For the IceCube Collaboration

New Measurement of Muon Neutrino Disappearance from the IceCube Experiment

Finn Mayhew, Shiqi Yu

Michigan State University

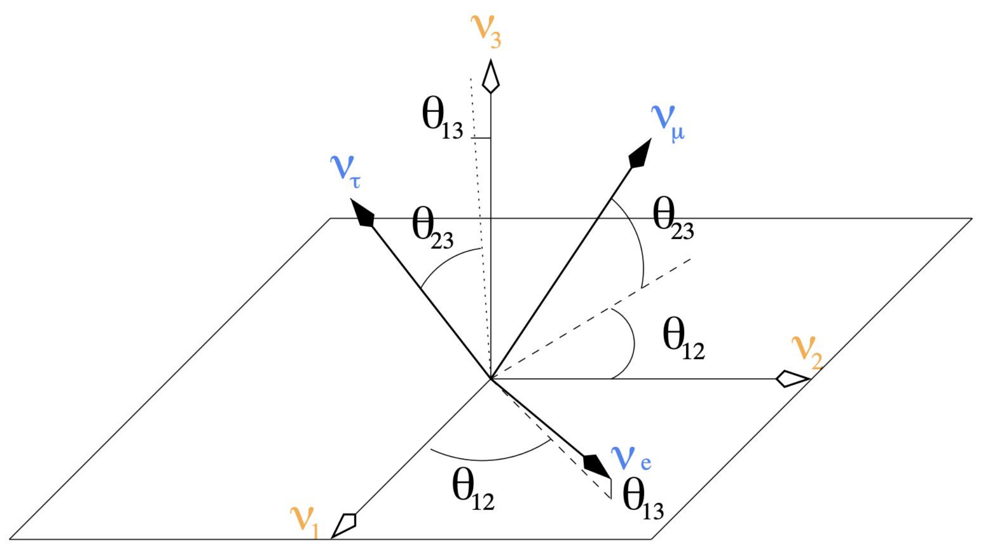
DIS2023, March 28th, 2023

Presentation Outline

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

Neutrino Oscillation

- Neutrinos come in
  - **mass states** ν_1, ν_2, ν_3 — eigenstates of the Hamiltonian
  - **flavor states** ν_e, ν_μ, ν_τ — eigenstates of the weak interaction



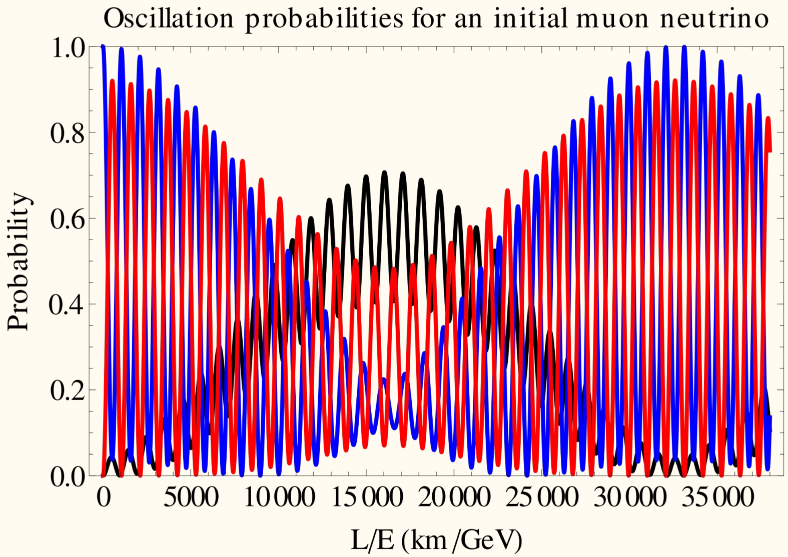
Neutrino Oscillation

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m^2 L}{E}\,\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

(two-flavor approximation)

- Neutrinos travel as their mass states and interact as their flavor states $\Rightarrow$ probability of a neutrino being detected as a given flavor state **oscillates** over the neutrino's flight

(for example)



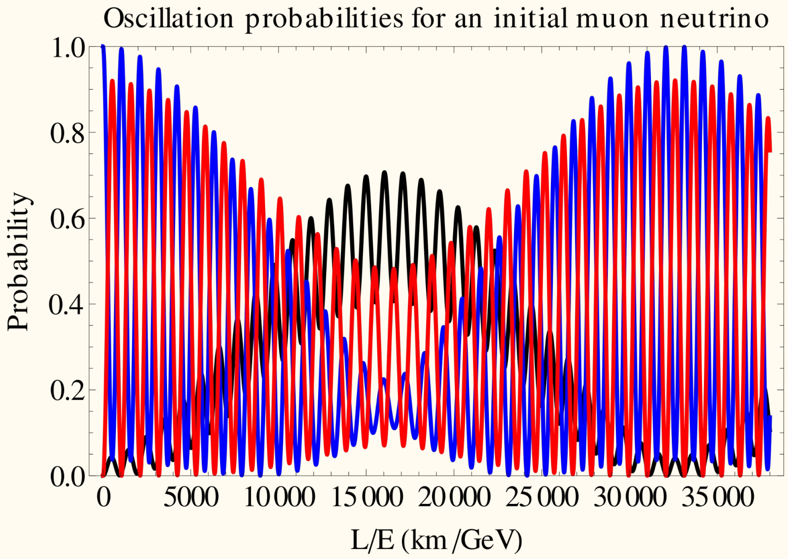
Red = ν_τ, Blue = ν_μ, Black = ν_e

Neutrino Oscillation

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\,\frac{\Delta m^2 L}{E}\,\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

(two-flavor approximation)

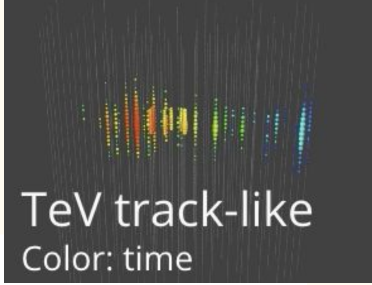
- Reconstruct **energy**, **baseline**, and **flavor** of neutrinos from detector data
- This information constrains the oscillation parameters $\sin^2\theta_{23}$ and $\Delta m^2{}_{32}$ (the ones atmospheric experiments are most sensitive to)

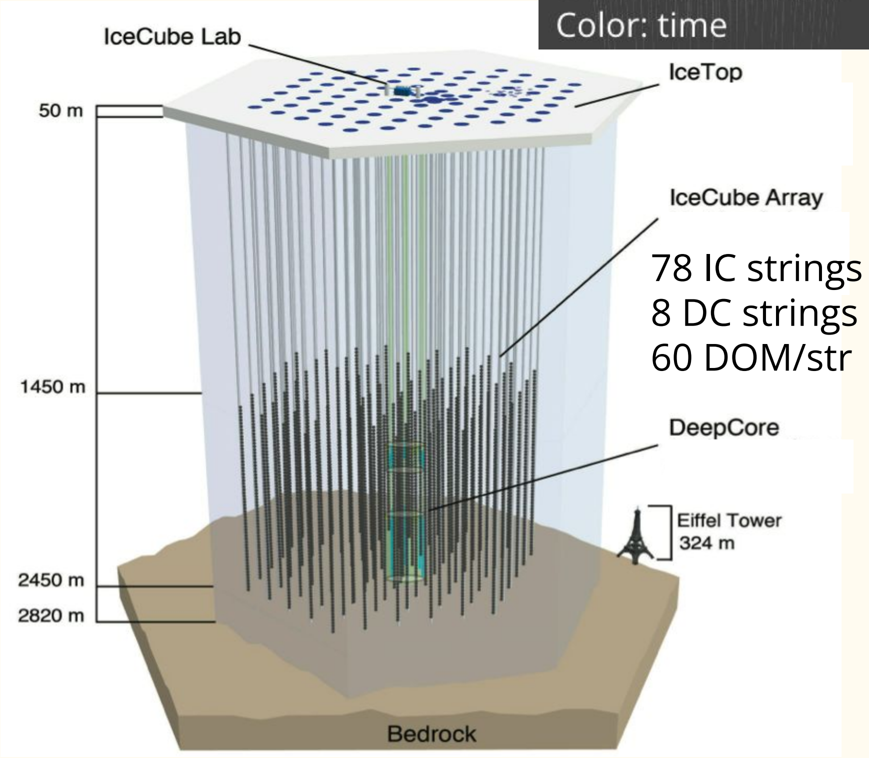


Red = ν_τ, Blue = ν_μ, Black = ν_e

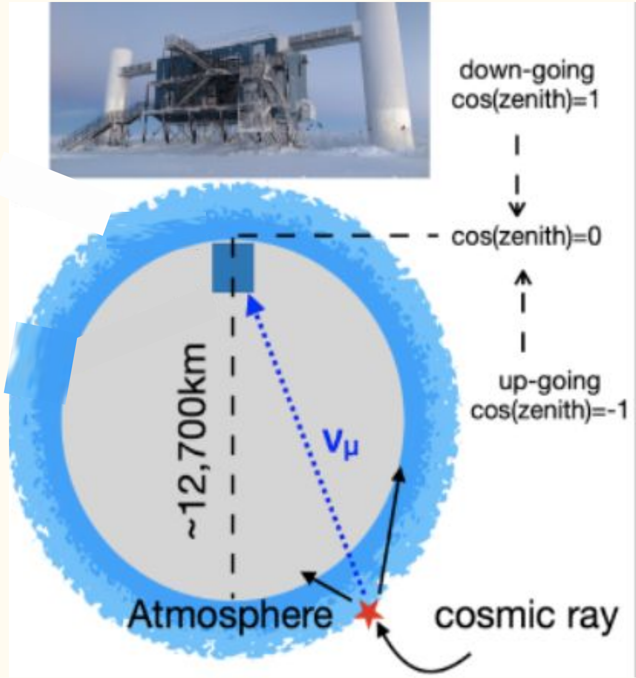
IceCube Neutrino Observatory

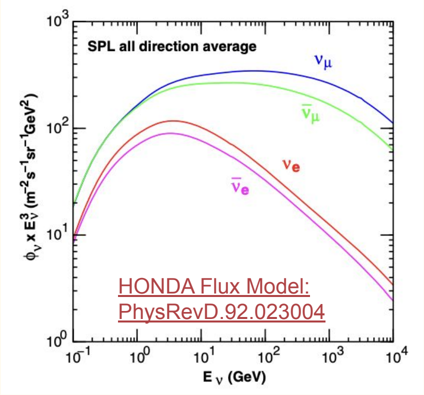
- 1 km^3 neutrino detector deep under South Pole ice;
- 5160 digital optical modules (DOMs) detect Cherenkov photons emitted during neutrino interactions;
- DOMs record pulse charges & times;
- **DeepCore**: denser configured sub-detector, can observe **GeV-scale neutrinos**.





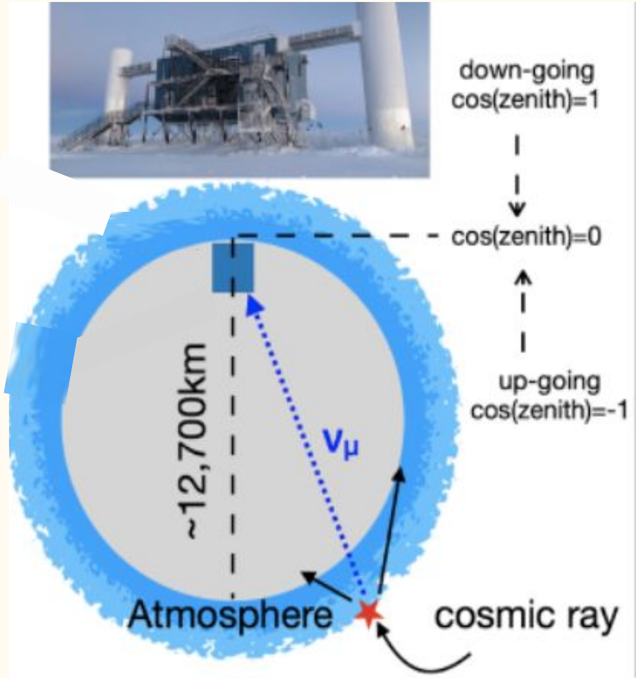
ν_μ Disappearance with IceCube





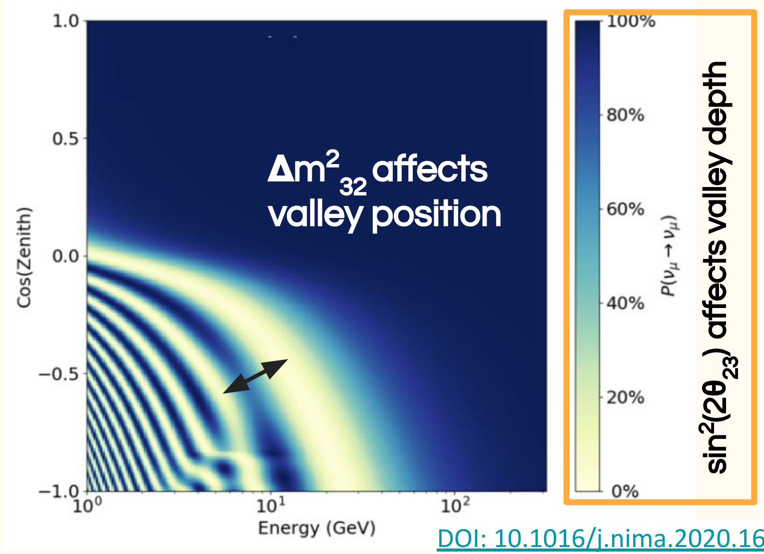
- **Atmospheric muon neutrinos** from cosmic ray interactions:
  - Wide ranges of both energy (E) and baseline (L), and largest values.

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



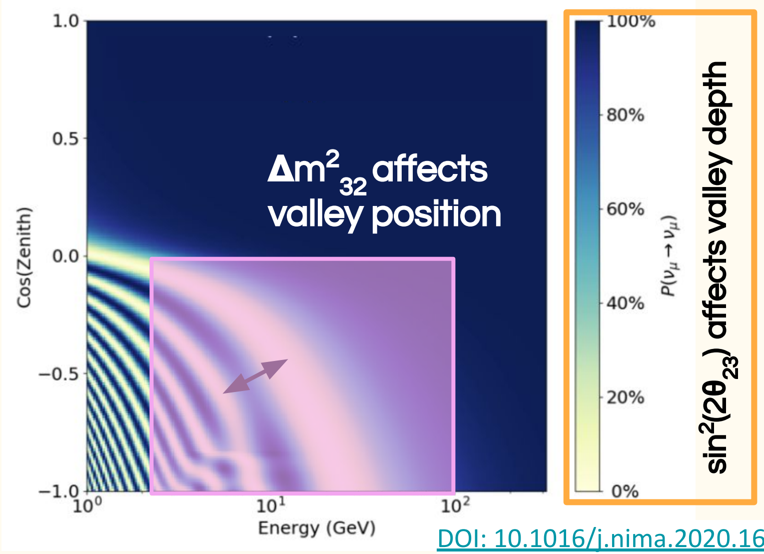
DOI: 10.1016/j.nima.2020.164332

- **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.):

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

Reconstruction

Machine learning techniques reconstruct:

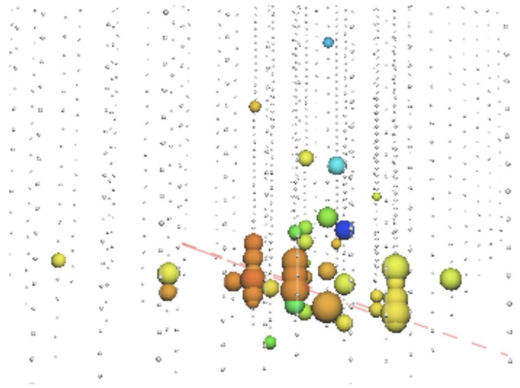
- Energy
- Direction (L)
- PID: ν_μ CC vs. others

} Analysis binning

- Interaction vertex
- Atm. muon classifier

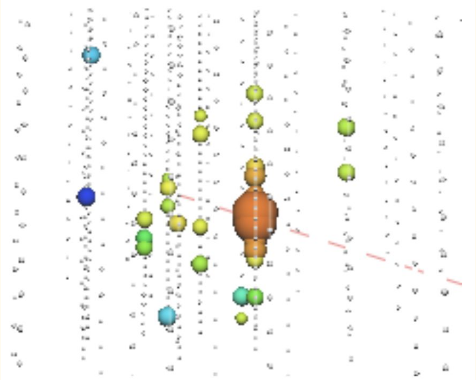
} Selections

Track-like events:
ν_μ CC, 17% ν_τ CC



$\nu_{\mu(65.4GeV)} \rightarrow \mu^-_{(62.7GeV)} + hadrons$

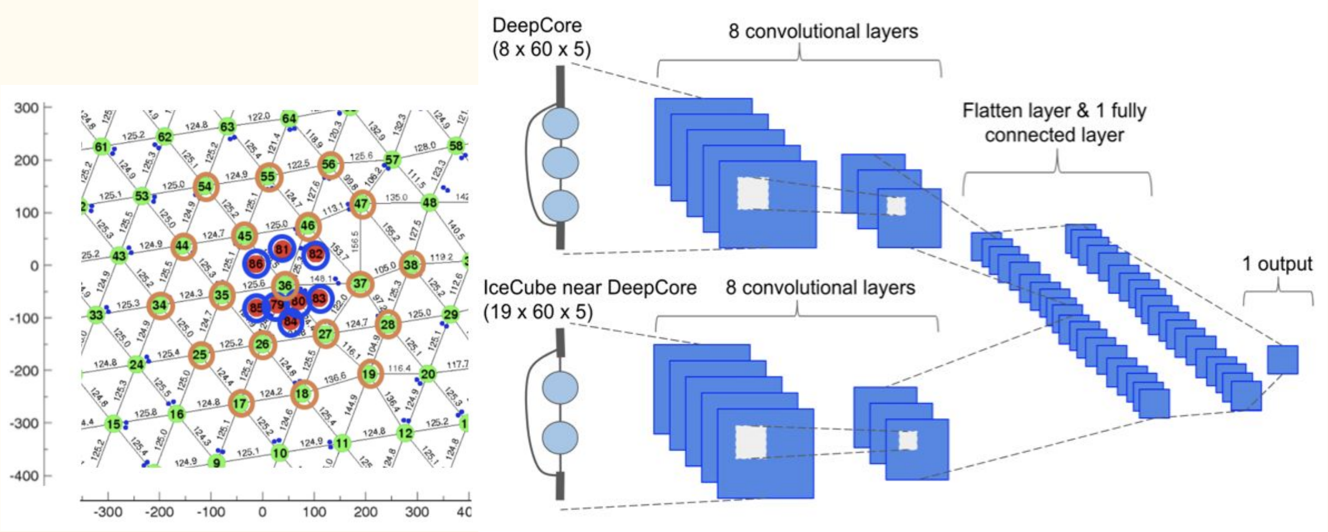
Cascade-like events:
ν_e CC, NC, ν_τ CC



$\nu_{e(67GeV)} \rightarrow e^-_{(57.5GeV)} + hadrons$

Convolutional Neural Networks (CNNs)

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



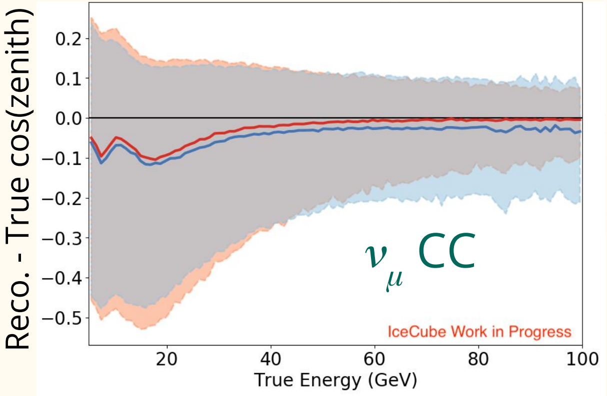
5 summarized variables per DOM:

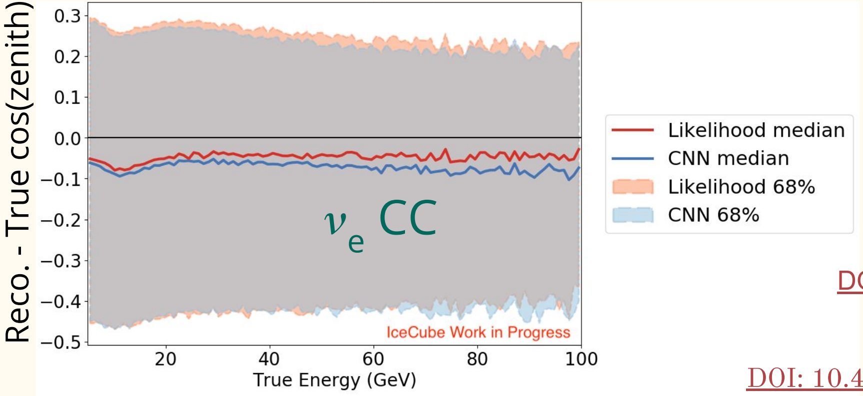
- sum of charges
- time of first (last) pulse
- charge weighted mean (std.) of times of pulses

DOI: 10.22323/1.395.1053

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.



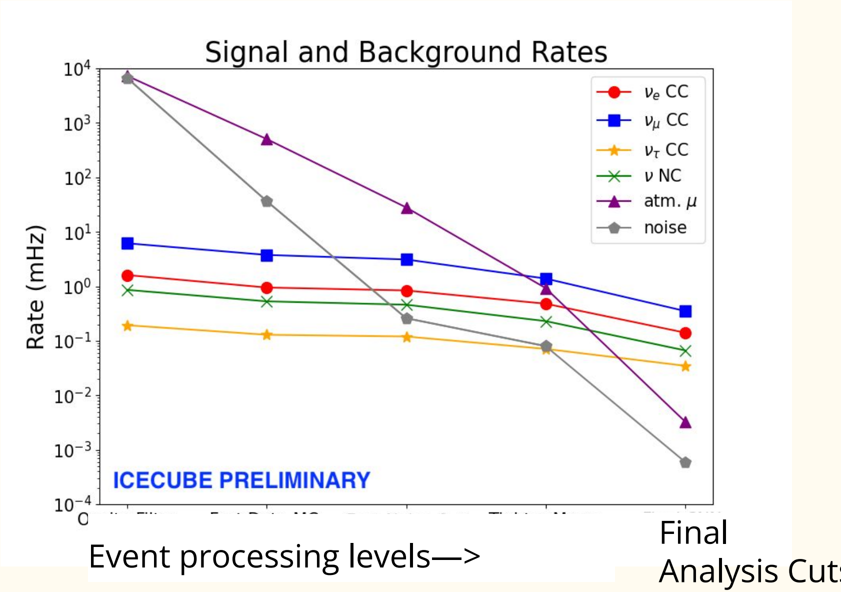


CNN-based method:
DOI: 10.22323/1.395.1053

Likelihood-based method:
DOI: 10.48550/arXiv.2203.02303

Preliminary Analysis Sample

- Data taken over 3,390 days between 2012-2021;
- Selections are applied to eliminate primary backgrounds (noise and atm. muon) : shared by all the oscillation analyses
- After final analysis cuts:
  - Total of 150,257 neutrino candidates;
  - High signal (ν_μ CC) and low background rates (~0.6%):

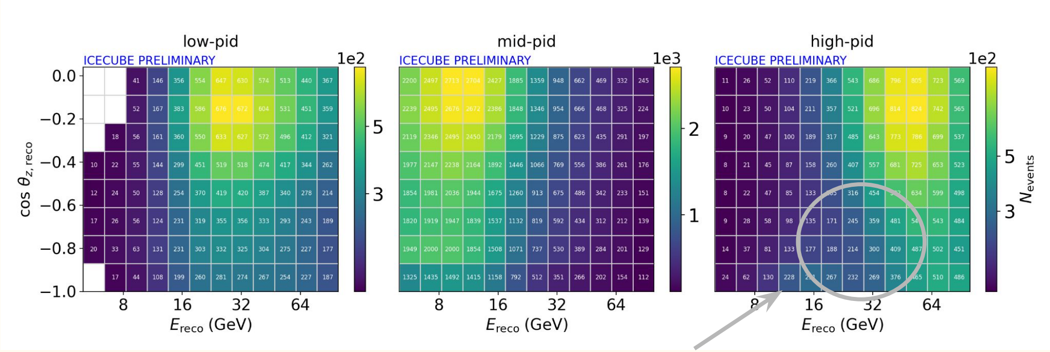


3D Binned Analysis Sample

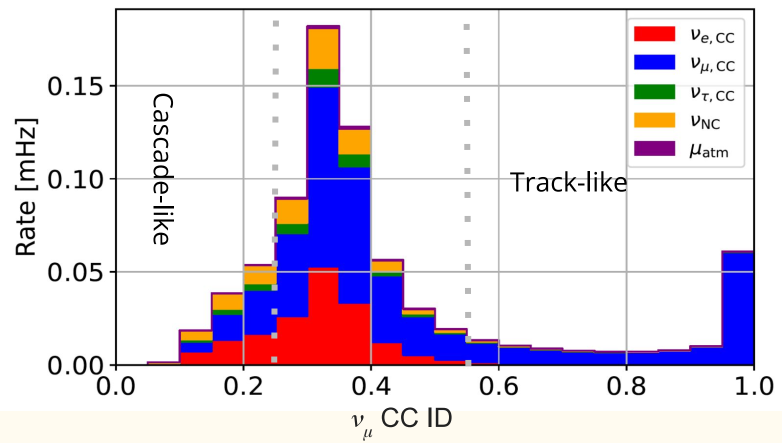
Measure 3D distortions in reconstructed [energy, cos(zenith), PID]:

- PID discriminates ν_μ CC vs. neutrino bkgs;
    - 27,352 track-like; 22,963 cascade-like candidates.

ICECUBE PRELIMINARY



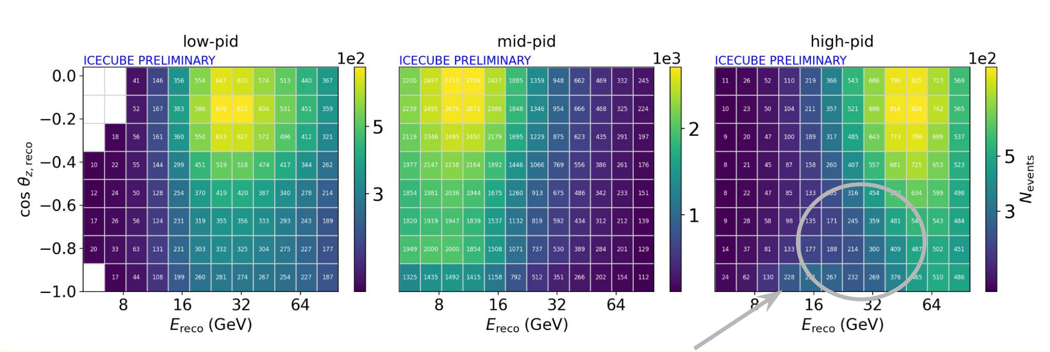
ν_μ disappearance signal



3D Binned Analysis Sample

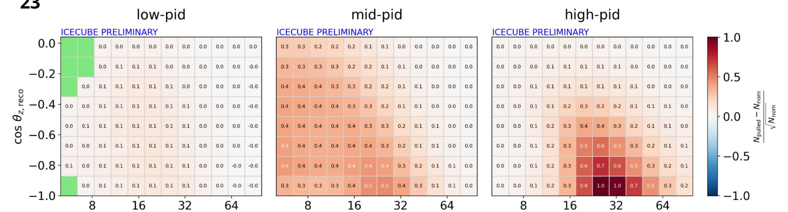
Measure 3D distortions in reconstructed [energy, cos(zenith), PID]:

- PID discriminates ν_μ CC vs. neutrino bkgs;
- Robust against systematic uncertainties.

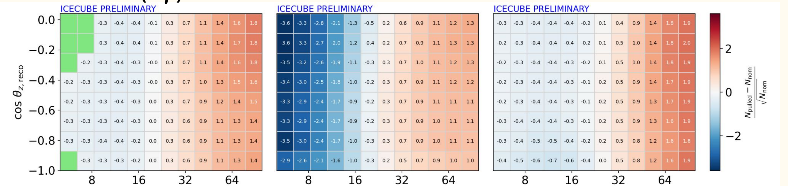


ν_μ disappearance signal

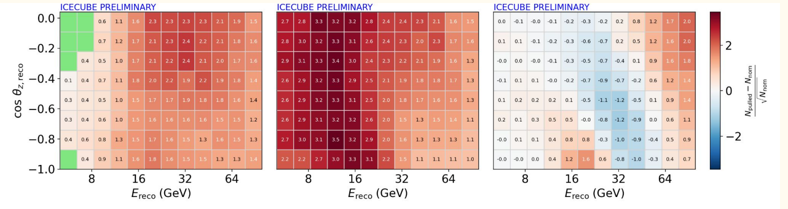
θ_{23}: +5° vs. Nominal



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

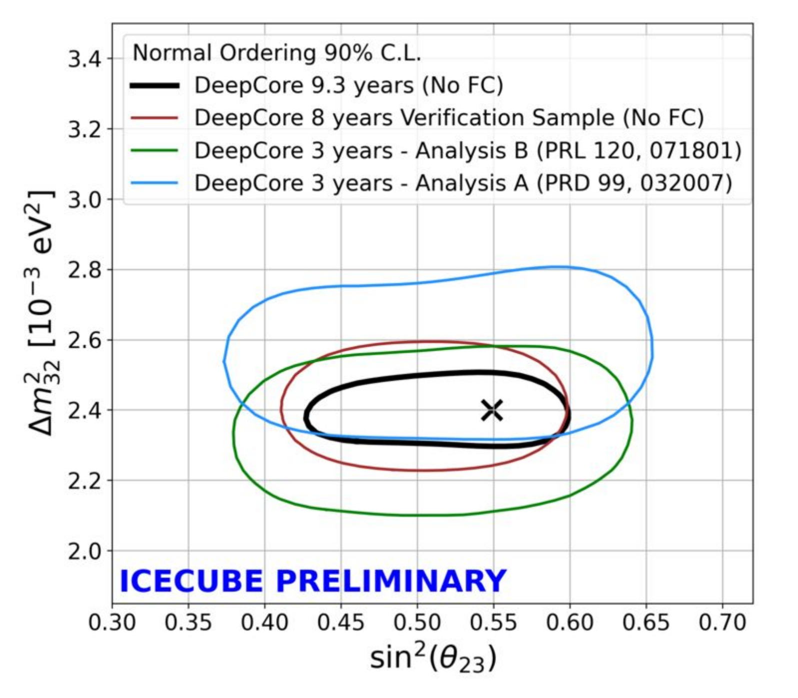


DOM eff.: +1σ vs. Nominal



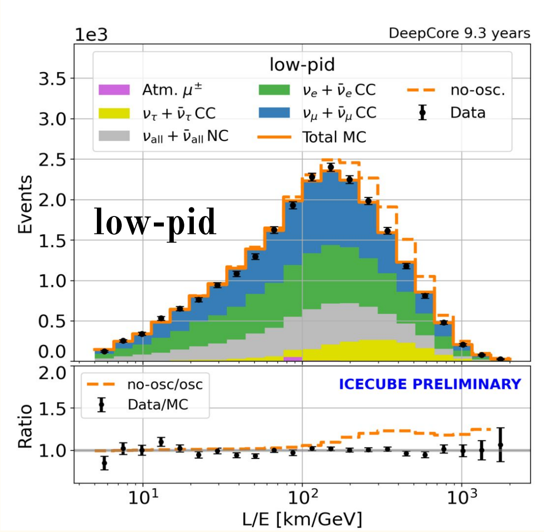
Oscillation Results

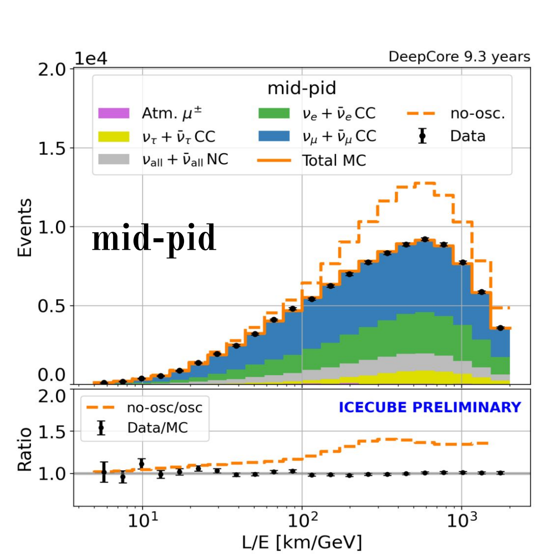
- Consistent with the previous IceCube results.
- Big updates on MC models and calibration since last publication (DeepCore 3-year).
- Compared to DeepCore 8-year result: New reconstruction, including mixed- and low-pid bins into analysis.

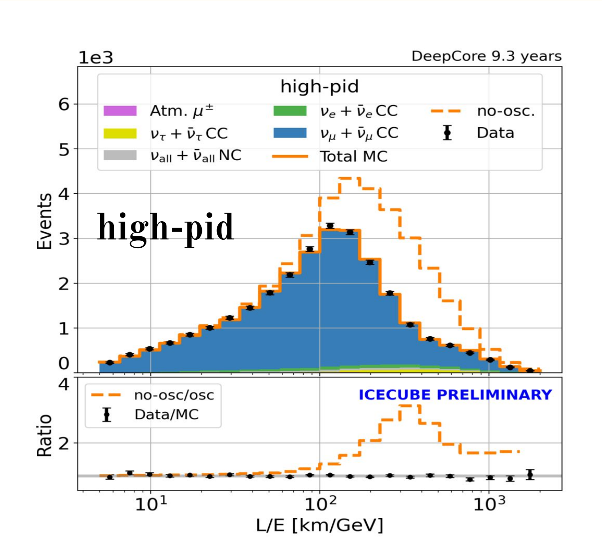


ν_μ Disappearance Analysis

- Overall good data/MC agreement;
- Most outstanding oscillation effect is in high-pid bin.

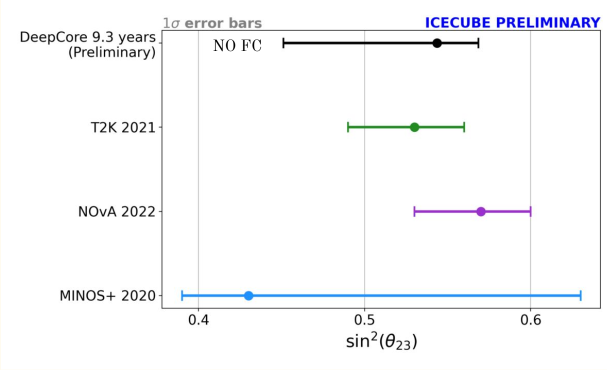


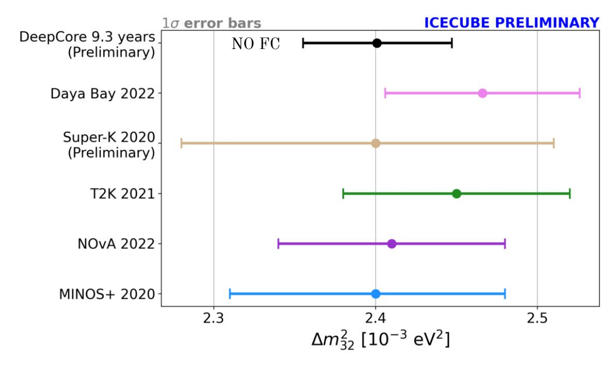


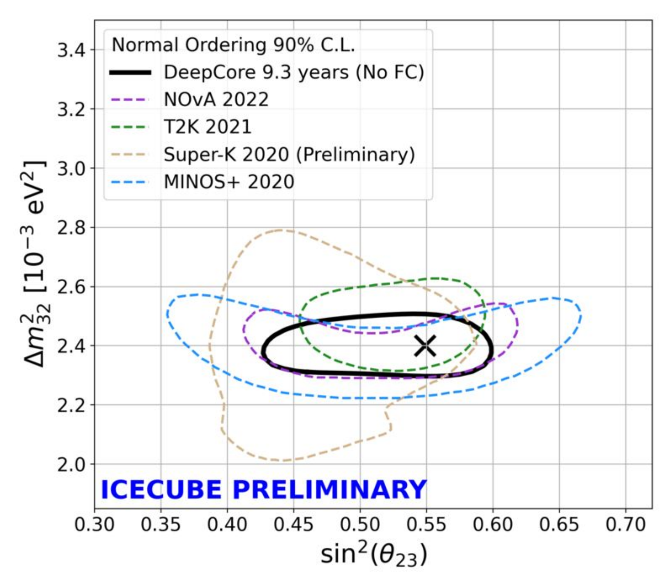


Oscillation Results

- The new result is compatible and complementary with the existing measurements:
  - IceCube uses very different sample and faces different systematics from the other experiments.
- Big updates on MC models and calibration since last publications (DeepCore 3-year).

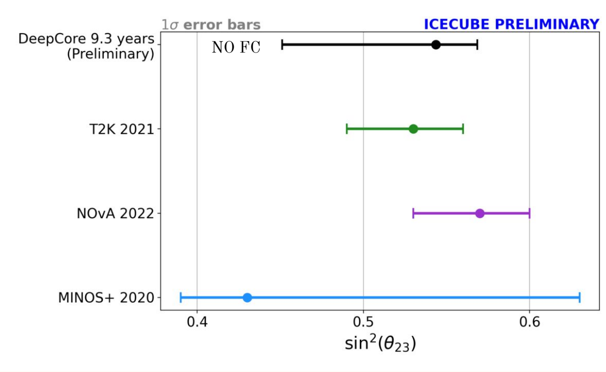


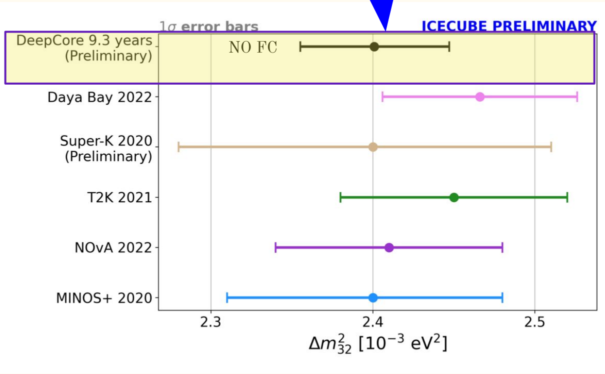


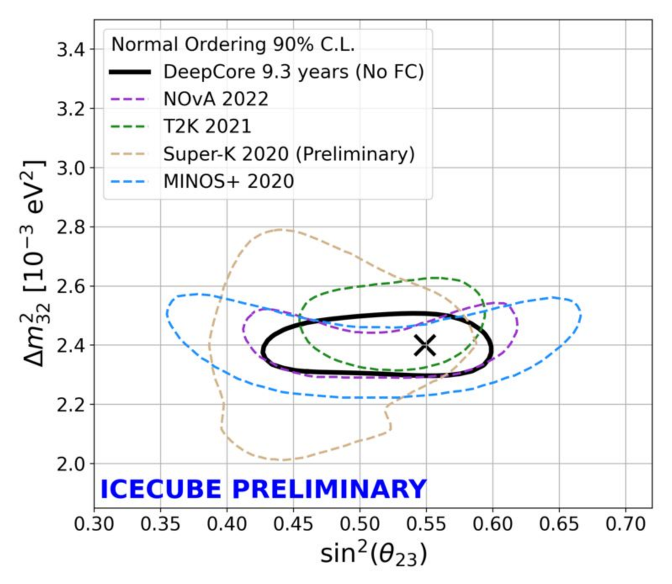


Oscillation Results

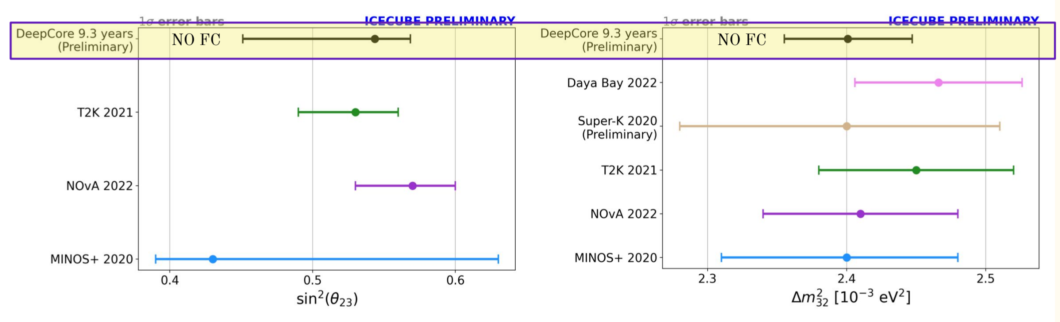
- The new result is compatible and complementary with the existing measurements.
- Competitive on Δm^2_{32} measurement.
- Room for future improvements!
  - MC models; calibration, etc







Conclusion



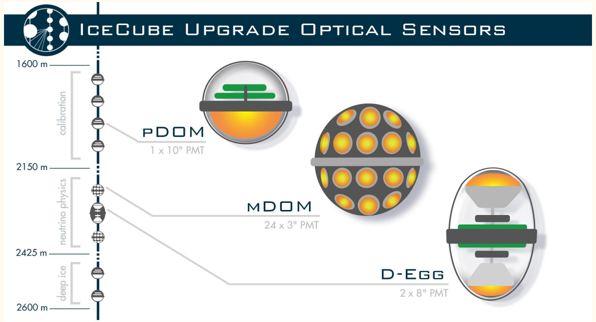
- First-time using the highest-statistic (9.3yr) DeepCore atmospheric neutrino dataset for oscillation measurements:
  - Machine learning tools (including CNNs) are used for multi-purpose reconstruction.
- Compatible, complementary results with the existing measurements:
  - Different sample and facing different systematics;
  - Competitive constraint on Δm^2_{32} .
- A lot of room for future improvements!
  - MC models, detector calibration, reconstruction...
- More oscillation results using this new sample on the way!
  - Neutrino mass ordering, non-standard interactions...

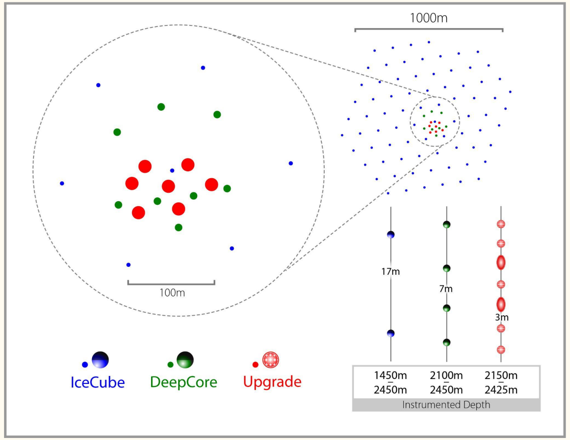
Stay tuned!


Thank you for your attention!

Backup

Future

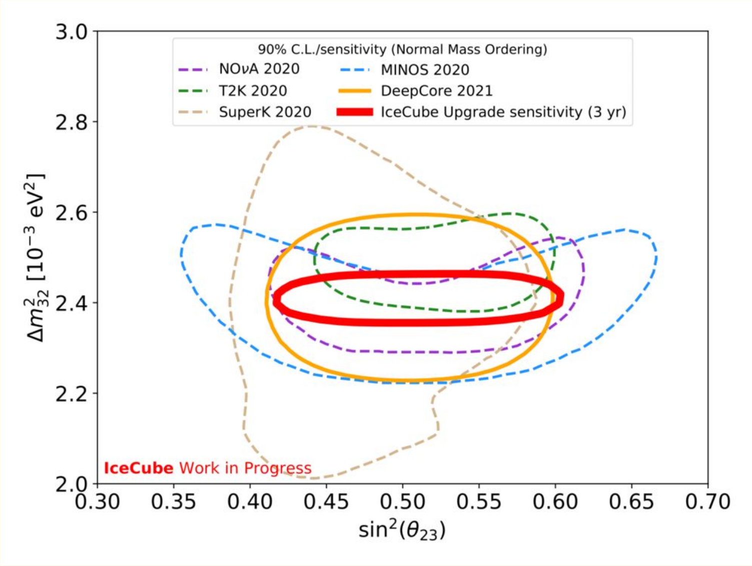




The Upgrade detector:

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

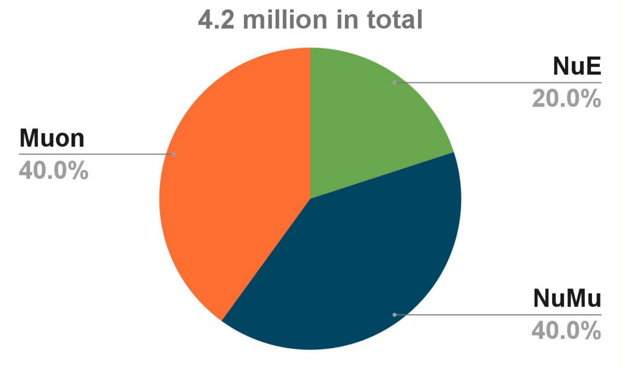
New sensitivity of Upgrade expected in summer!

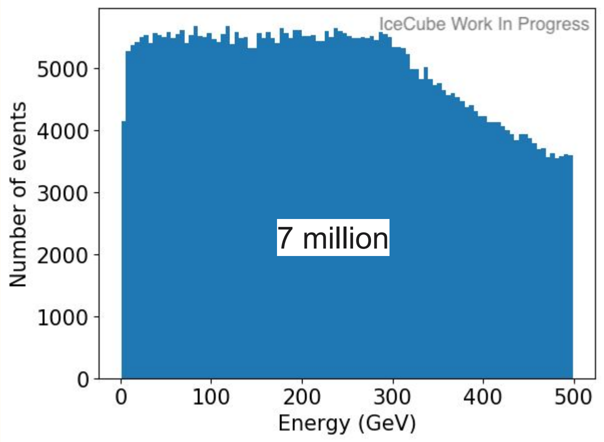


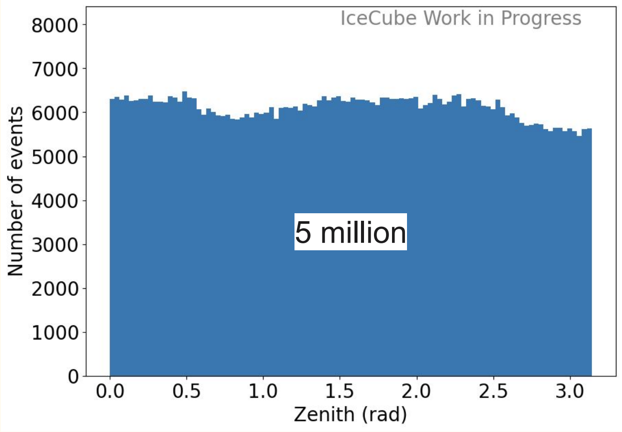
Training Samples

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

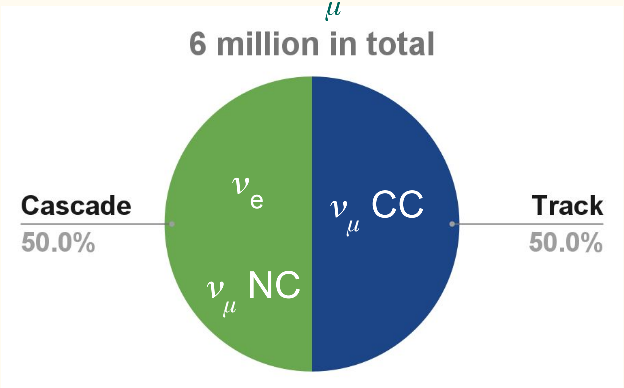
Muon Classifier







PID: ν_μ CC



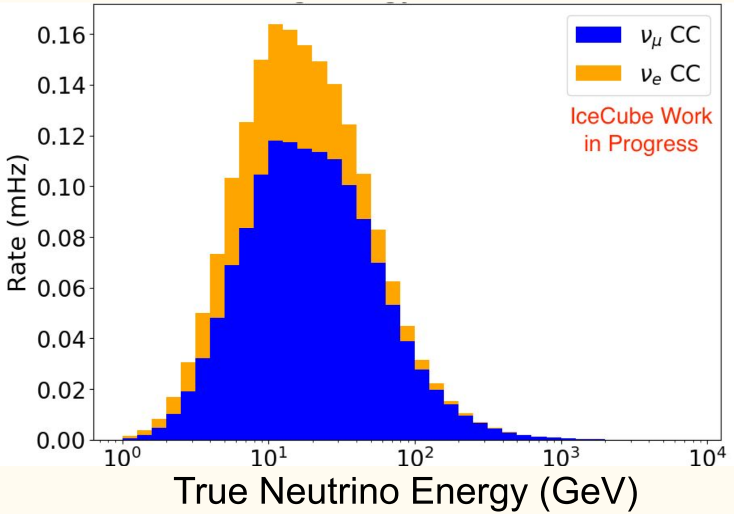
Performance: Speed

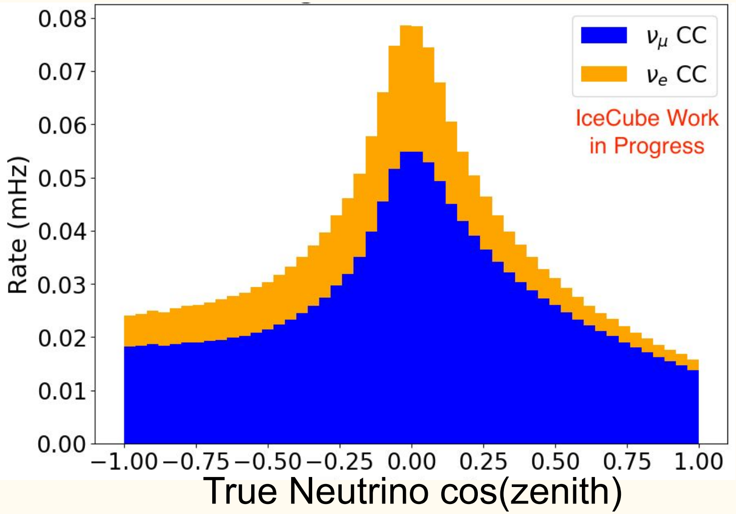
	Second per file (~3k events)	Time for full sample assuming 1000 cores
CNN on GPU	21	~ 13 minutes
CNN on CPU	45	~ 7.5 hours
Current Likelihood-based method (CPU only)	120,000	~ 46 days

- 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

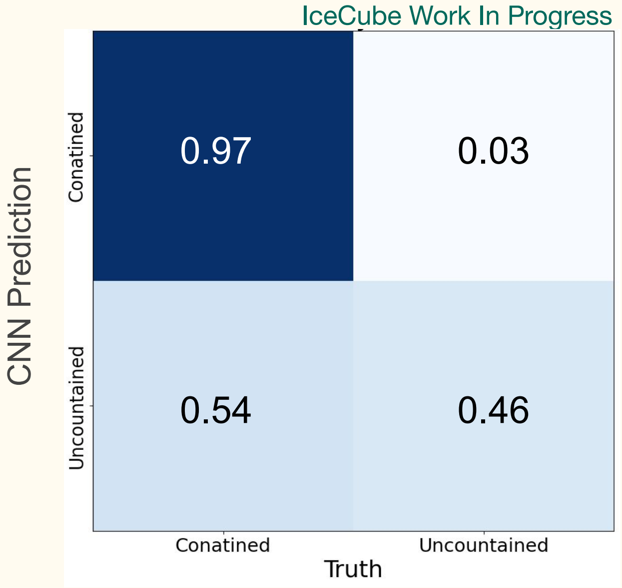
- Nominal MC sample with flux, xsec, and oscillation weights applied;
- Testing on signal (ν_μ CC) and major background (ν_e CC);
- Baseline: current reconstruction method (likelihood-based)

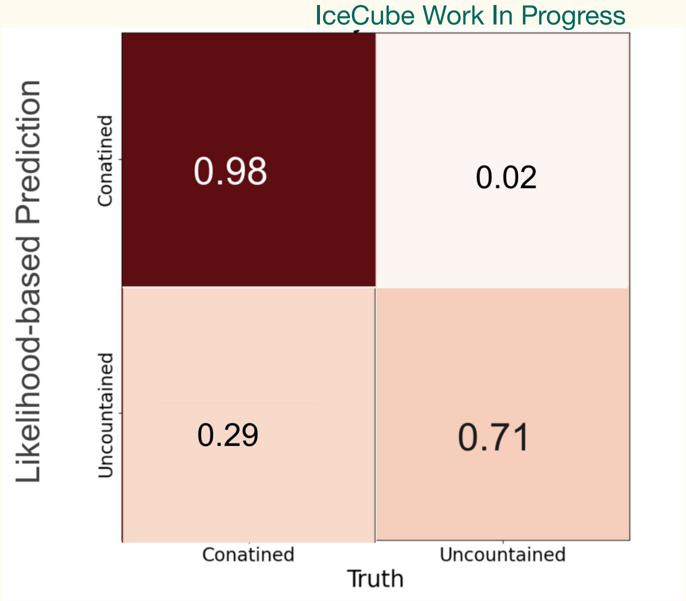




Performance: Vertex

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

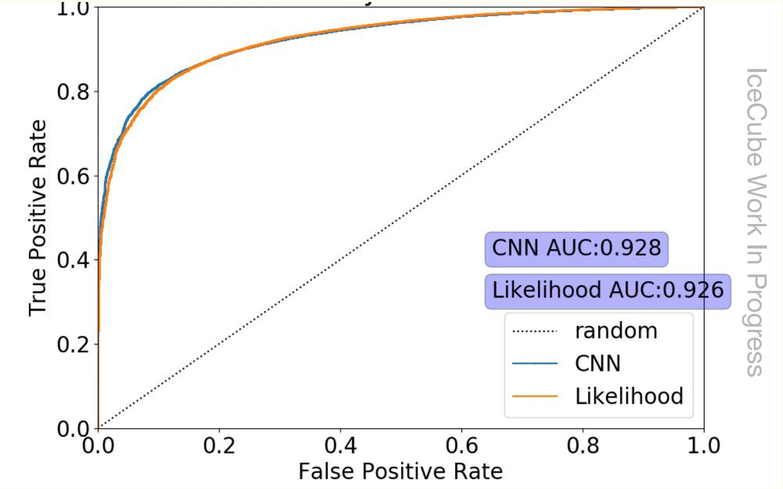




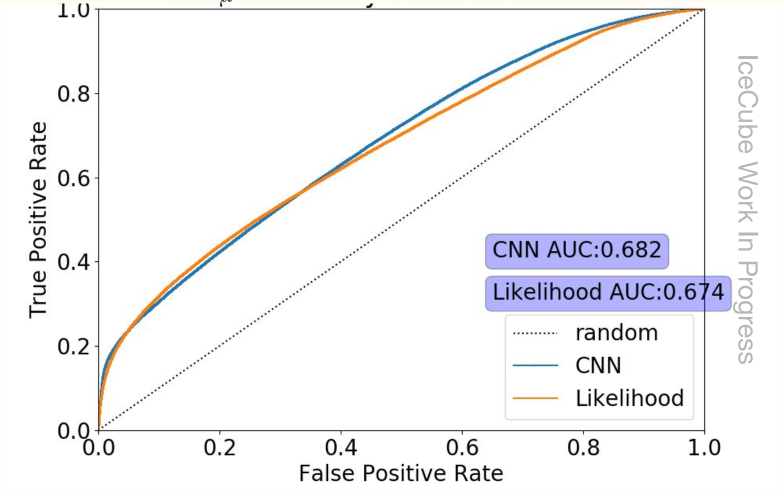
Performance: Muon and PID Classifiers

- 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



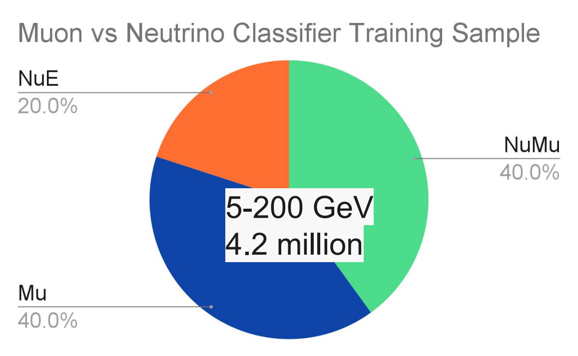
Training Samples

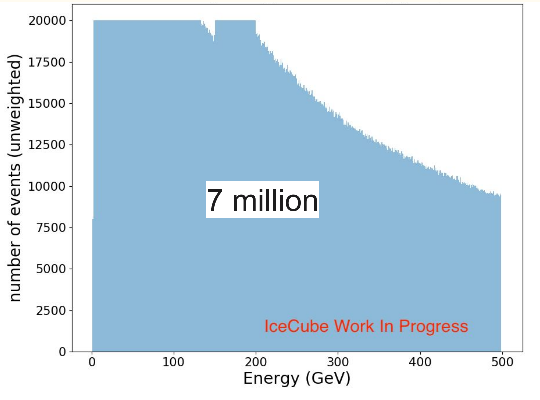
Energy: nDOM >= 7

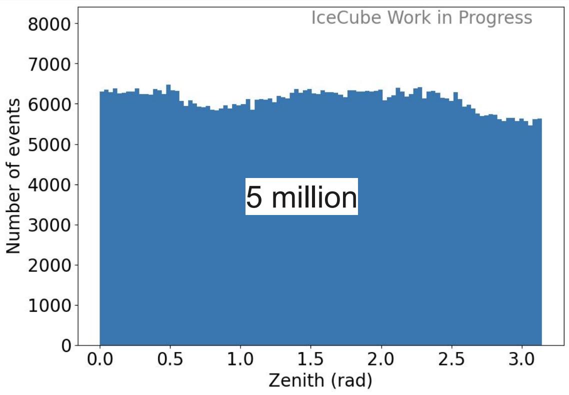
Muon : nDOM >= 4; 5–200 GeV

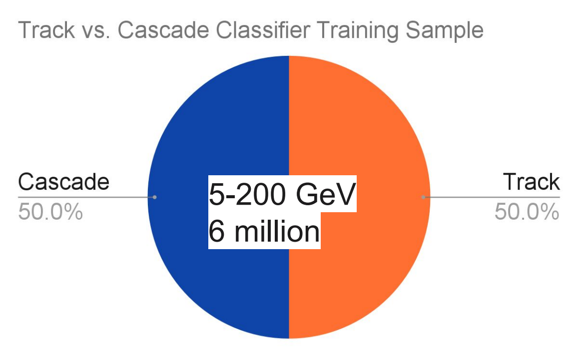
Muon, PID, Vertex: nhits >= 8 hit 5-200 GeV

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



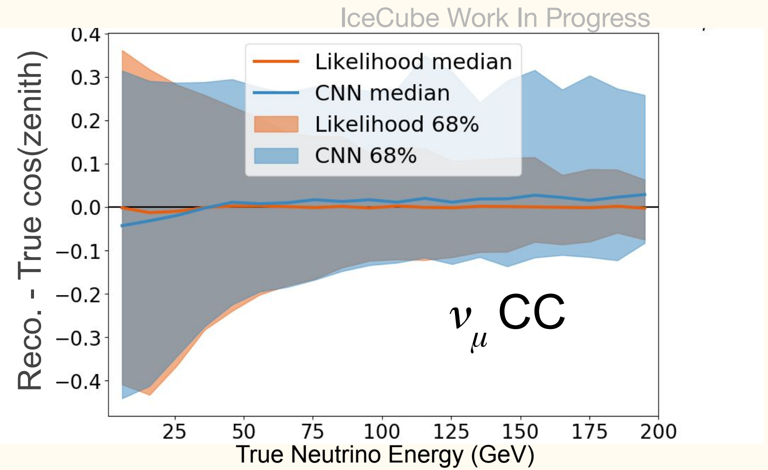


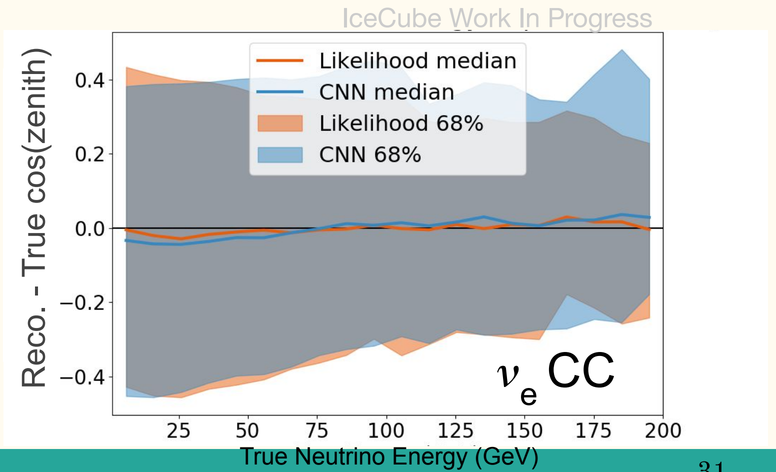




Performance: Direction

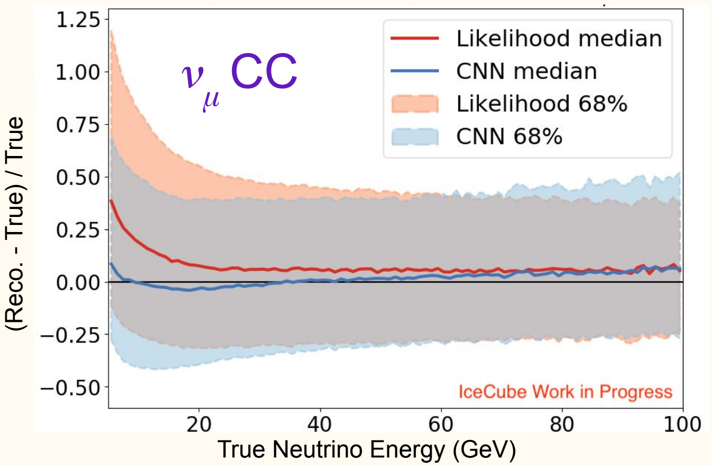
- Direction bias flat against true energy;
- Comparable to current method;
- Better resolution for ν_μ CC (signal);
- High energy (>100 GeV) neutrinos leaving DeepCore
  - Need containment cut: interaction vertex reconstruction.

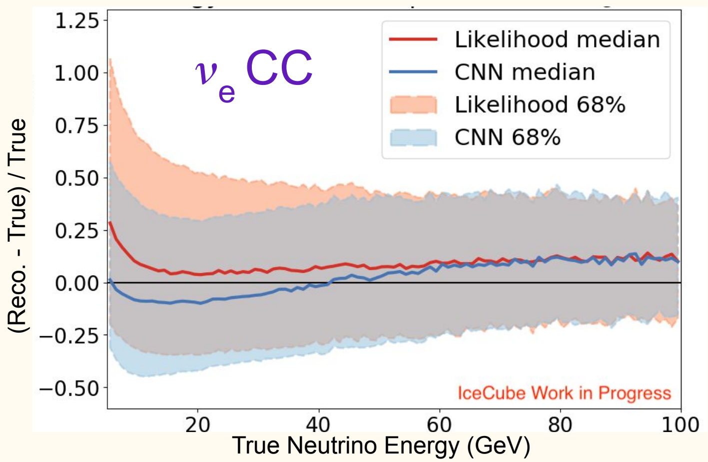




Performance: Energy

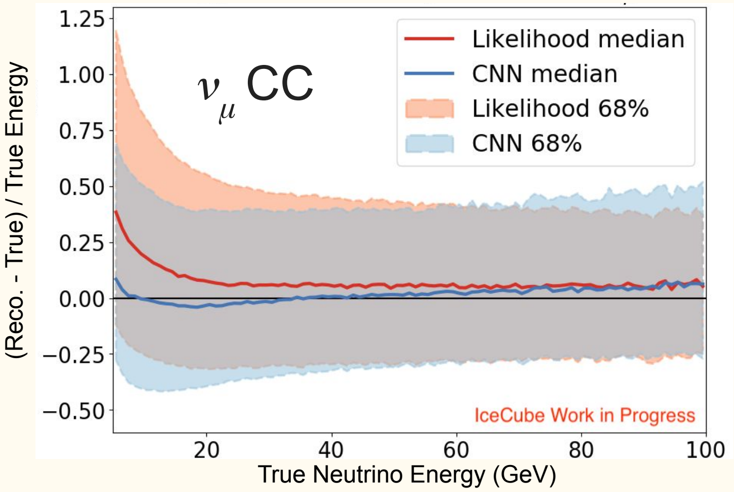
- Flat median against true neutrino energy;
    - CNN has better resolution at low energy (majority of sample)
- Comparable performance to current method at higher energy and in background;

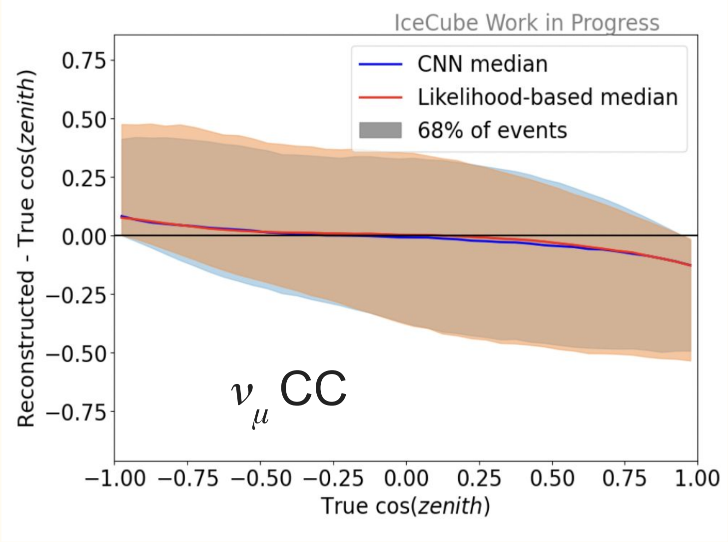




Reconstruction Performance

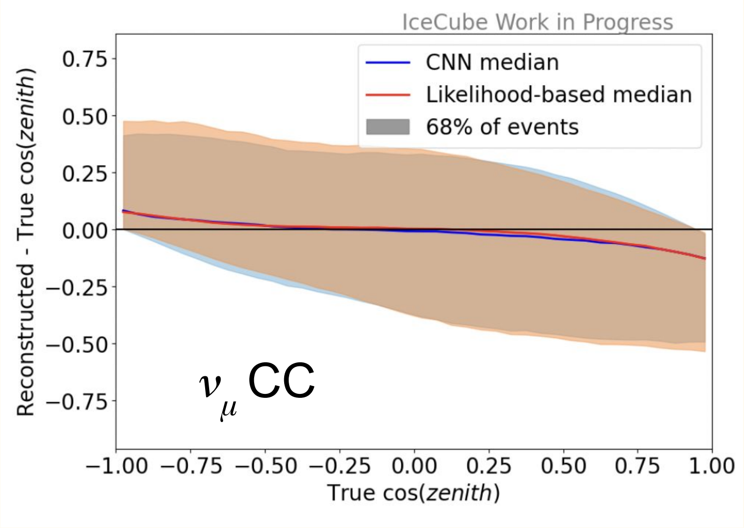
- Flat median against true neutrino energy and zenith;
- CNN has comparable resolution to current method, and better at low energy (majority of sample)

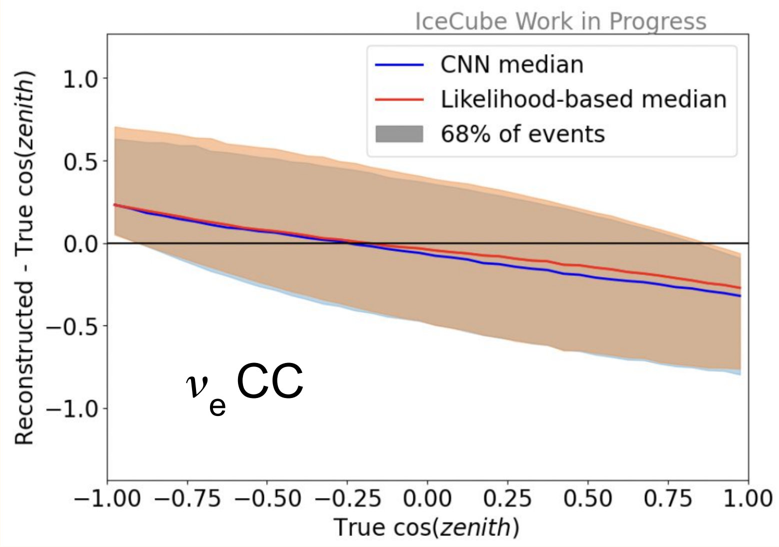




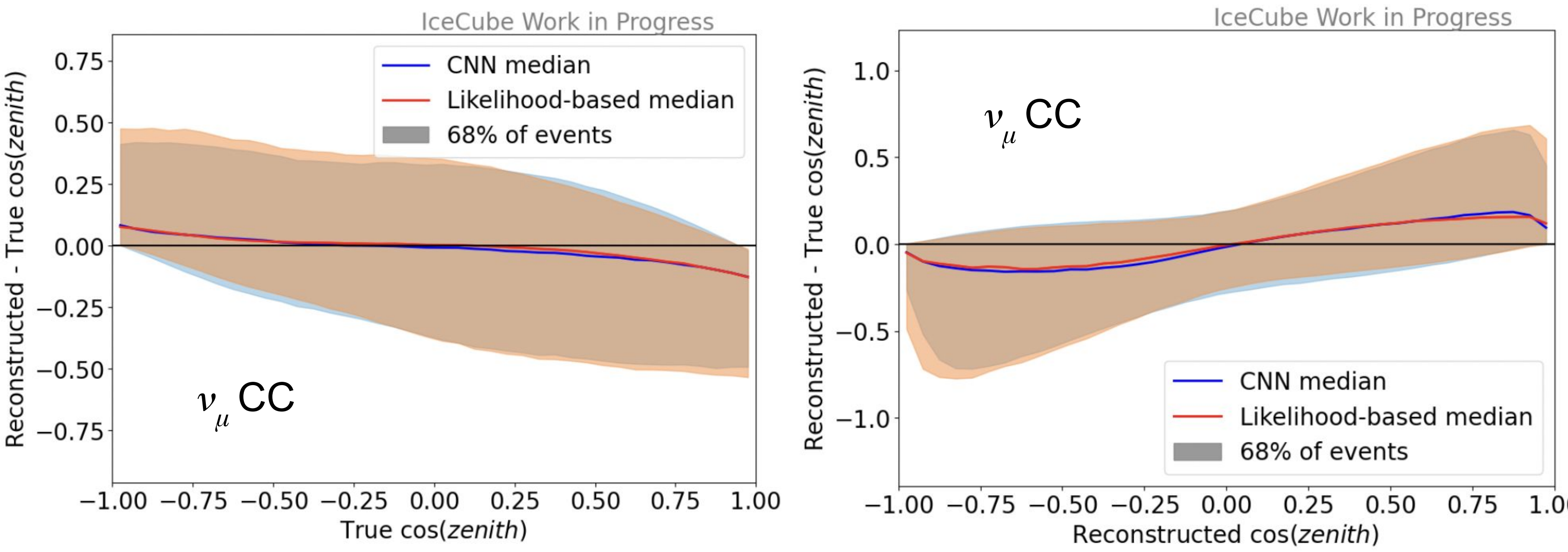
Performance: Zenith

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



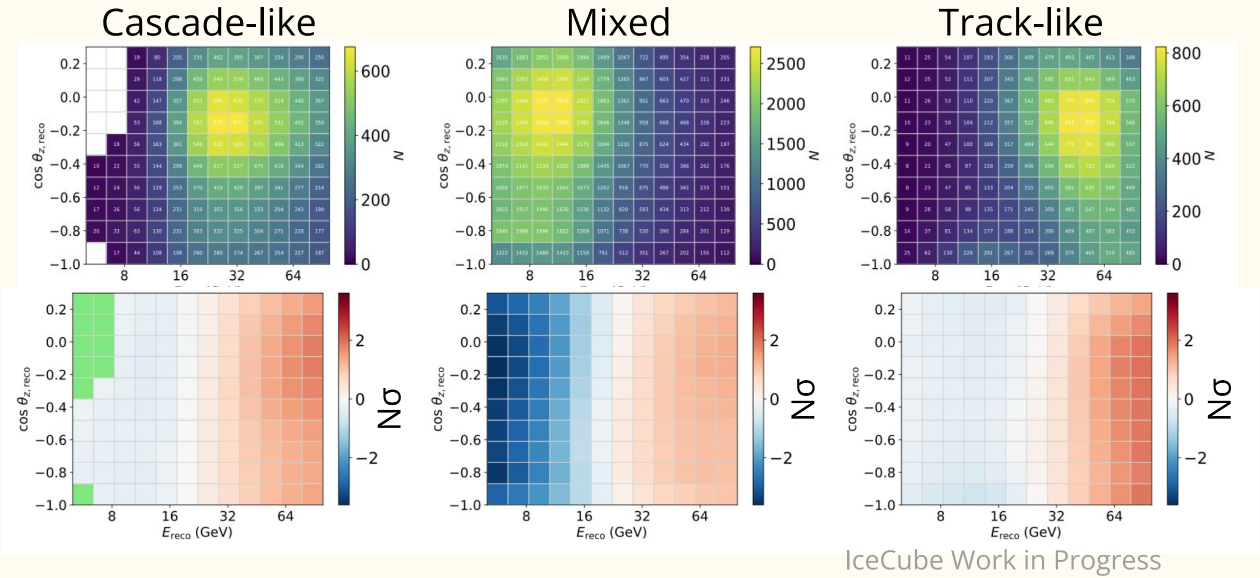


Performance: Zenith (Contained, 5-300 GeV Sample)



Systematic Effect: Neutrino Flux Model

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



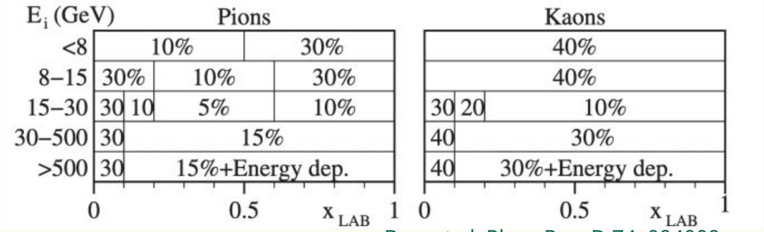
Fit for spectral index among other model systematics

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

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

Systematic Uncertainty Consideration

- Flux uncertainty
  - Pion & Kaon production uncertainties



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