For the IceCube Collaboration

IceCube Neutrino Observatory

New Measurement of Muon Neutrino Disappearance with IceCube-DeepCore

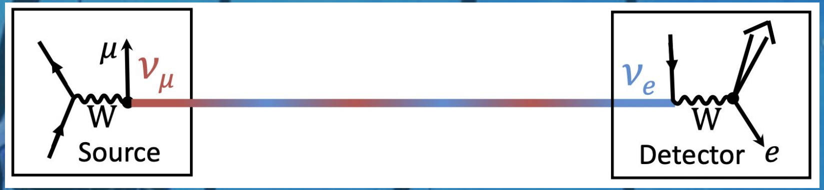
Shiqi Yu[1], Jessie Micallef[2]

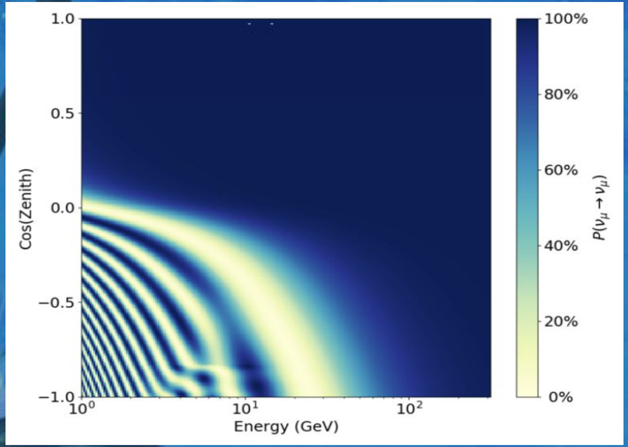
Michigan State University[1]

AI Institute for Artificial Intelligence and Fundamental Interactions[2]

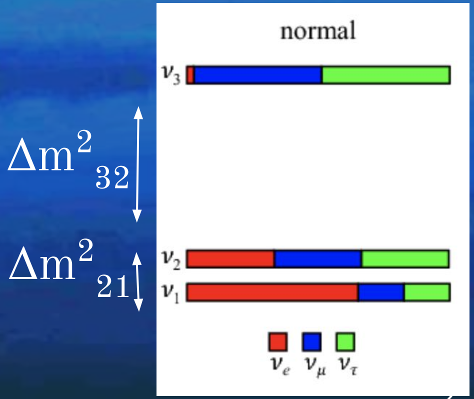
TAUP 2023 @ Vienna

ν_μ Disappearance





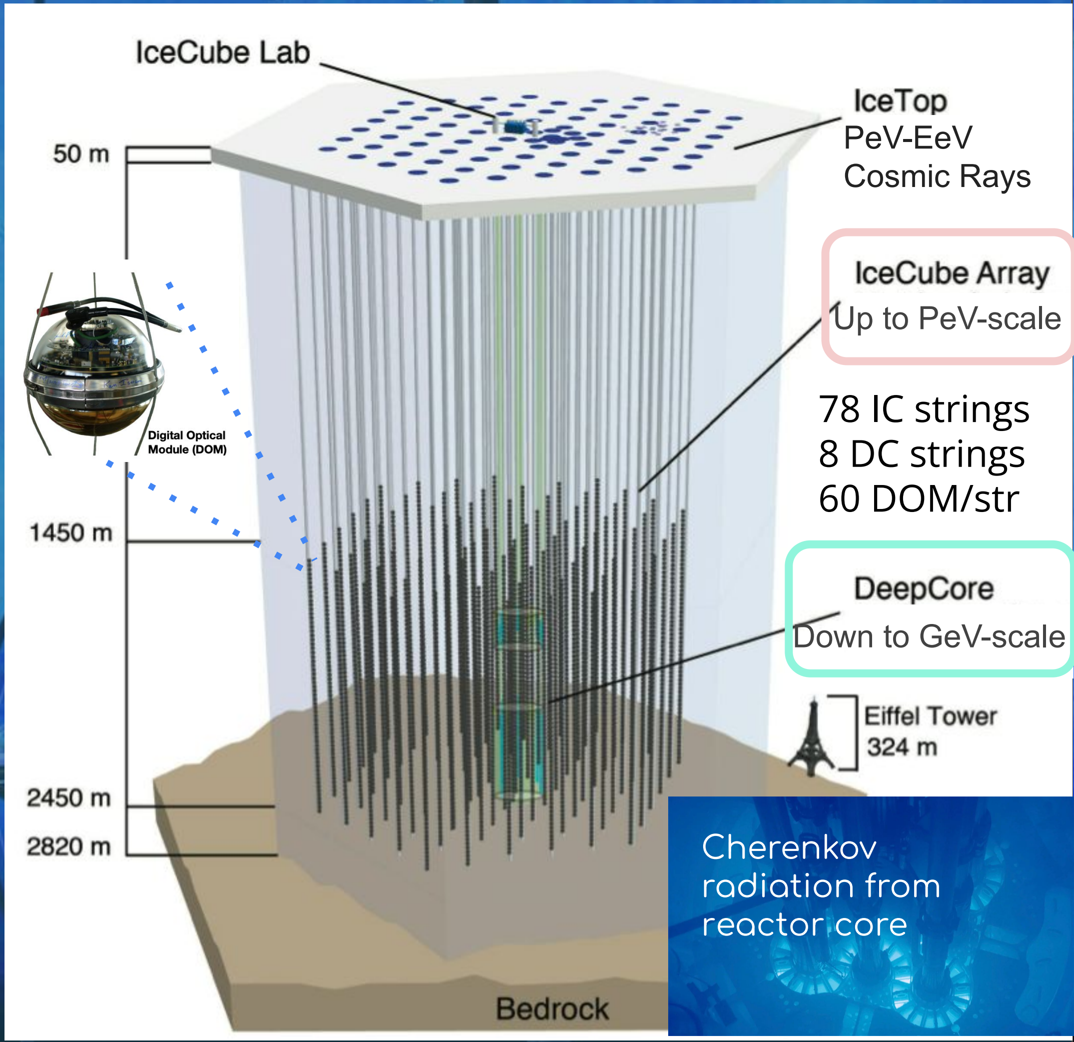
Each flavor (e, μ, τ) is a superposition of masses (1, 2, 3)



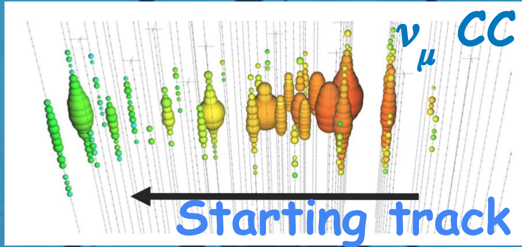
Oscillations are described by:

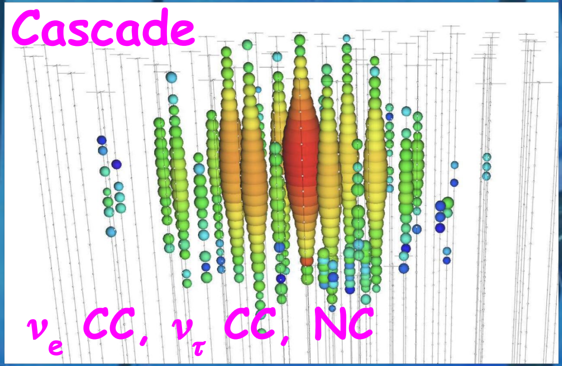
- Mixing angles (θ_{23}, θ_{13}, θ_{12}), δ_{CP}
- Squared mass differences: Δm^2_{32}, Δm^2_{21}

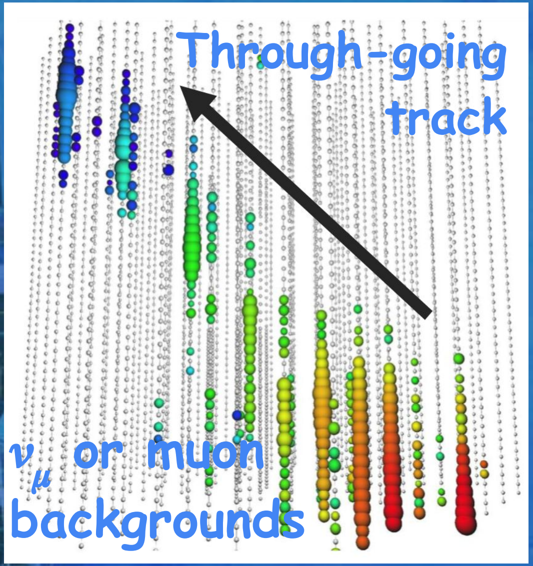
- 1 km^3 deep under antarctic ice;
- 5160 digital optical modules (DOMs) detect Cherenkov photons;
- DOMs record pulse charges & times;
- Can see up to PeV-scale neutrinos.
- DeepCore: denser configured sub-detector, can observe GeV-scale neutrinos.

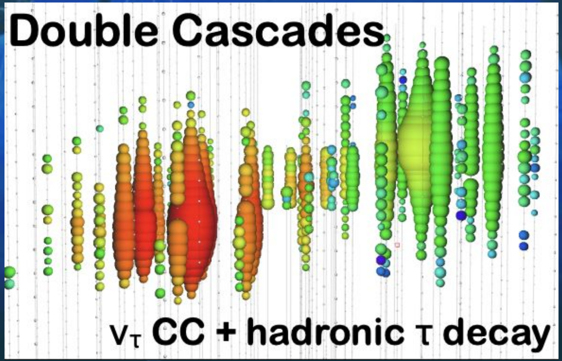


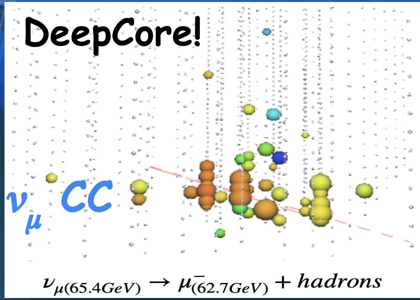
Typical Events in IceCube



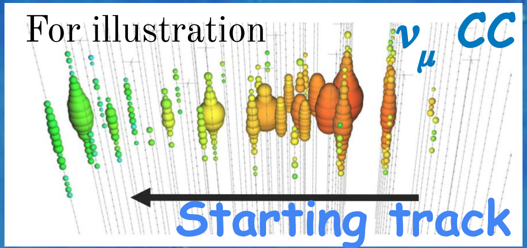


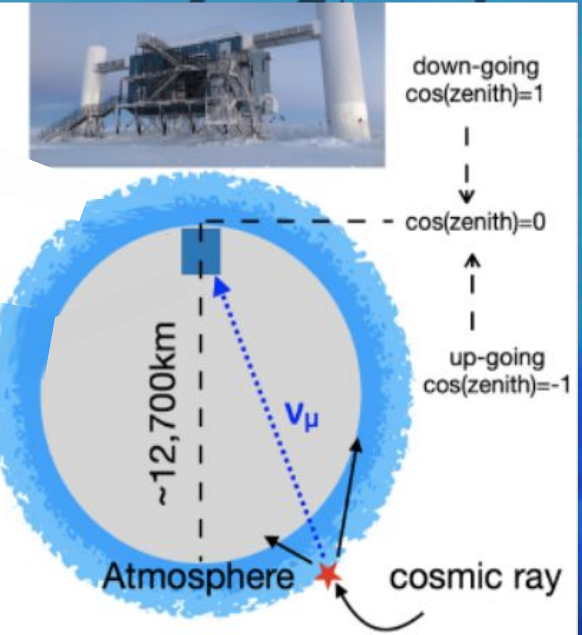




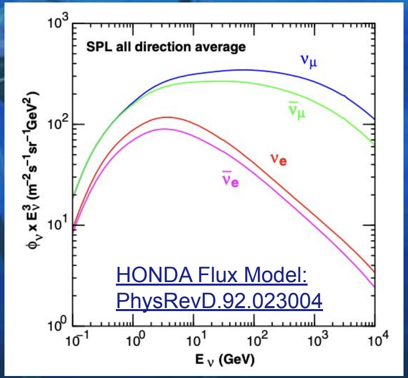


ν_μ Disappearance with IceCube





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



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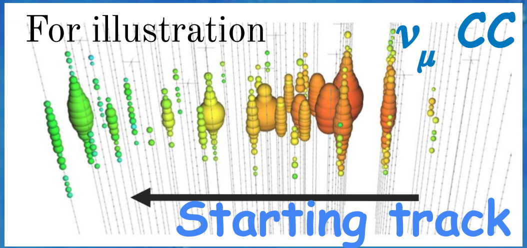
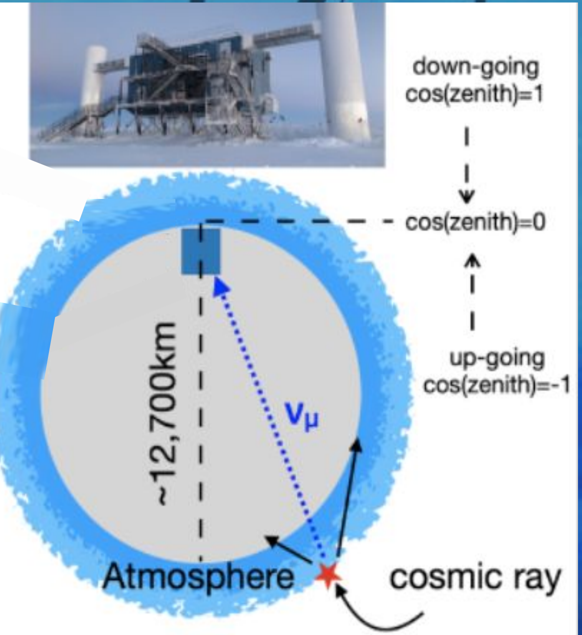
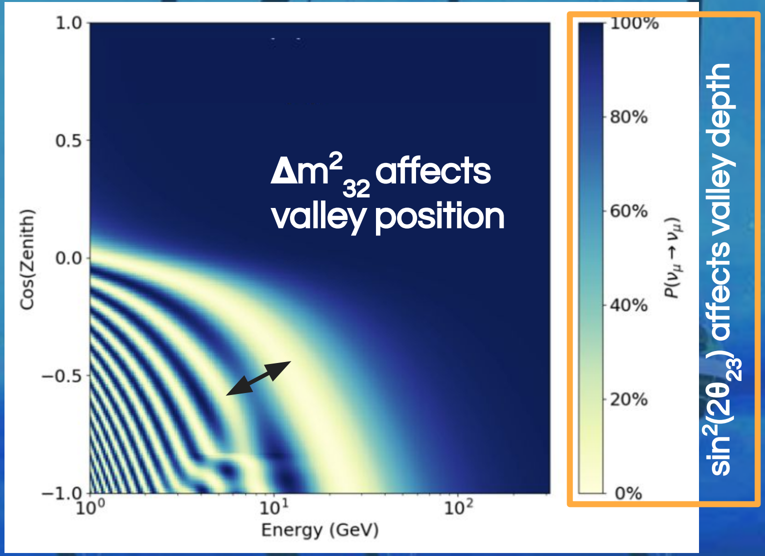




- Atmospheric muon neutrinos from cosmic ray interactions:
  - Wide ranges of both energy (E) and baseline (L).
- Neutrino **distance of travel** (L) calculated using **arrival direction (zenith)**.

ν_μ Disappearance with IceCube



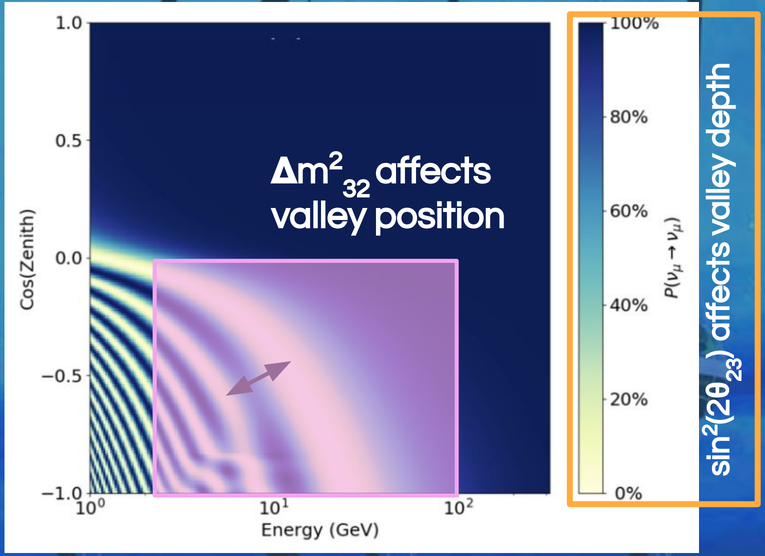
DOI: 10.1016/j.nima.2020.164332

- 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



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

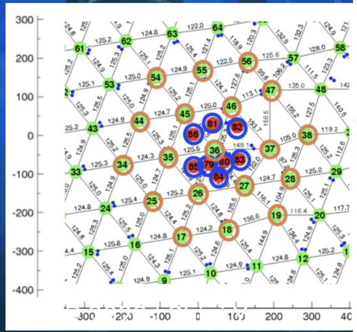
Convolutional Neural Networks

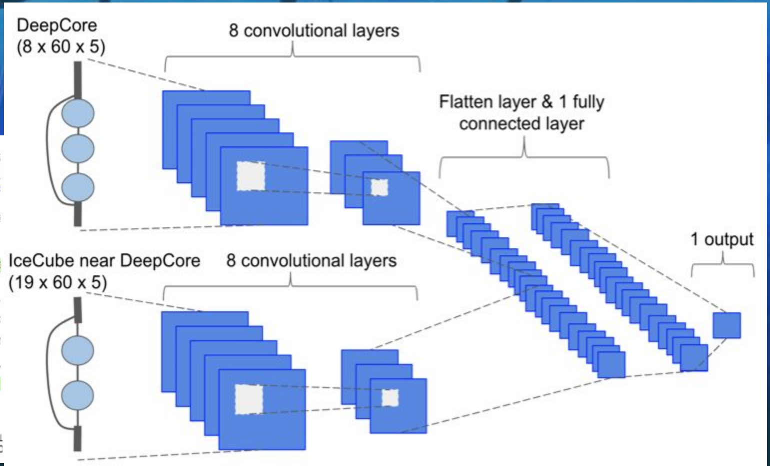
- Only use DeepCore & nearby IceCube strings;
- Five CNNs trained: optimized for different variables;
- Comparable resolution to the current likelihood-based* method;
  - ~3,000 times faster in runtime: big advantage for full MC production of atmospheric neutrino datasets.

*Eur. Phys. J. C 82 (2022) 9, 807

5 summarized variables per DOM:

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





Reconstruct variables at final level

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

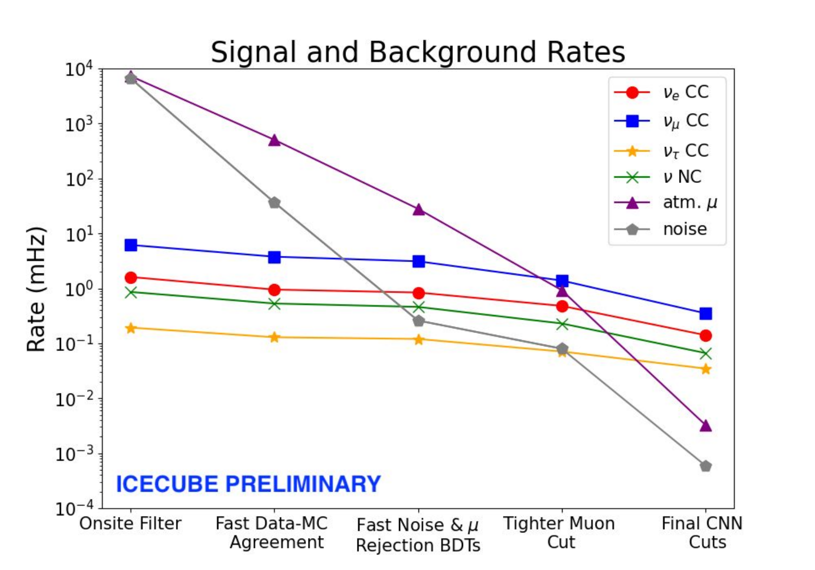
} Analysis binning

- Interaction vertex
- Atm. muon classifier

} Selections

Preliminary Analysis Sample

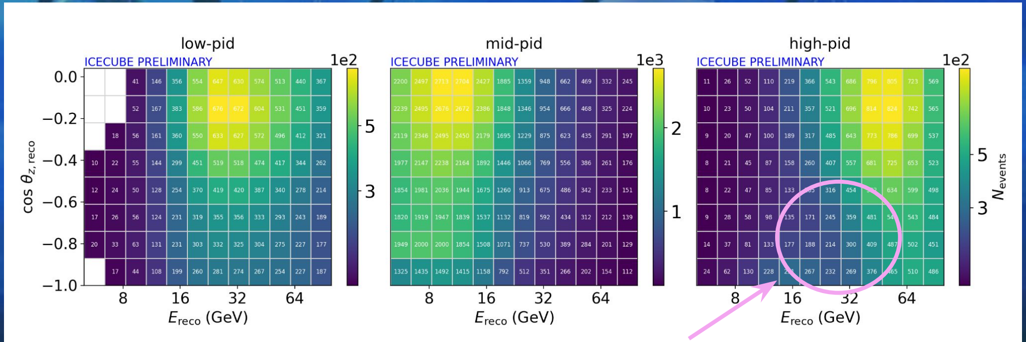
- Data taken over ~3,390 days between 2012-2021;
- Total of 150,257 candidates;
- High signal (ν_μ CC) and low background (noise and atm. muon) rates (~0.6%):
  - Several levels of selection are applied to eliminate the primary atm. muons and noise backgrounds.



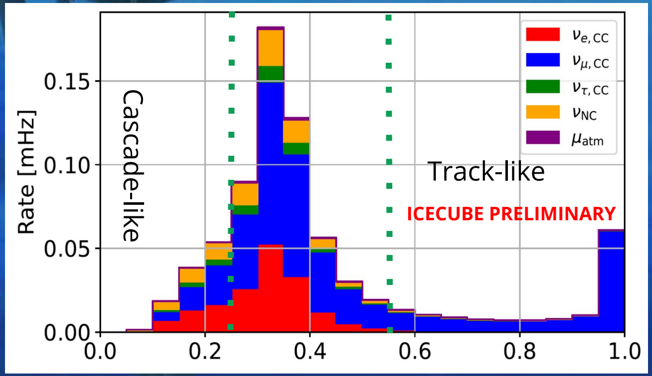
3D Binned Analysis Sample

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



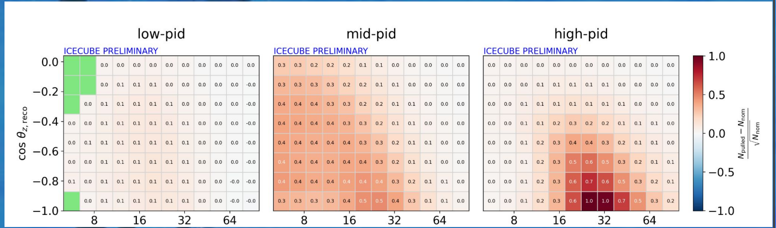
ν_μ CC ID

3D Binned Analysis Sample

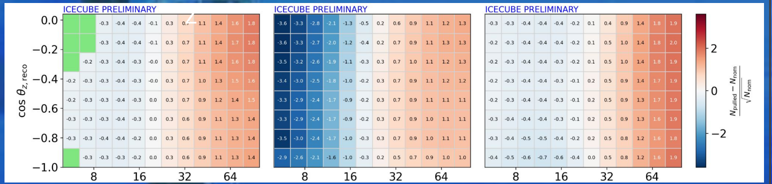
Measure 3D distortions in reconstructed [energy, cos(zenith), PID]:

- PID discriminates ν_μ CC vs. neutrino bkgs;
  - 27,352 tracks; 22,963 cascades.
- Help constraining systematic parameters

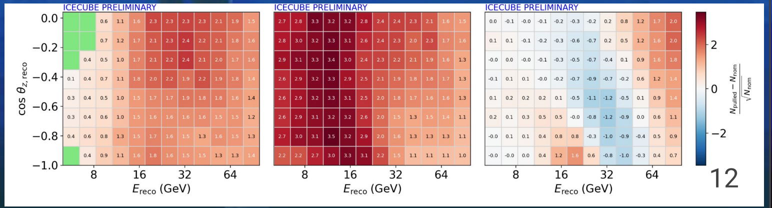
θ_{23}: +5° vs. Nominal

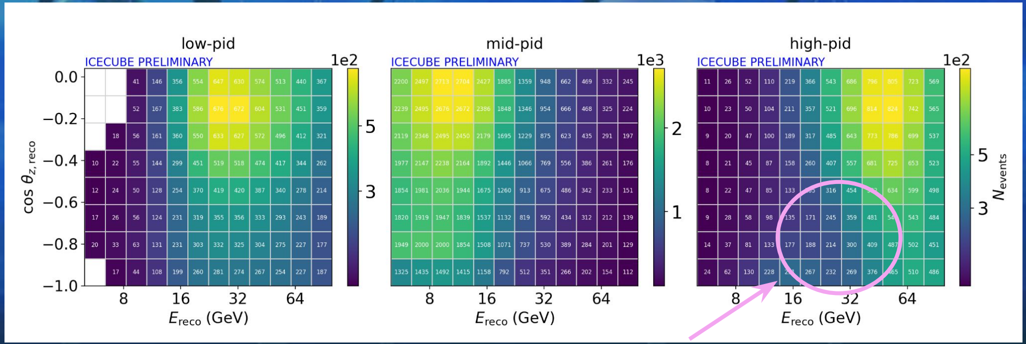


Spectral index ($\Delta\gamma$): +1σ vs. Nominal



DOM eff.: +1σ vs. Nominal

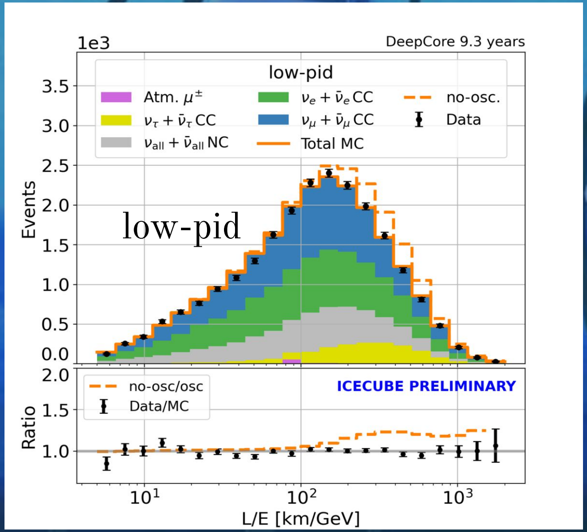


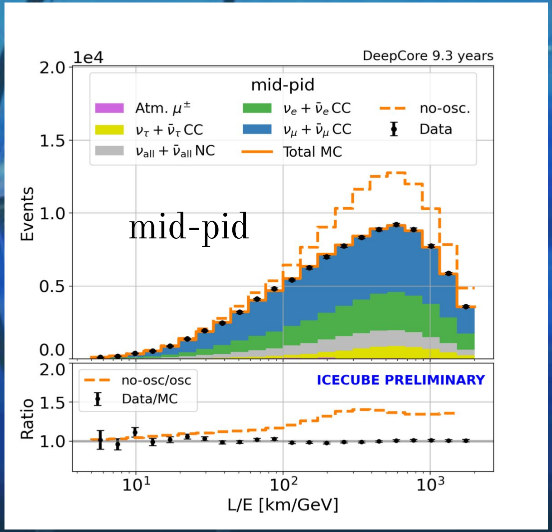


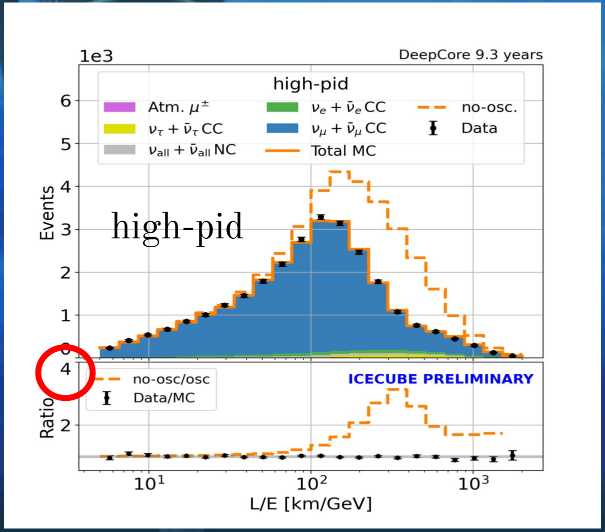
ν_μ disappearance signal

Oscillation Result: L/E

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

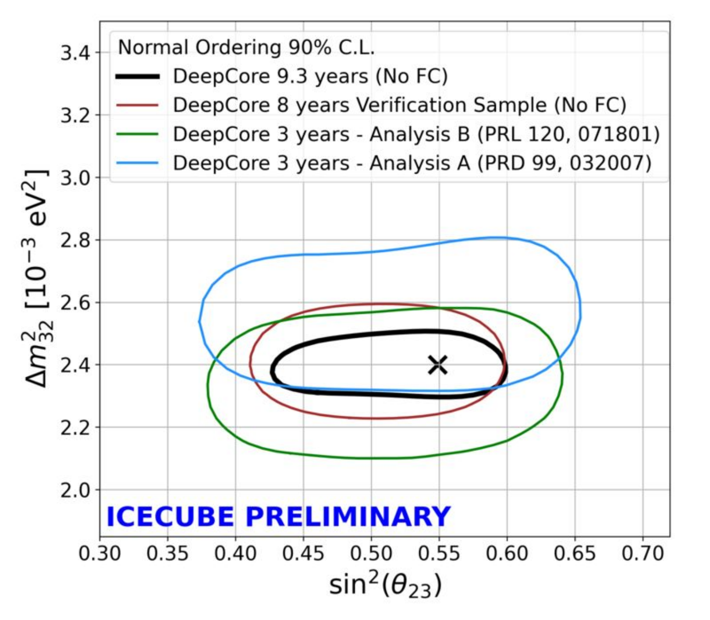






Oscillation Result: Contours

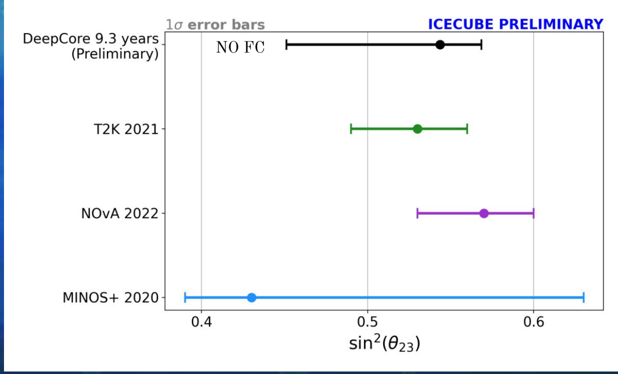
- Consistent with the previous IceCube results.
- Significant improvements to MC models and calibration since DeepCore 3-year results.
- Compared to DeepCore 8-year result: New reconstruction, including cascade-like bin into analysis, more statistics.

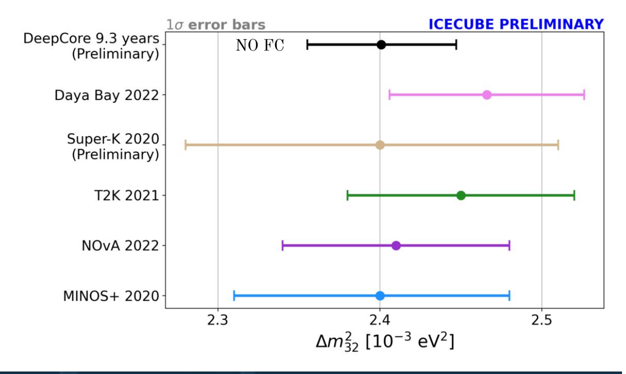


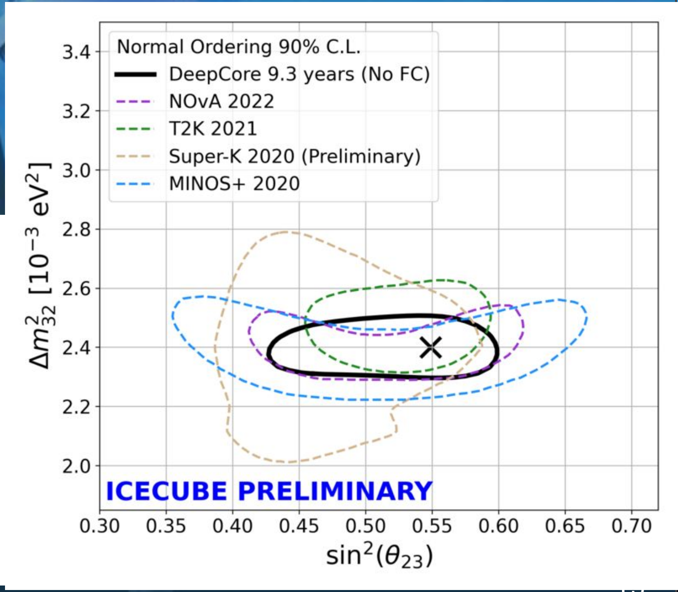
*8-year result: Phys. Rev. D **108**, 012014 (2023)*

Oscillation Result: 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

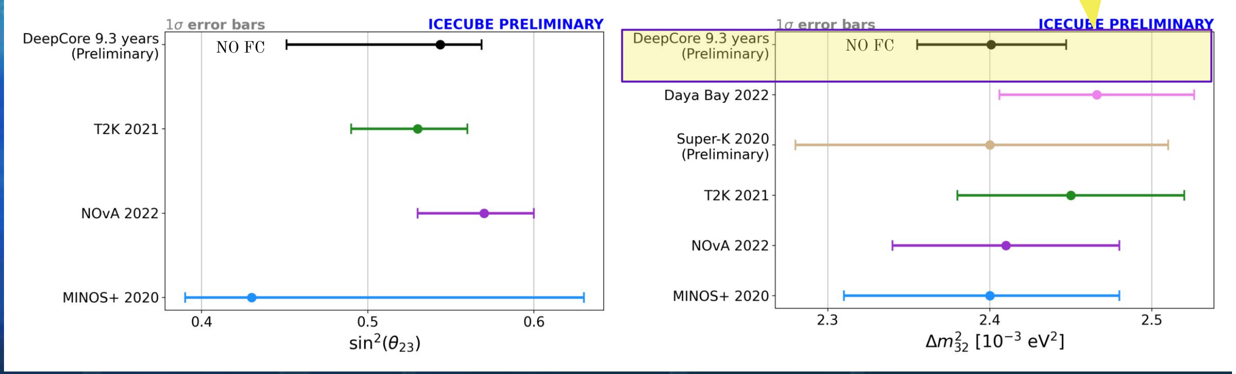


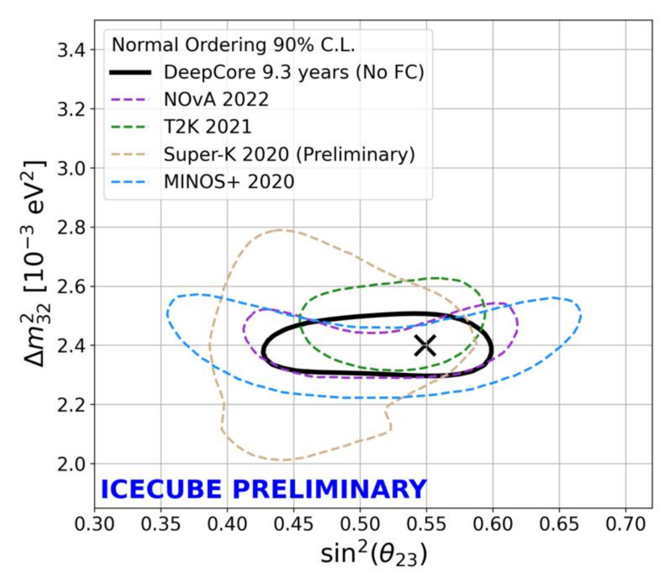




Oscillation Result: Contours

- 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, etc





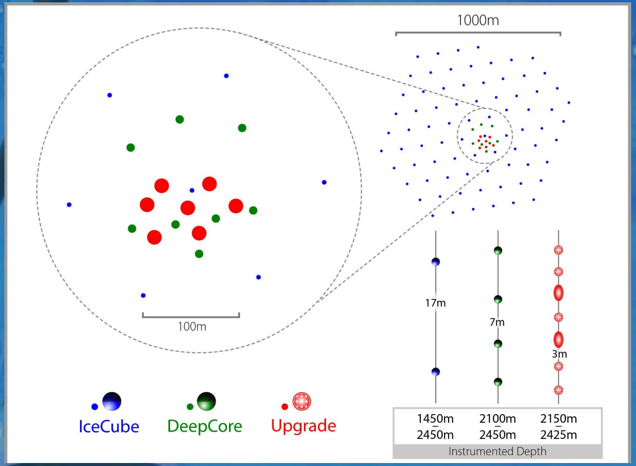
Future

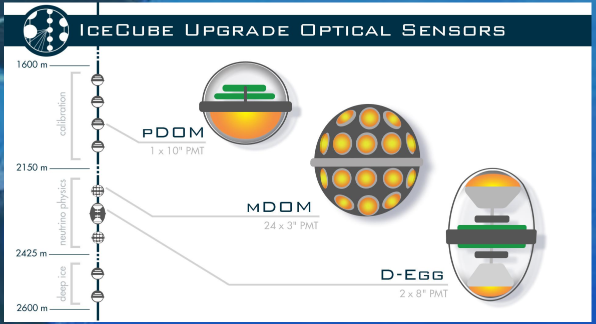
Upcoming results of neutrino physics:

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

<u>The Upgrade detector:</u>

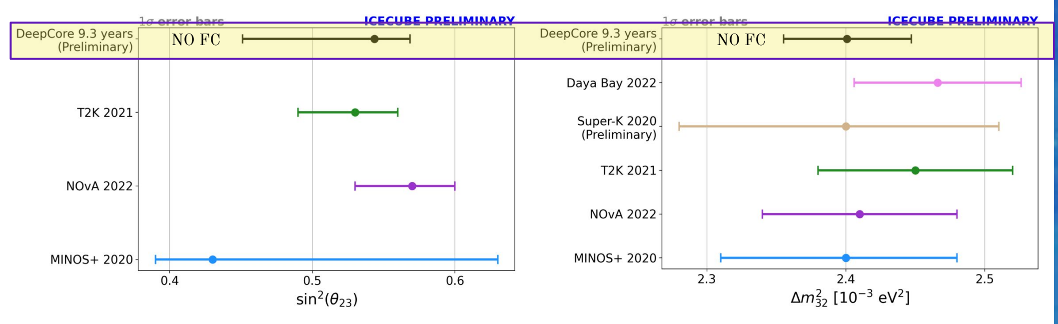
- More densely instrumented strings in the center
  - Better event resolution!
- DOM: multiple PMT designs to improve photon-collection efficiency and thereby reconstruction
- Will improve calibration!
- Target deploying 2025/26





Later talk in this session: "Atmospheric neutrino oscillation sensitivities with the IceCube Upgrade", Jan Weldert

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!

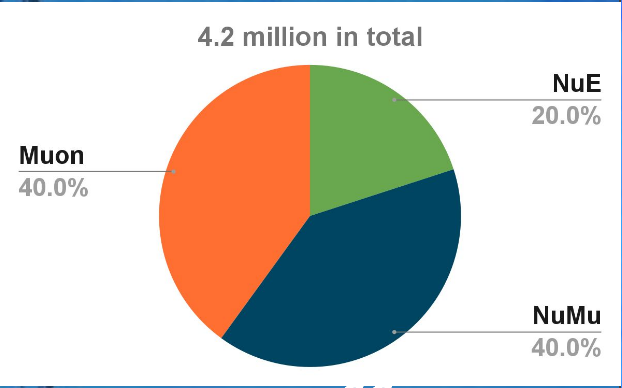
Hey I'm a D-Egg

Overflow Slides

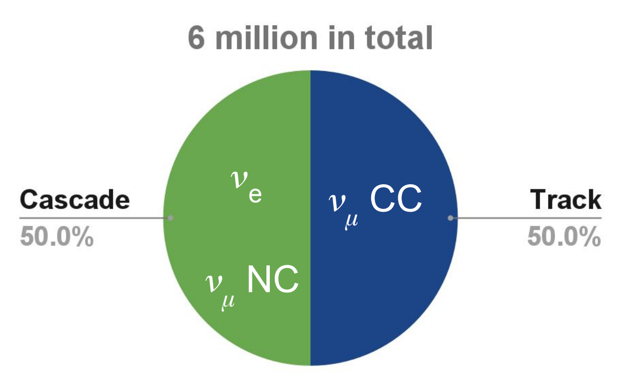
Training Samples

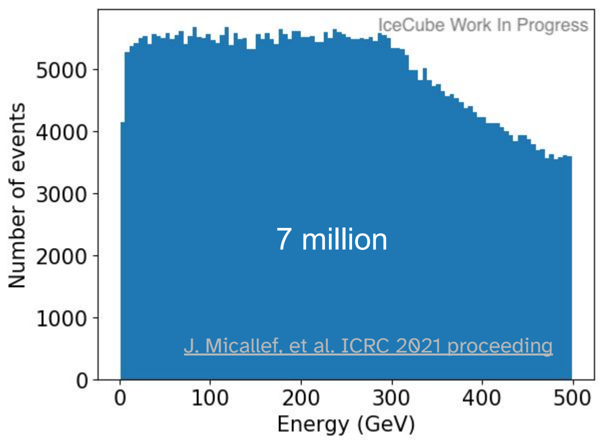
- Balanced MC samples;
- Energy, direction, interaction vertex are trained on ν_μ CC events (signal).

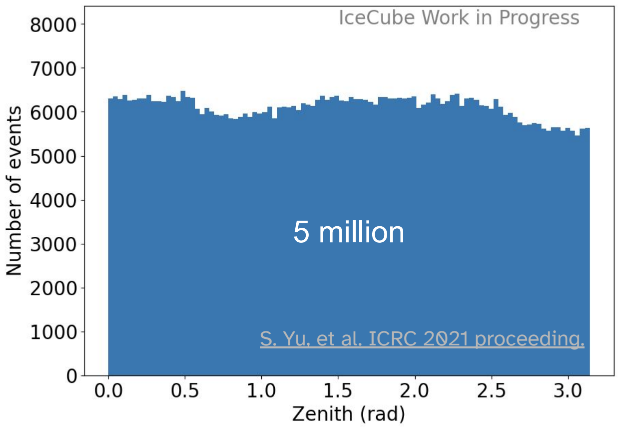
Muon Classifier



PID: ν_μ CC

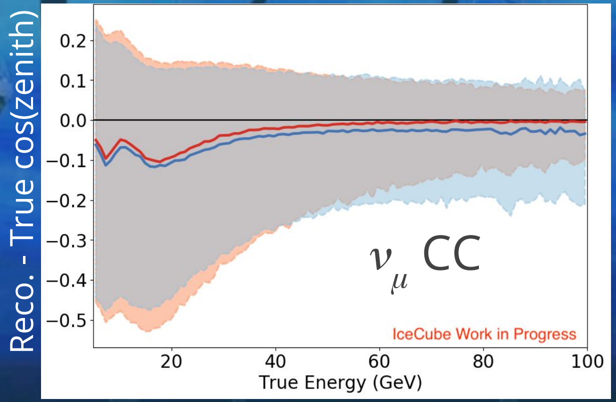


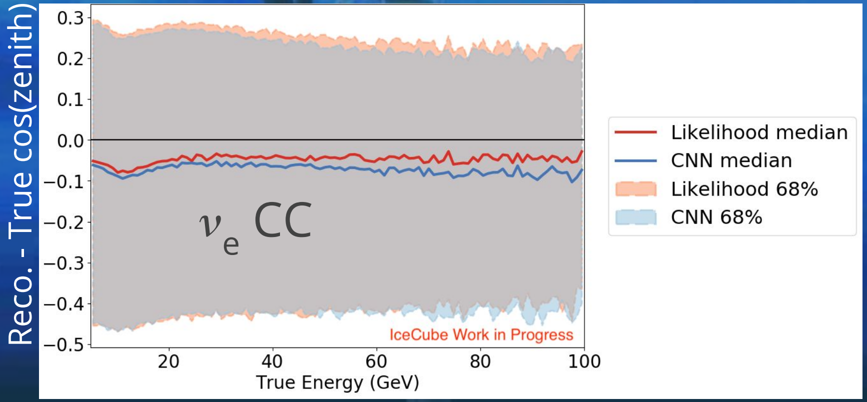




Reconstruction Performance

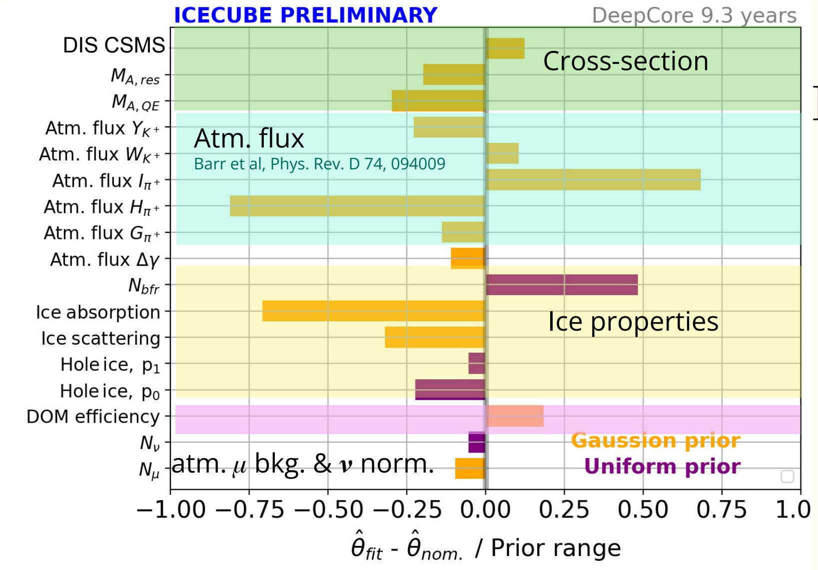
- Nominal MC with analysis cuts and flux, xsec, and oscillation weights applied;
- Comparable resolution to current (likelihood-based) method;
- *~3,000 times faster in runtime*: big advantage for full MC production of atmospheric neutrino datasets.





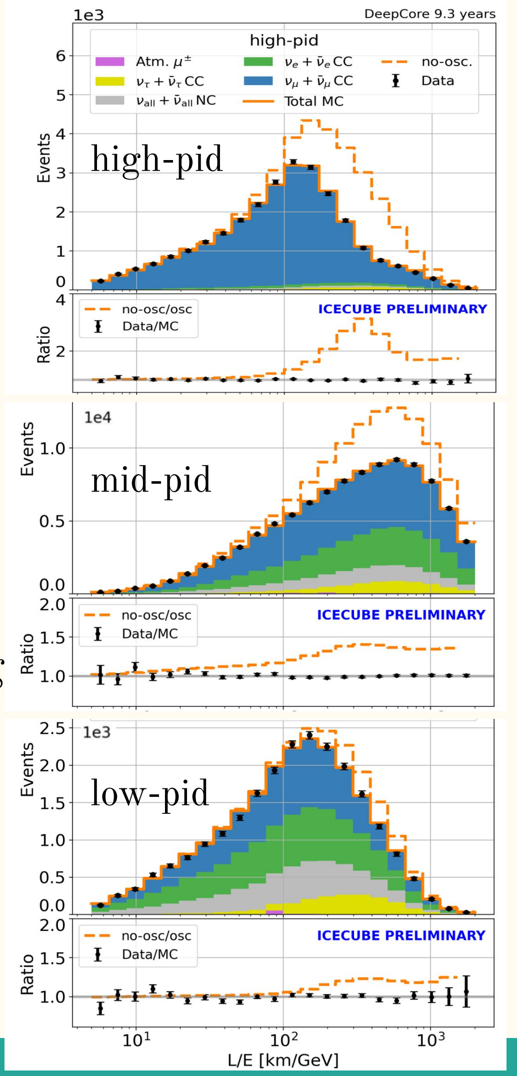
ν_μ Disappearance Analysis

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



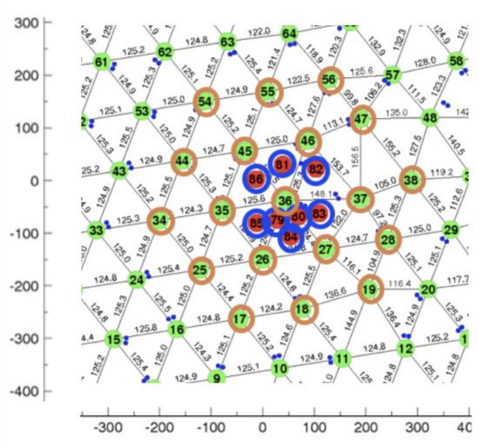
Future improvements:

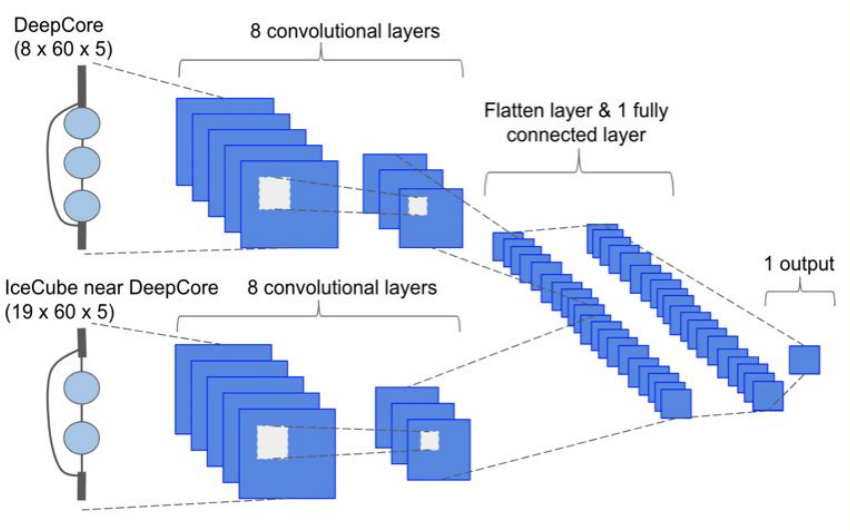
- Reduce correlations among flux uncertainties: PCA;
- Further MC improvements underway.



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:

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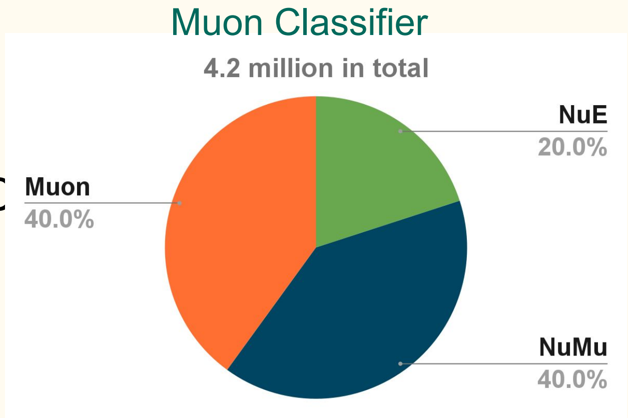
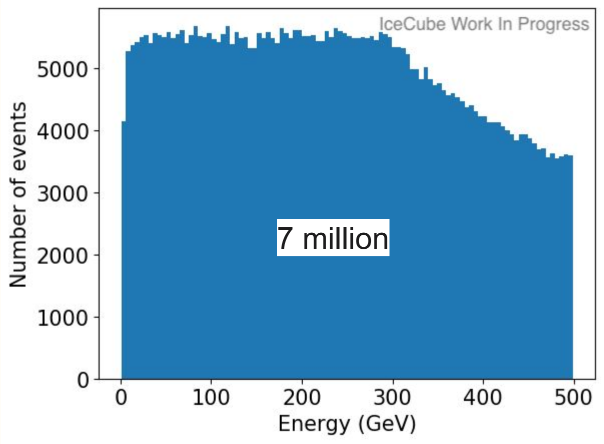
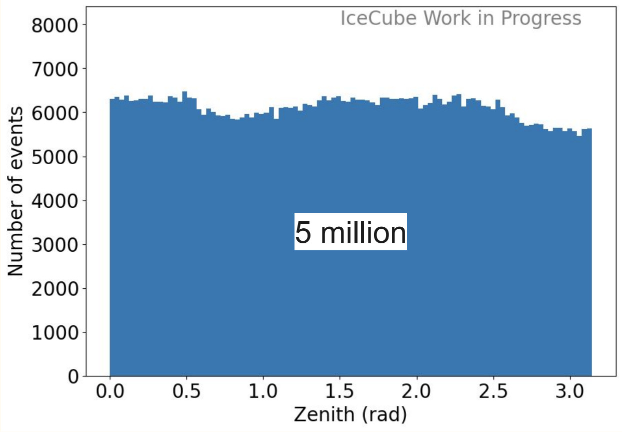
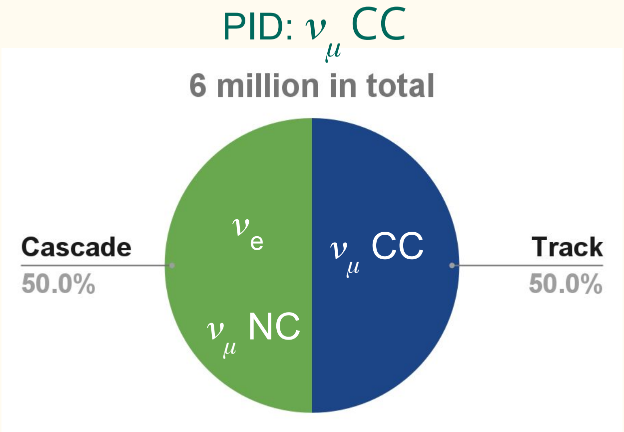
Training Samples

- Balanced MC samples;
- Energy, direction, interaction vertex are trained on ν_μ CC









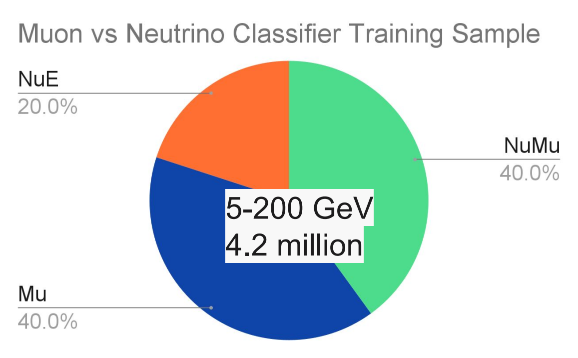
Training Samples

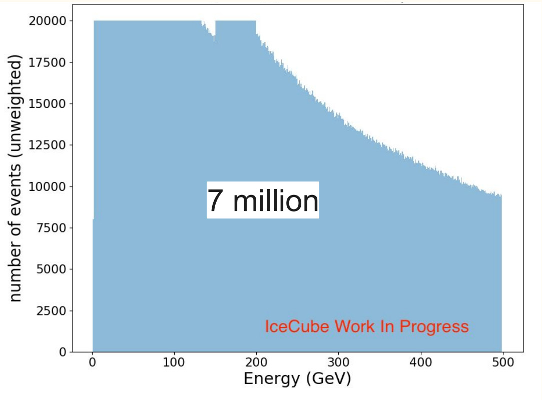
Energy: nDOM >= 7

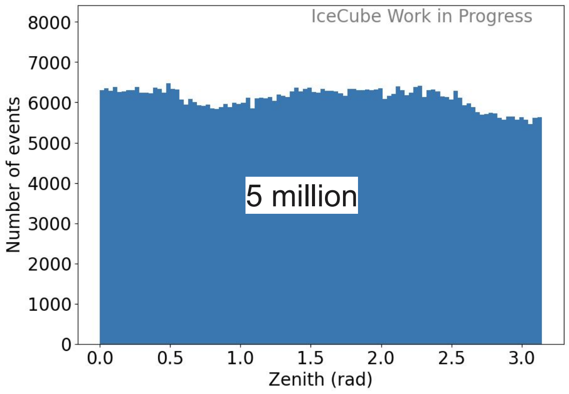
Muon : nDOM >= 4; 5–200 GeV

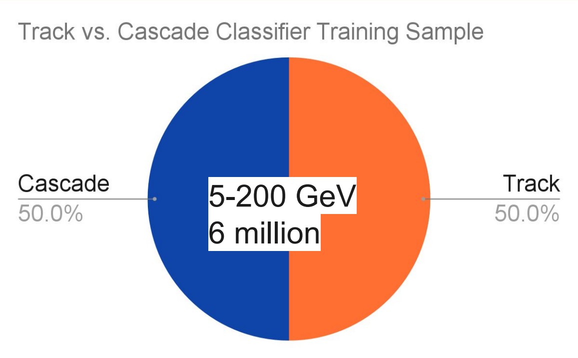
Muon, PID, Vertex: nhits >= 8 hit 5-200 GeV

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









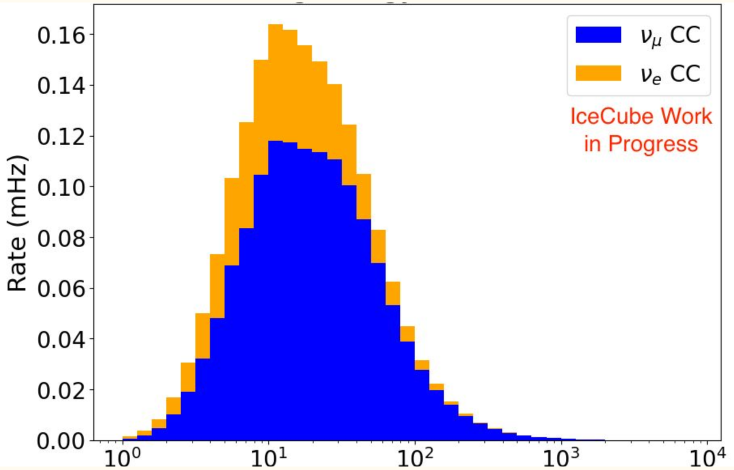
Performance: Speed

	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

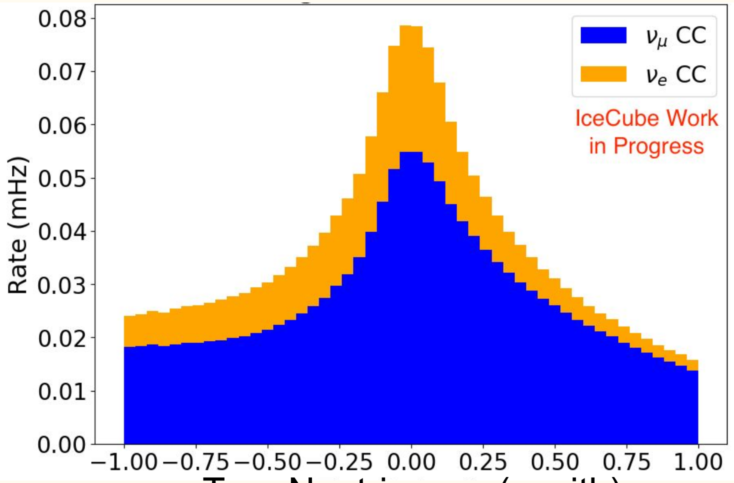
- CNN runtime improvement: ~3,000 times faster;
    - CNNs are able to process in parallelize with clusters → can be even faster!
- Big advantage: large production of full Monte Carlo simulations ~O(10^8).

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)



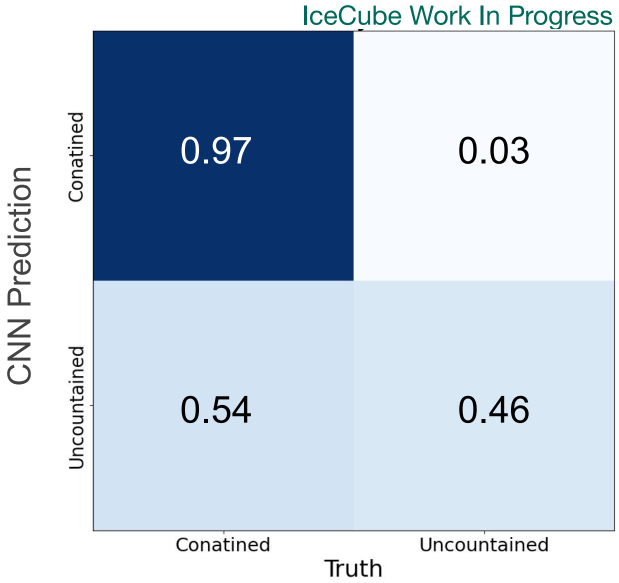
True Neutrino Energy (GeV)

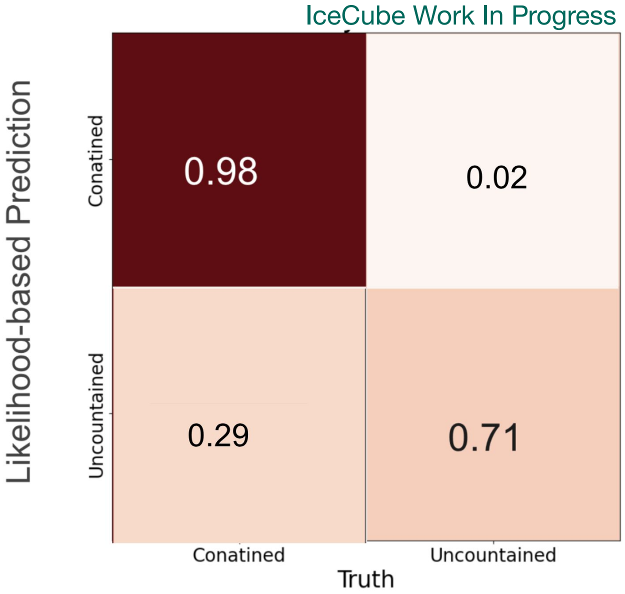


True Neutrino cos(zenith)

Performance: Vertex

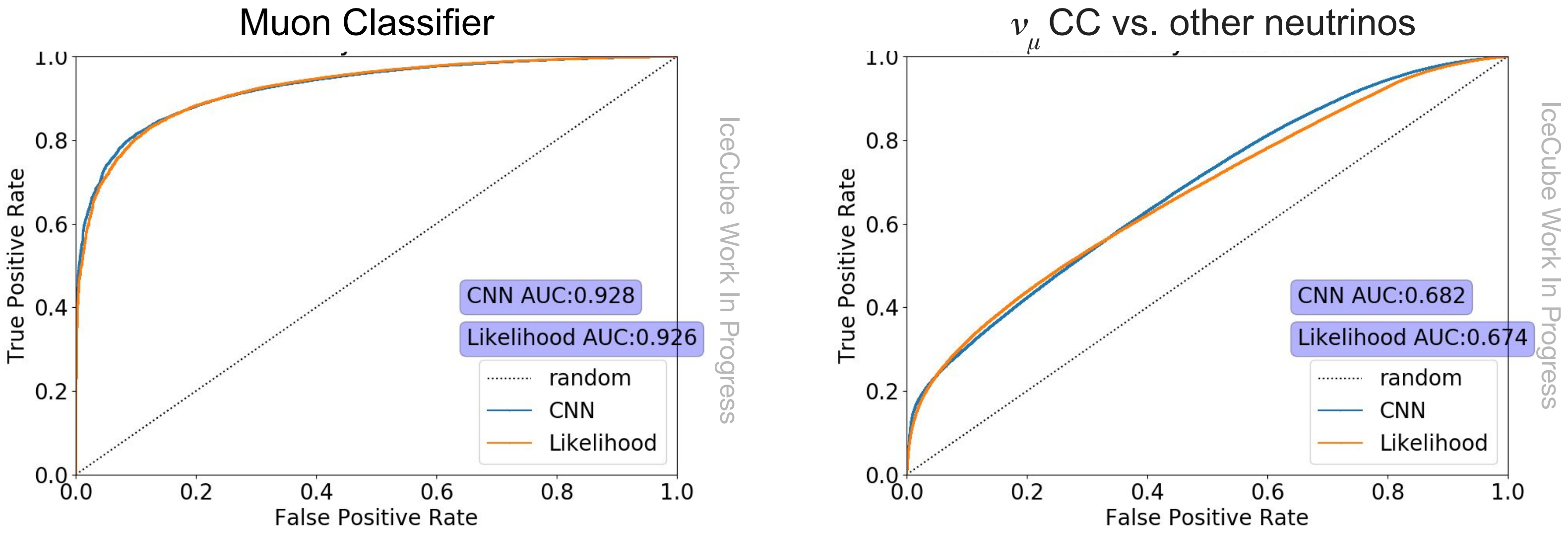
- Selecting events starting near DeepCore;
- Comparable purities in selected ν_μ CC samples.





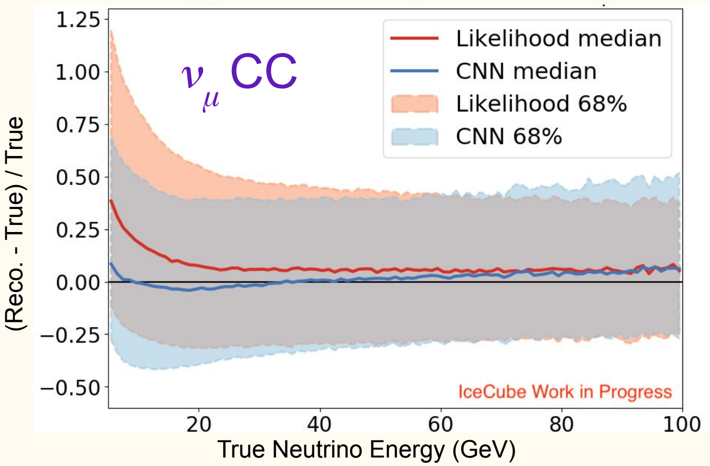
Performance: Muon and PID Classifiers

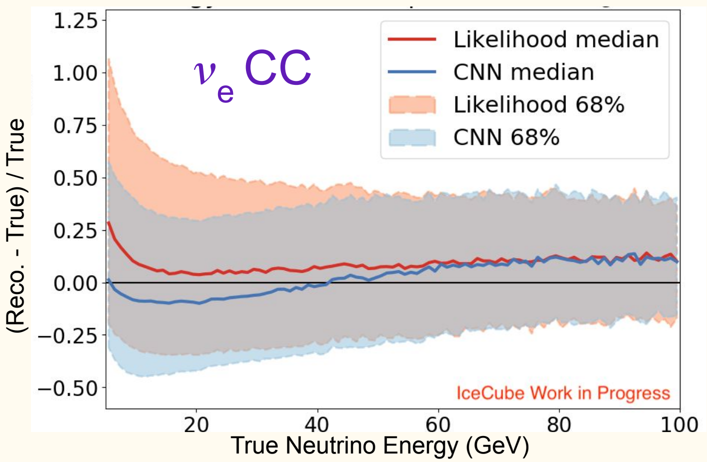
- Comparable performance to the current methods:
  - Similar AUC values.
- Hard to identify track from cascades at low energy → less DOMs see photons.



Performance: 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;





Performance: Zenith

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