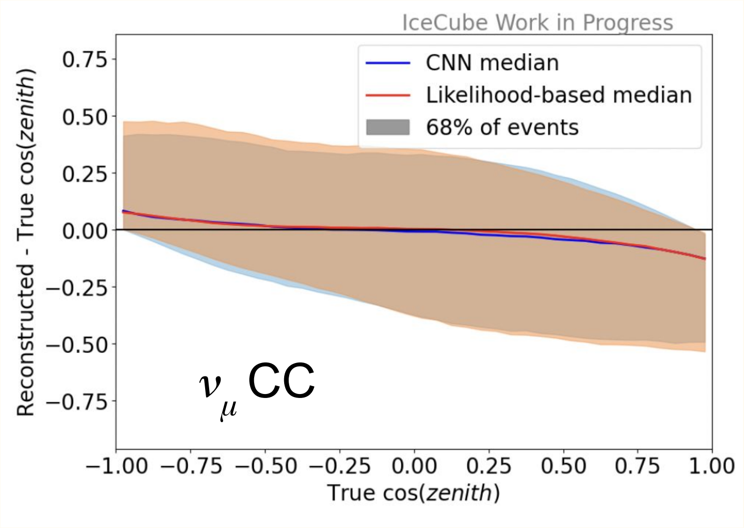
- Flat median against true neutrino energy and zenith;
- CNN has comparable resolution to current method, and better at low energy (majority of sample)

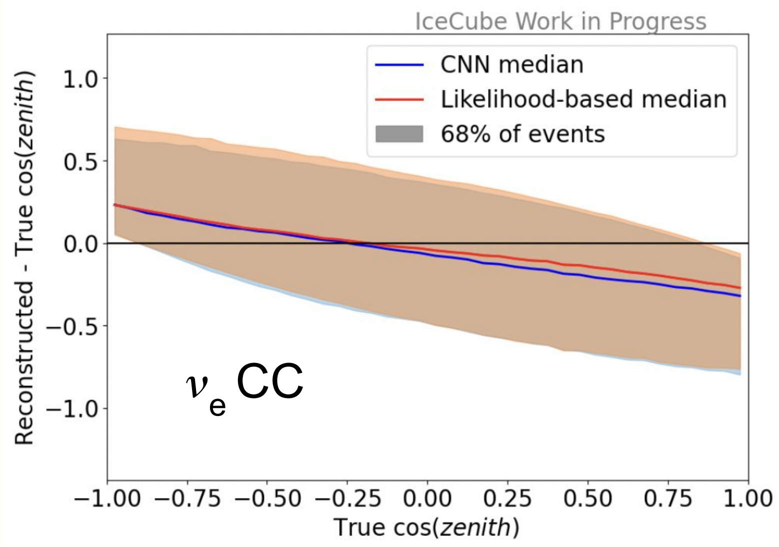




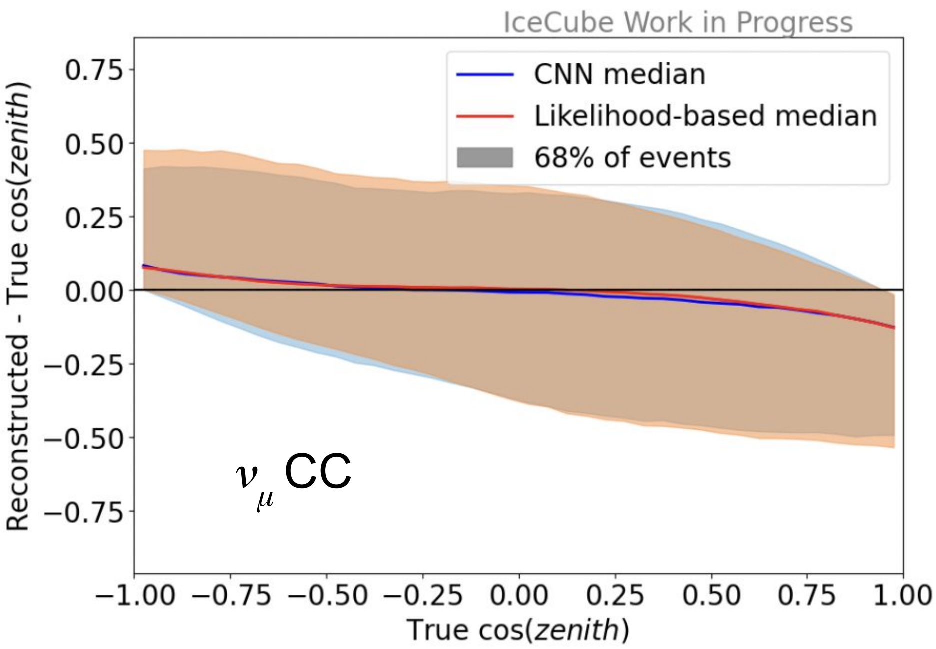
Performance: Zenith

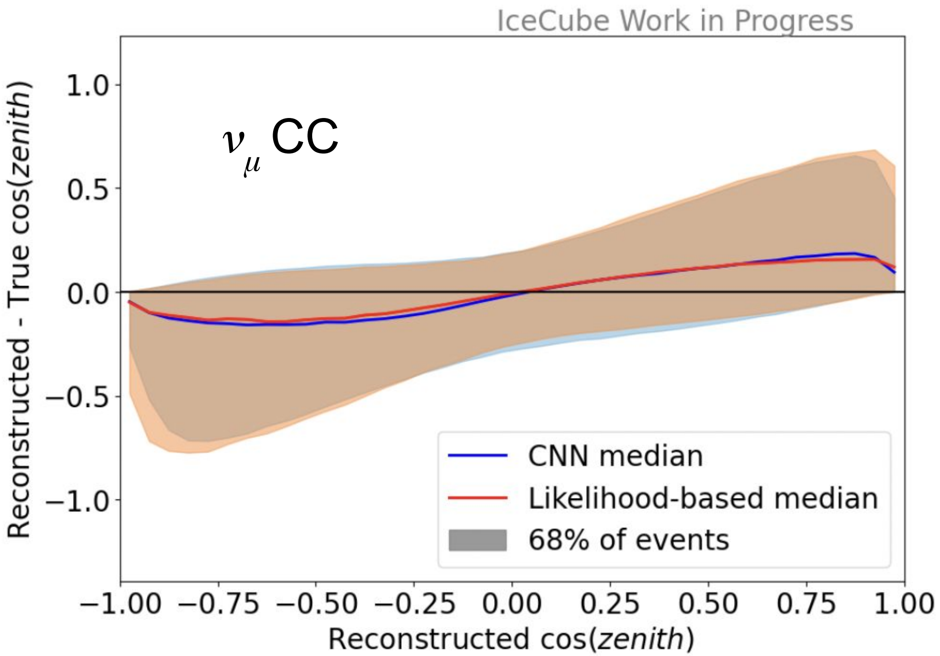
- Flat median against true direction;
- Comparable to current method in both signal and background.





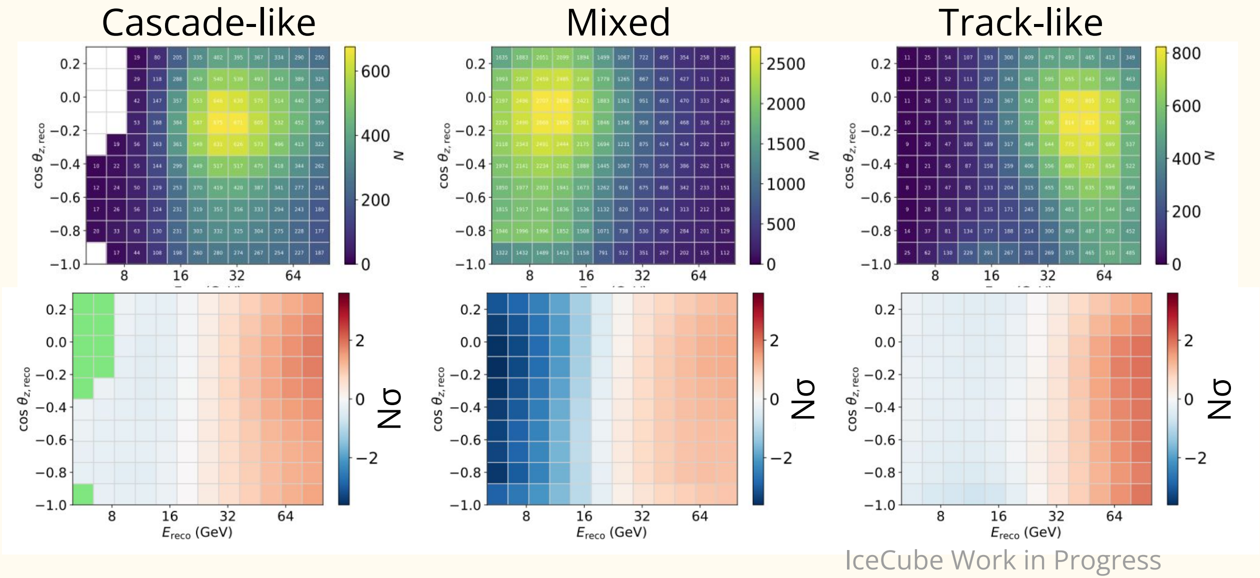
Performance: Zenith (Contained, 5-300 GeV Sample)





Systematic Effect: Neutrino Flux Model

Neutrino flux spectral index variation has different signature to expected oscillation signal



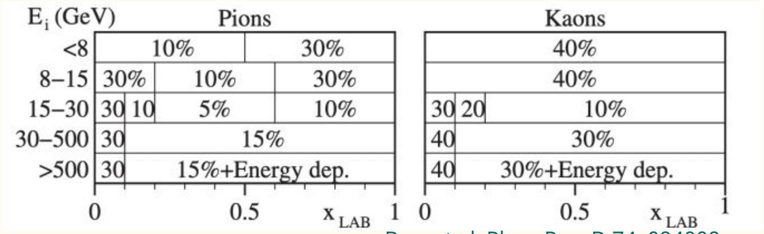
Fit for spectral index among other model systematics

$$N_\sigma = \frac{N_{\text{pulled}} - N_{\text{nominal}}}{\sqrt{N_{\text{nominal}}}}$$

Flux model systematic: Neutrino flux spectral index changed by +1**σ**

Systematic Uncertainty Consideration

- Flux uncertainty
  - Pion & Kaon production uncertainties



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