For the IceCube Collaboration

Measurement of Atmospheric Muon Neutrino Disappearance using CNN Reconstructions with IceCube

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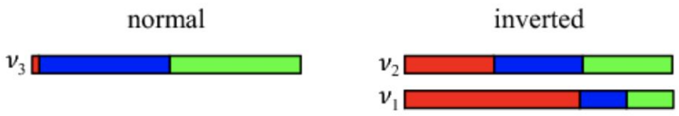
NuFact 2022

Neutrino Oscillation

- Produced and detected in 3 flavor states;
- Propagate in mass states;
- Described by PMNS matrix.



[IceCube NMO: M. Rodriguez]

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \boxed{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

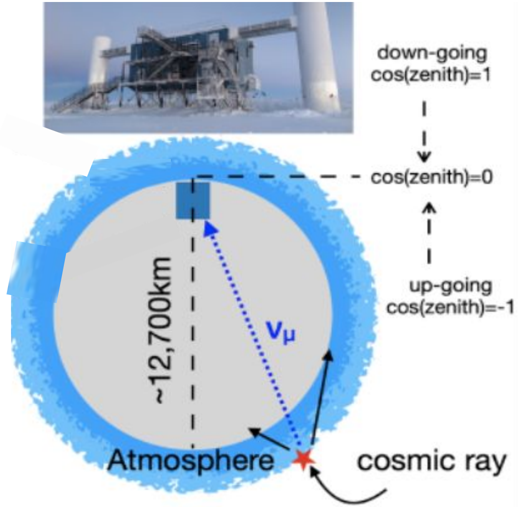
Atmospheric & LBL   reactor & LBL   Solar

Some parameters need to be better measured: θ_{23} , Δm^2_{32}

Neutrino Oscillation

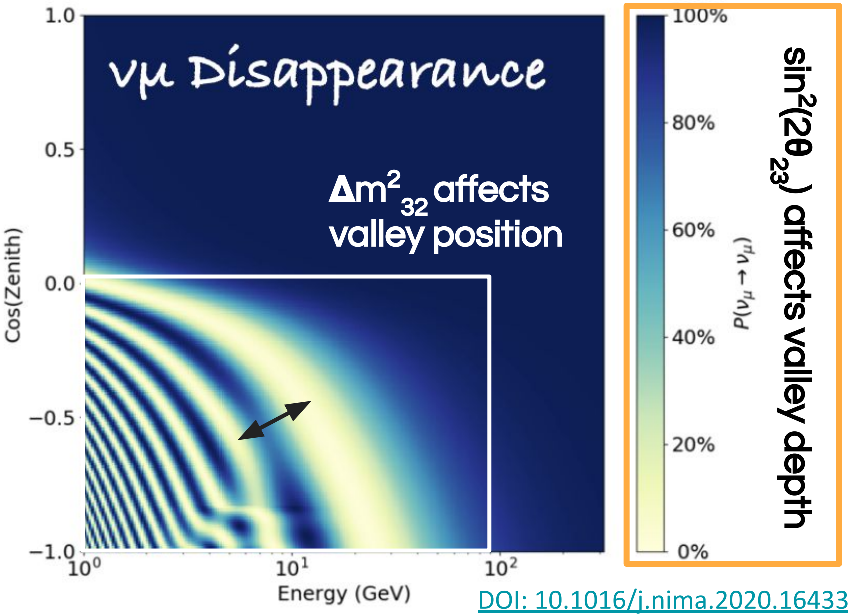
- **Atmospheric muon neutrino** beam from cosmic ray interactions;
- Neutrino **distance of travel** (L) calculated using **arrival direction (zenith)**

Reconstruction is critical for studying atmospheric neutrino oscillation at 10-GeV scales



- ν_μ disappearance probability:

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



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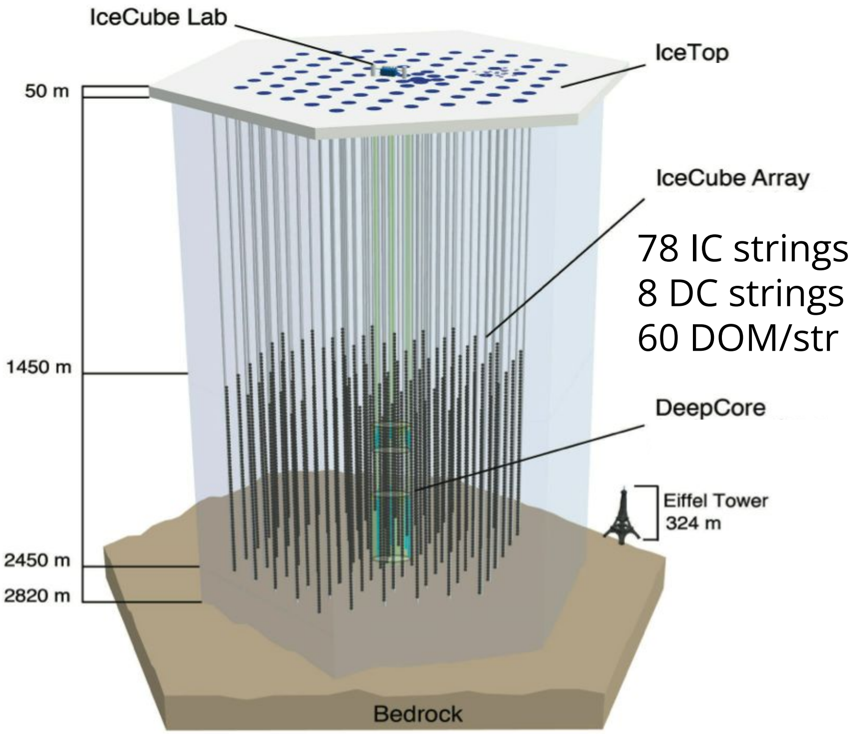
IceCube Neutrino Observatory

- 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**;



List of Reconstructed Variables

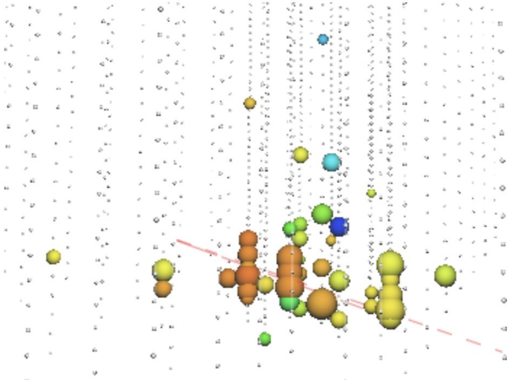
Reconstructions:

- Energy
- Direction (L)
- PID
- Interaction vertex
- Muon classifier

} Analysis binnings (Energy, Direction (L), PID)

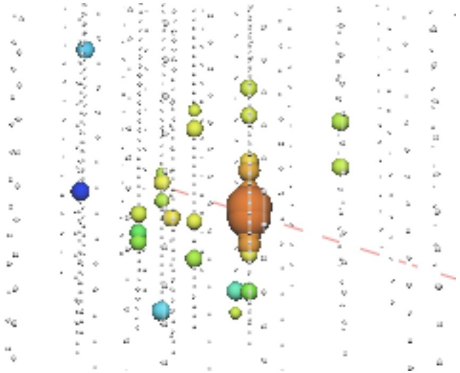
} Selections (Interaction vertex, Muon classifier)

Track-like events:
ν_μ CC, 17% ν_τ CC



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

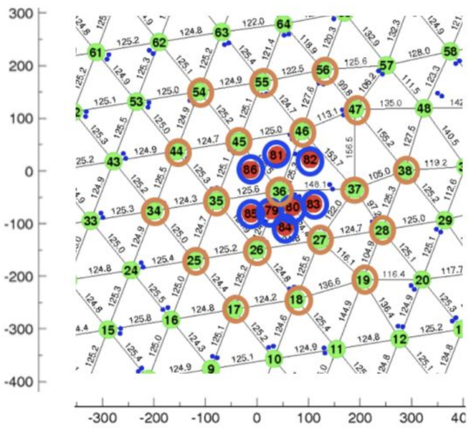
Cascade-like events:
ν_e CC, NC, ν_τ CC

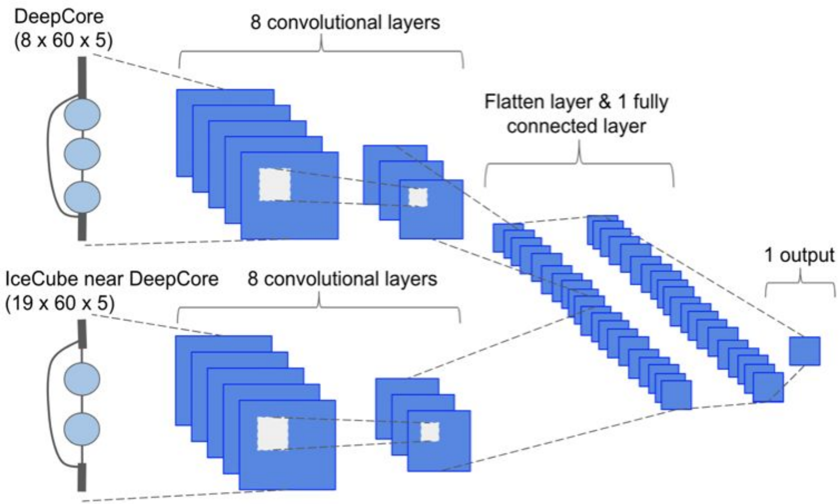


$\nu_{e(67GeV)} \rightarrow e^-_{(57.5GeV)} + hadrons$

GeV-Scale CNN Architecture

- Only use DeepCore & nearby IceCube strings
- Five CNNs trained & optimized separately





Inputs: 5 summarized variables

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

Regression:

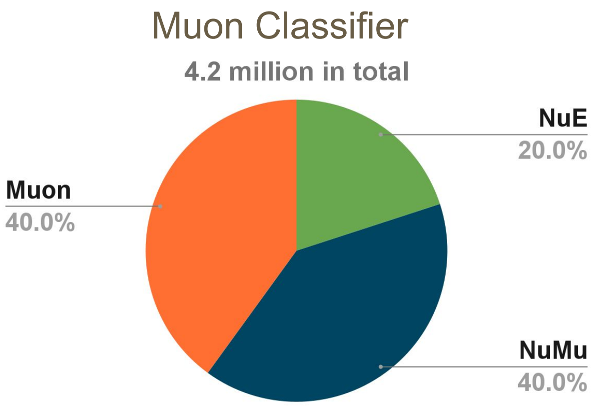
- Energy, direction, interaction vertex

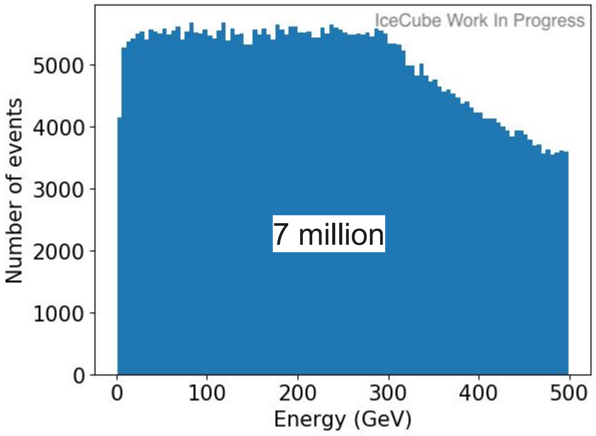
Classification:

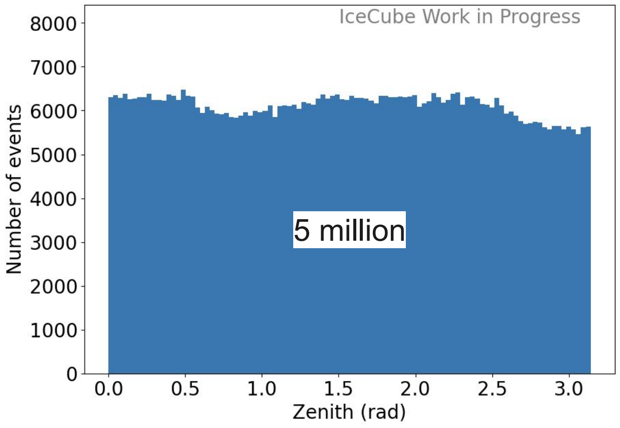
- PID, muon classifier

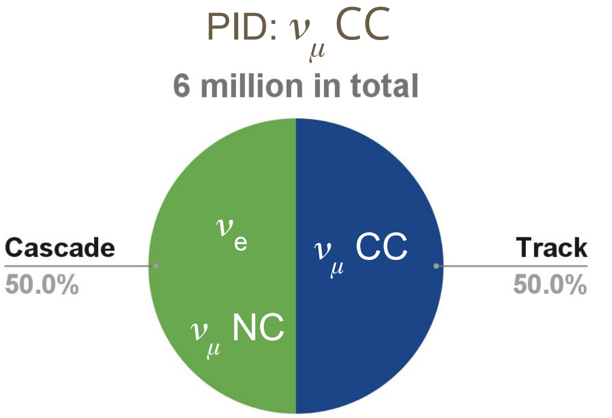
Training Samples

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





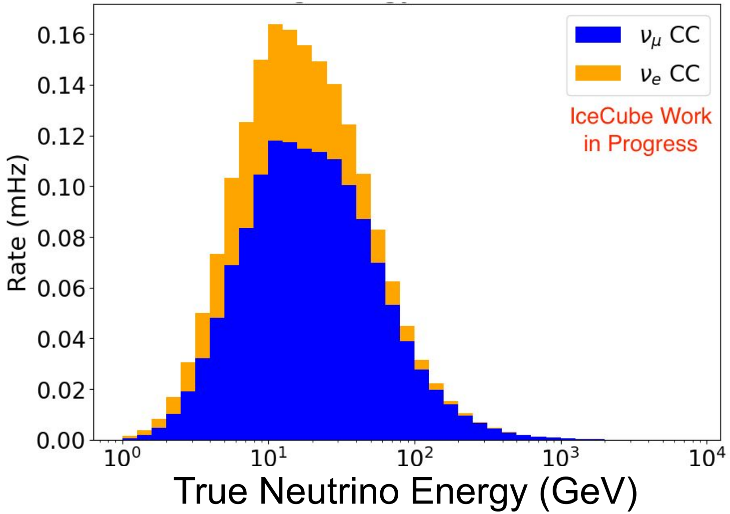


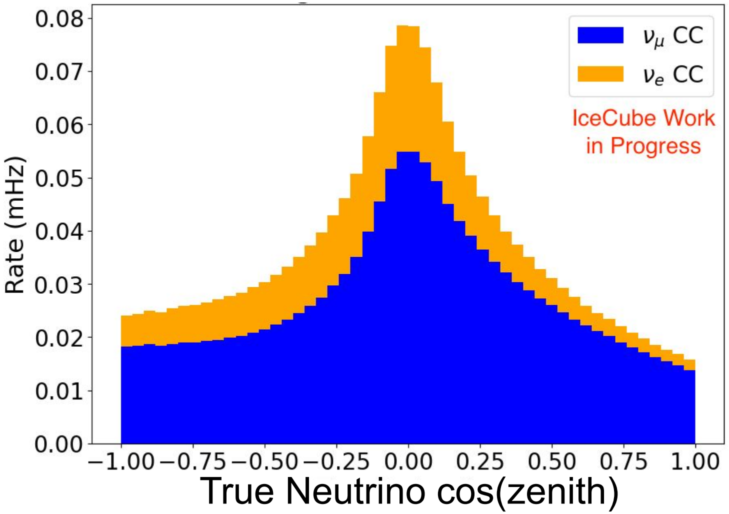


Testing Samples

- 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)

K. Leonard IceCube plenary talk

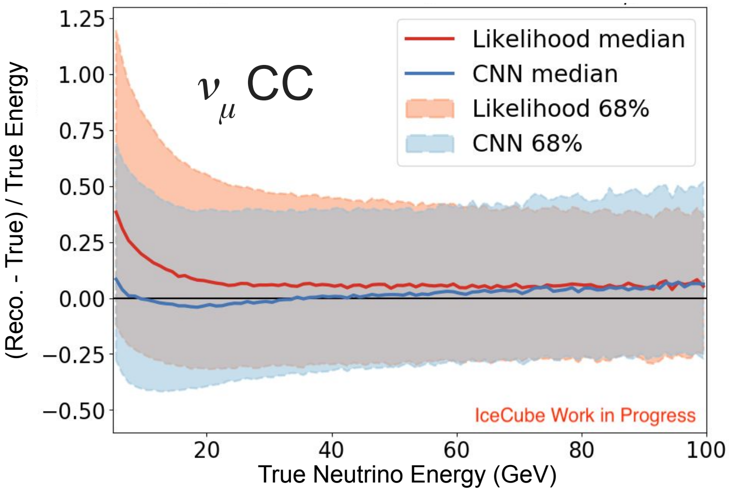


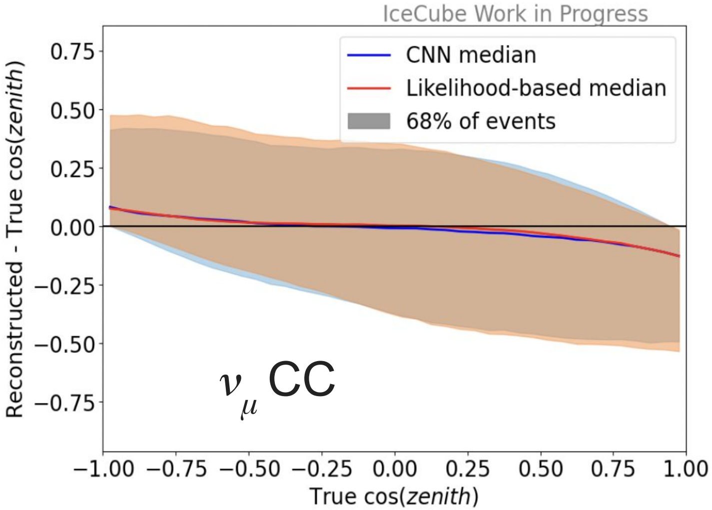


S. Yu, *et al.*
ICRC2021 proceeding: zenith
ICRC2021 proceeding: energy

Reconstruction Performance

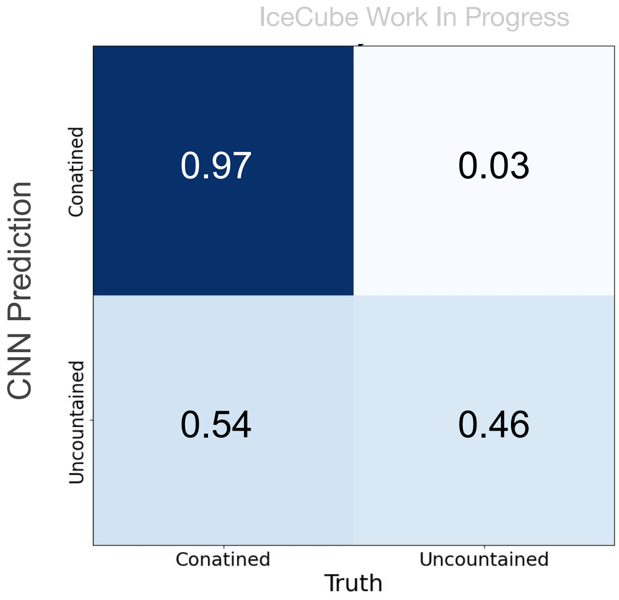
- Flat median against true neutrino energy and zenith;
- CNN has comparable resolution to current method, and better at low energy (majority of sample)

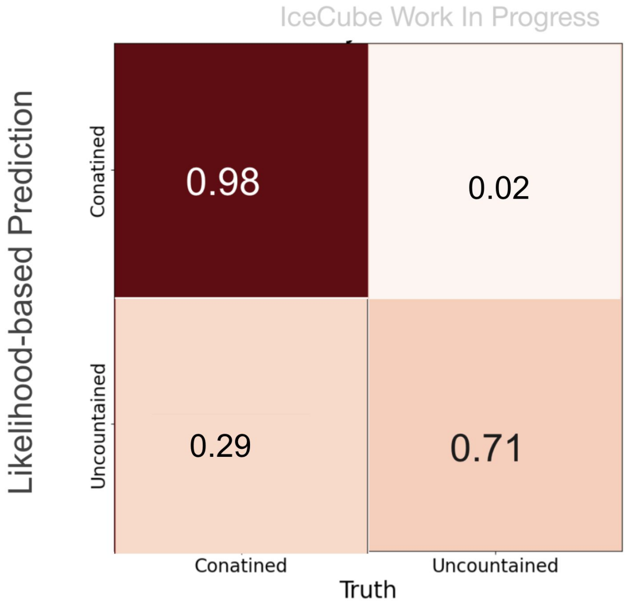




Performance: Vertex

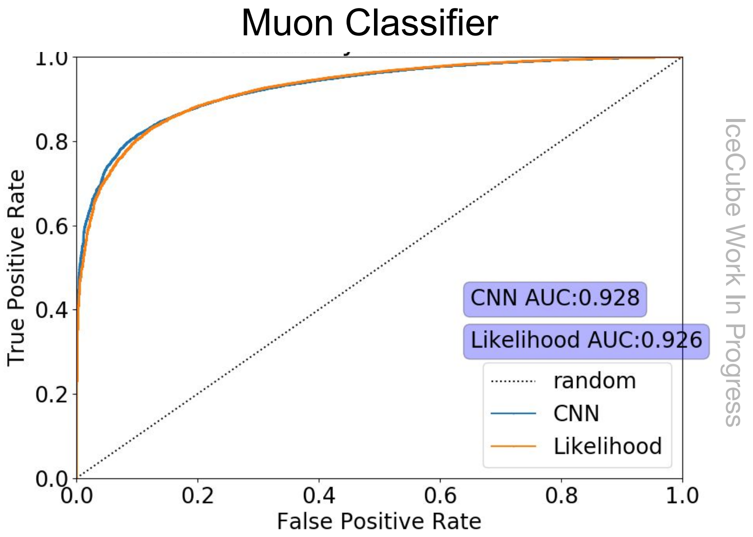
- Selecting events starting near DeepCore;
- Comparable purities in selected ν_μ CC samples.

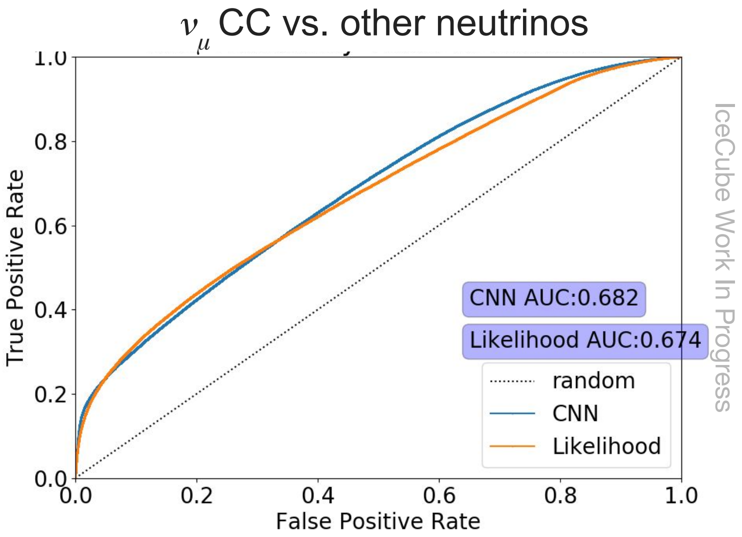




Performance: Muon and PID Classifiers

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





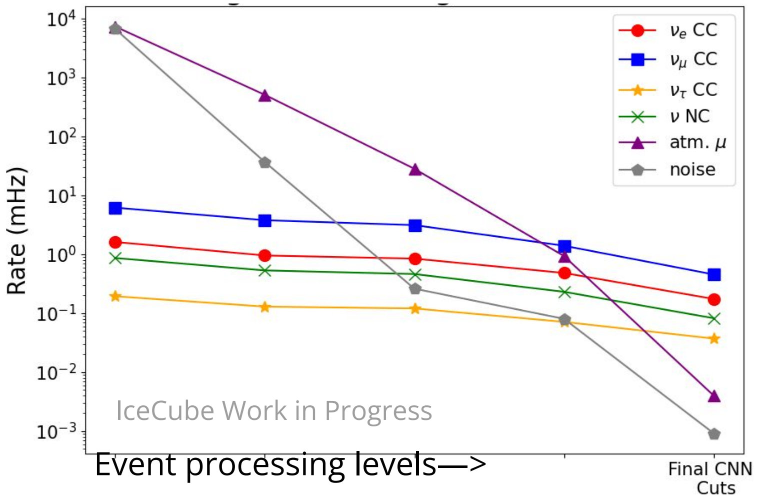
Performance: Speed

	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: ~6,000 times faster;
  - CNNs are able to process in parallelize with clusters → can be even faster!
- Big advantage: large production of full Monte Carlo simulations ~$O(10^8)$.

Preliminary Sample

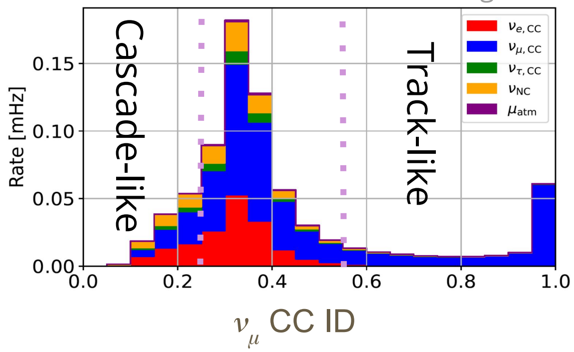
- Event processings up to final level shared with the current analysis: K. Leonard IceCube plenary talk
- Final sample: high signal (ν_μ CC) and low background (noise and cosmic-ray muon) rates (~0.6%).

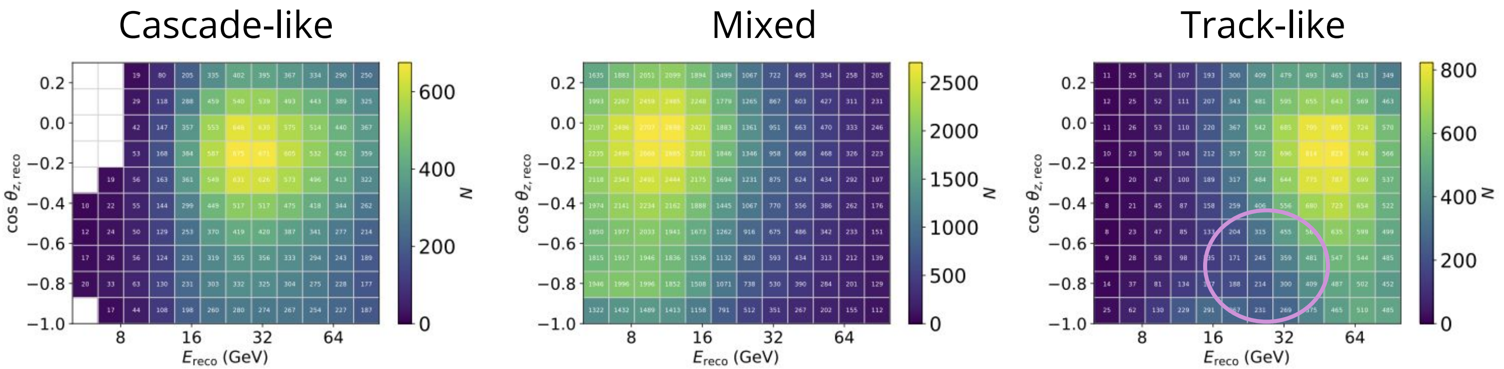


Measuring Oscillation

Measure atmospheric muon neutrino disappearance in 3D binning: reconstructed [energy, cos(zenith), PID]

- PID discriminates ν_μ CC vs. all other interactions
- Robust against systematic uncertainties



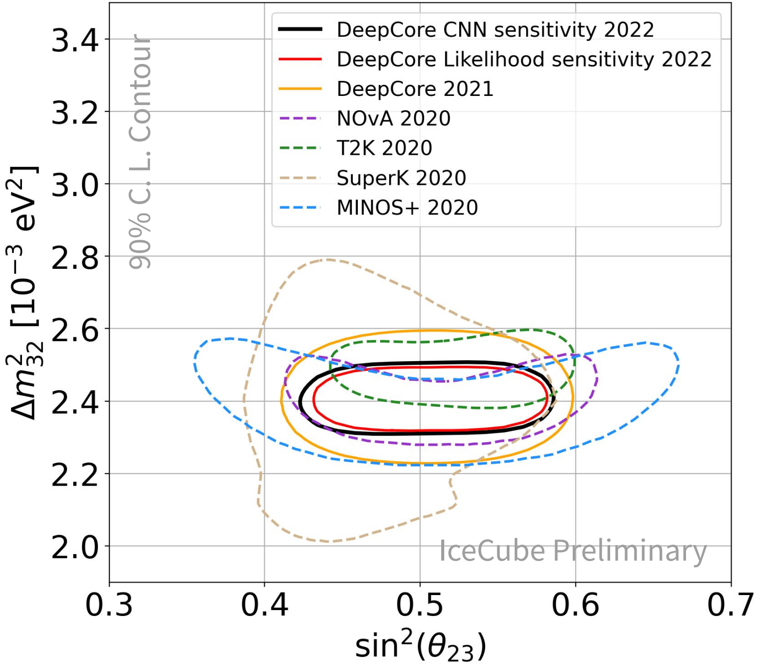


IceCube Work in Progress

Oscillation Sensitivity

Oscillation analysis using CNN reconstruction has similar sensitivity (black) as IceCube's current likelihood-based analysis (red)

- Sensitivities projected from DeepCore 2021 (golden [K. Leonard IceCube plenary talk](#)
- 6000 times faster!
- Apply to future detector — the Upgrade
- Analysis is unblinding, new results soon!



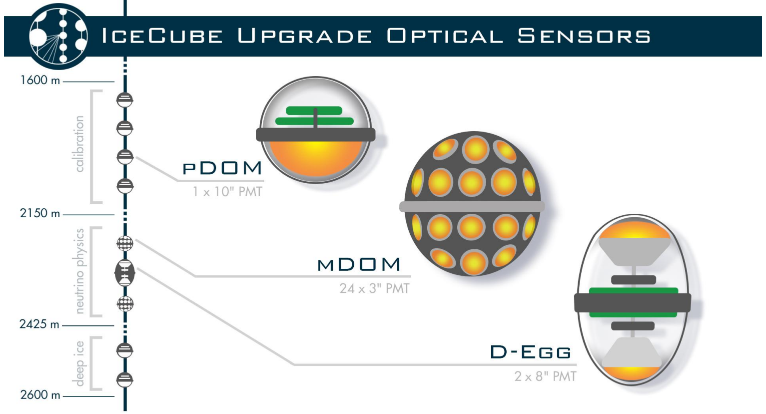
Future

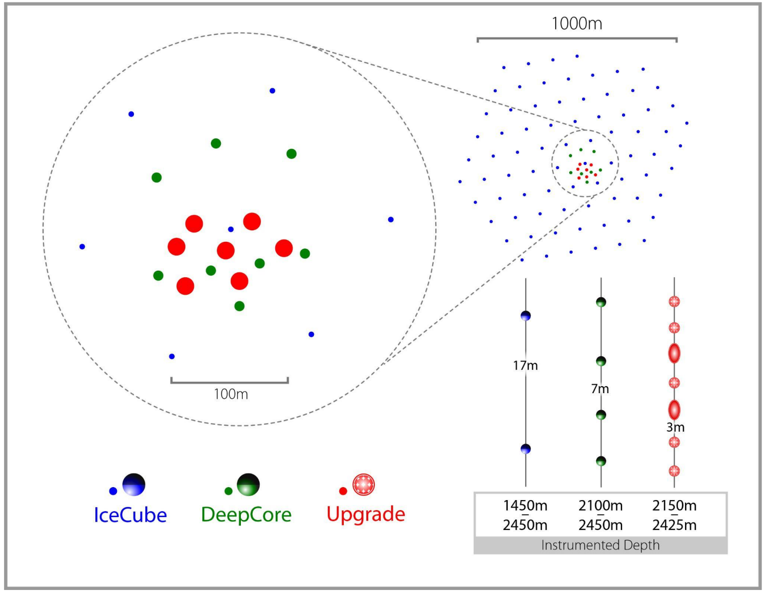
The Upgrade detector:

- More densely instrumented strings in the center
- DOM: multiple PMT designs
- **Target deploying 2024/25**

New reconstruction methods needed:

CNN is one solution





Conclusion

- CNNs are used for multipurpose reconstructions for IceCube oscillation analysis:
  - Energy, direction, interaction vertex;
  - PID (numu CC vs. background neutrinos), muon classifier.
- Approximately 6000 times faster in runtime than the current method;
  - Big advantage for IceCube full production → large atmospheric neutrino sample.
- CNNs have better or comparable performances to the current reconstruction method;

- Ongoing and future work:
  - numu disappearance analysis using CNN reconstructions;
  - Optimizations on CNN itself;
    - Train for "ending point", etc.
  - Implement it for future experiment → Upgrade.

Thank you!

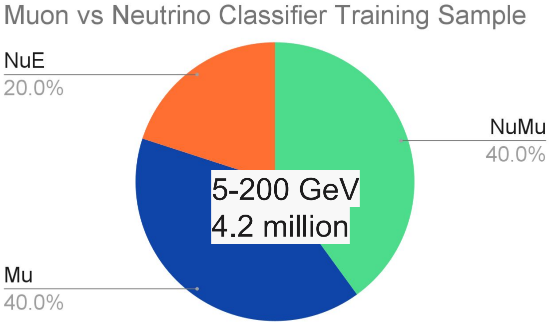
Training Samples

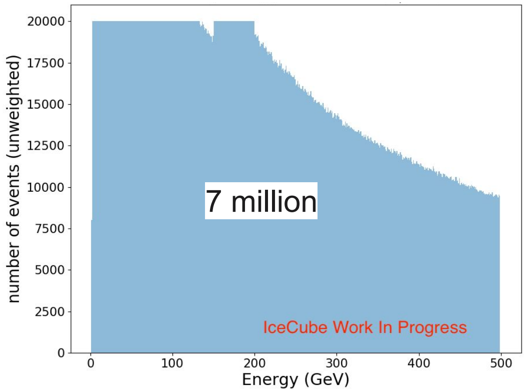
Energy: nDOM >= 7

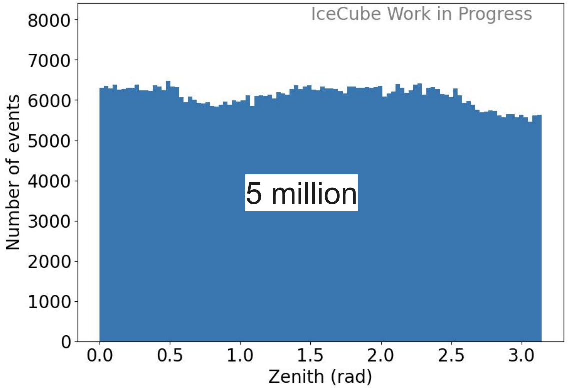
Muon : nDOM >= 4; 5–200 GeV

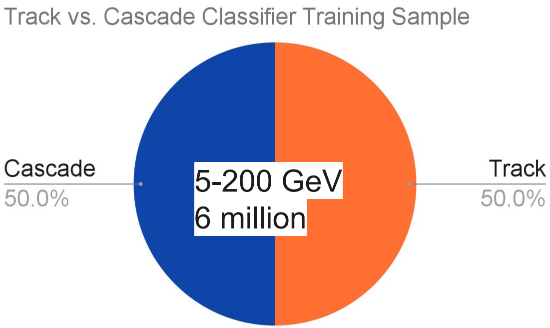
Muon, PID, Vertex: nhits >= 8 hit 5-200 GeV

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





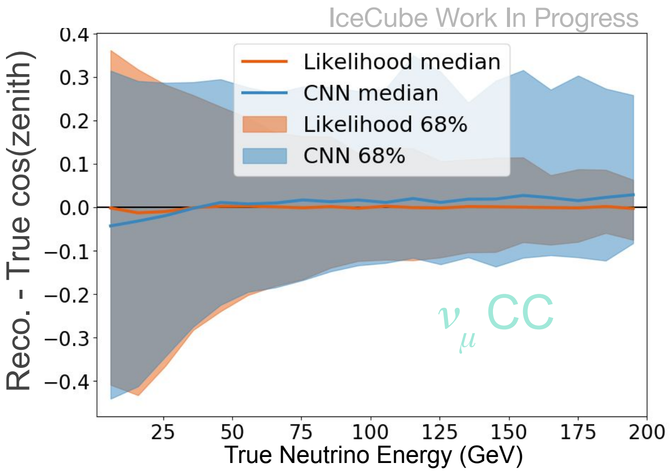


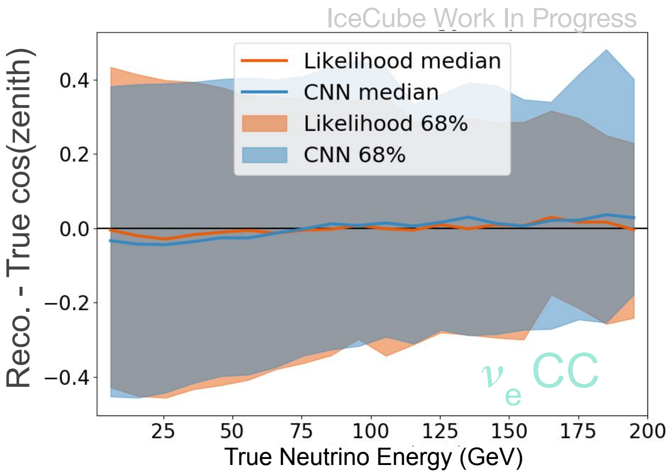


S. Yu, et al. ICRC 2021 proceeding.

Performance: Direction

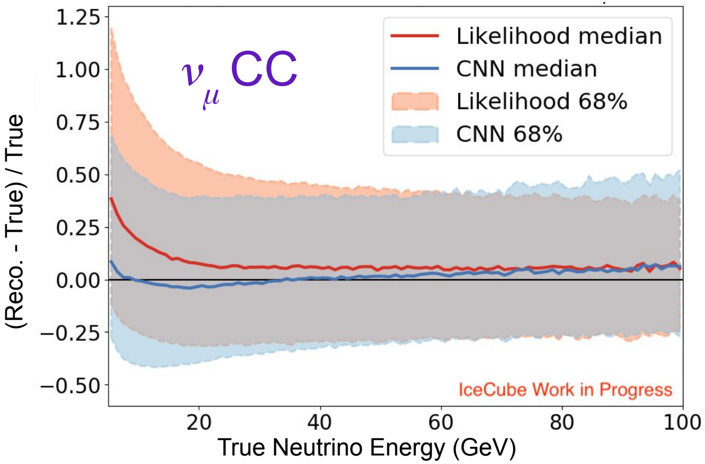
- Direction bias flat against true energy;
- Comparable to current method;
- Better resolution for ν_μ CC (signal);
- High energy (>100 GeV) neutrinos leaving DeepCore
  - Need containment cut: interaction vertex reconstruction.

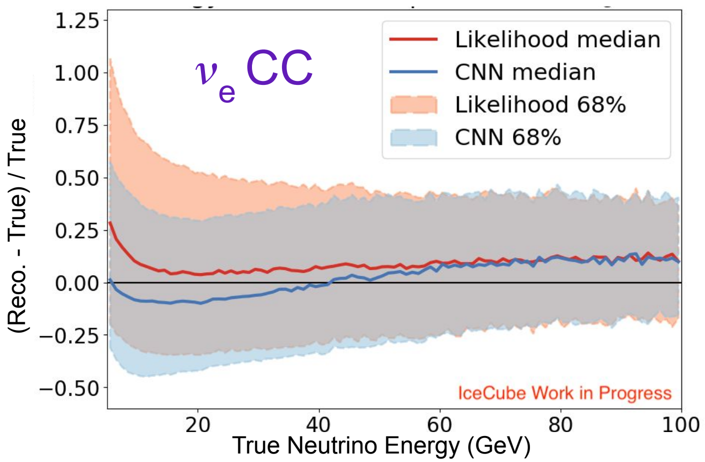




Performance: Energy

- 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;

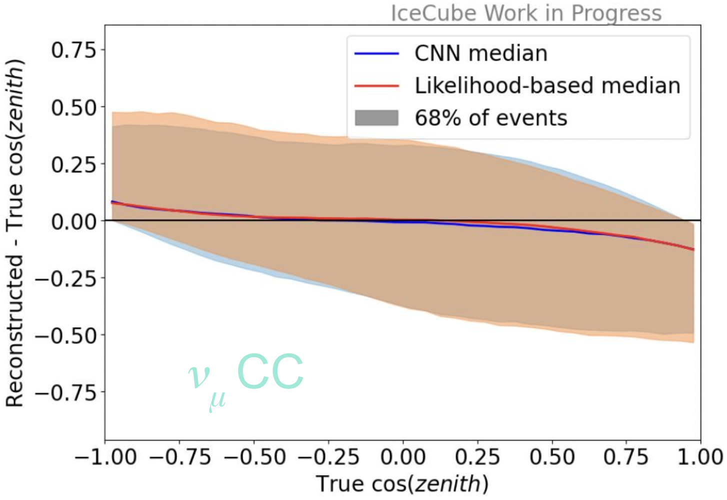


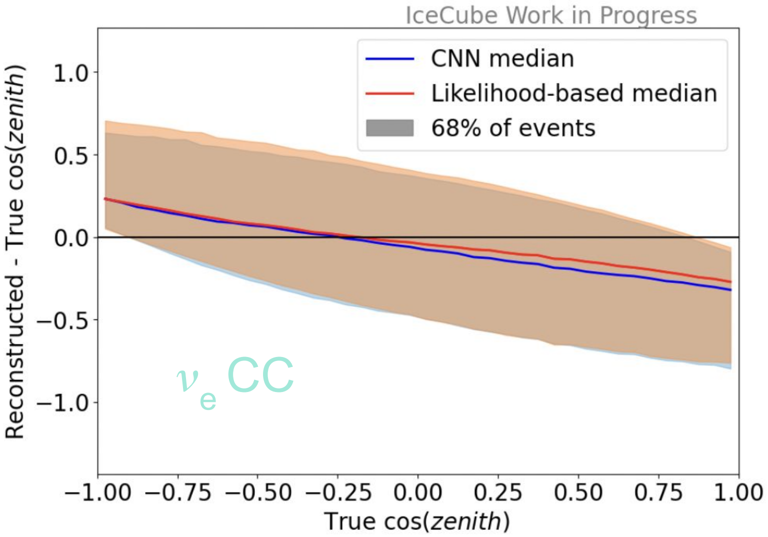


S. Yu, et al. ICRC 2021 proceeding.

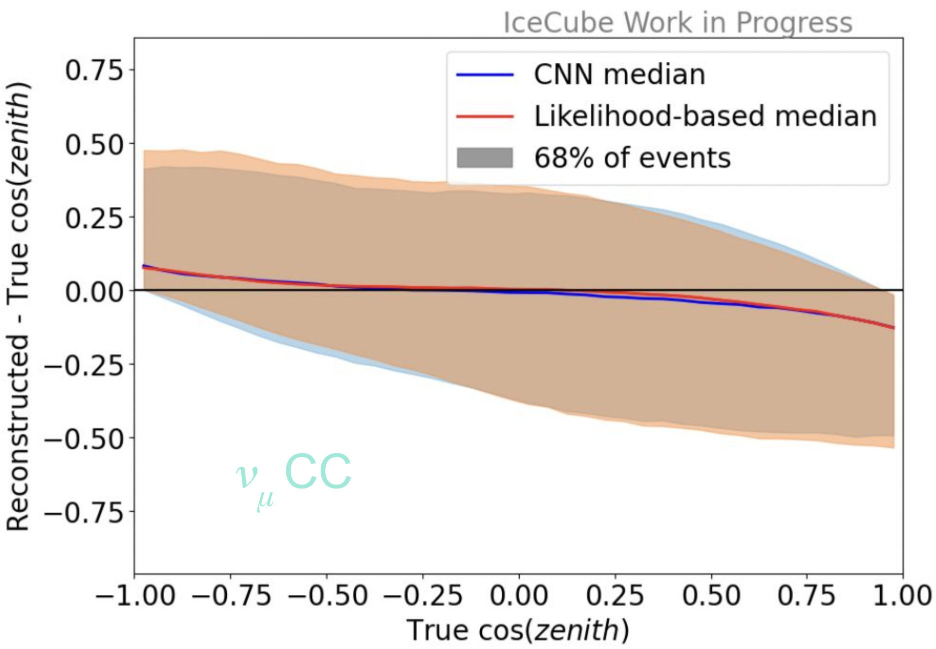
Performance: Zenith

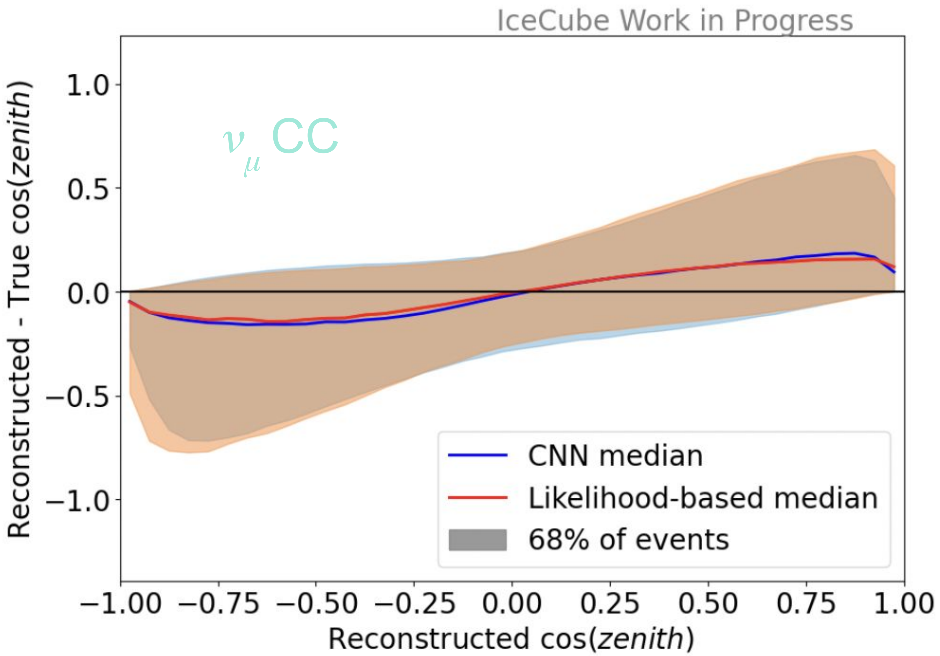
- Flat median against true direction;
- Comparable to current method in both signal and background.



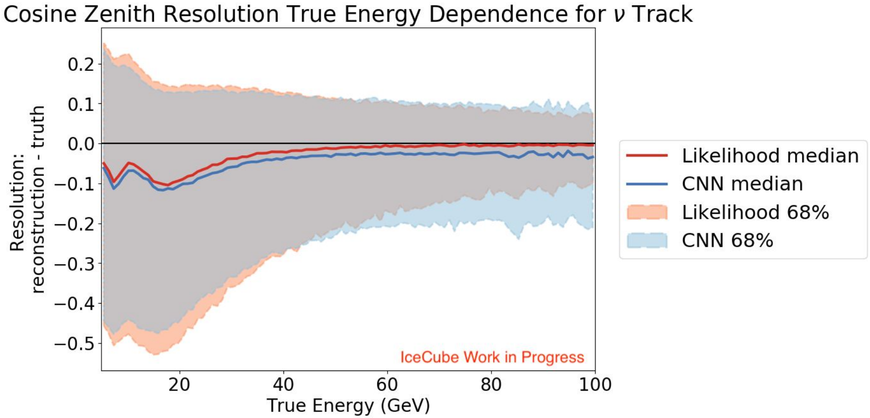


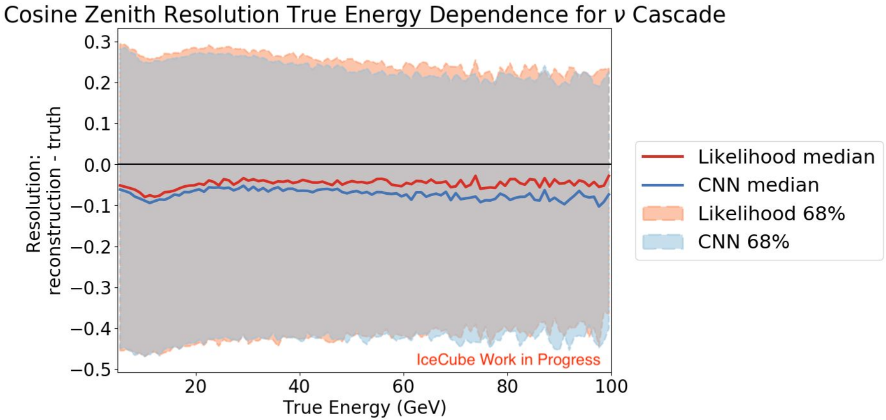
Performance: Zenith (Contained, 5-300 GeV Sample)





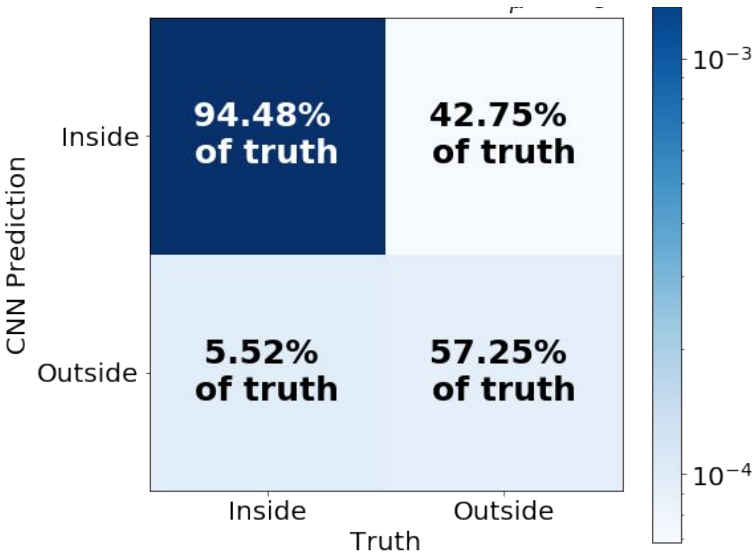
Performance: Zenith (Analysis Samples)

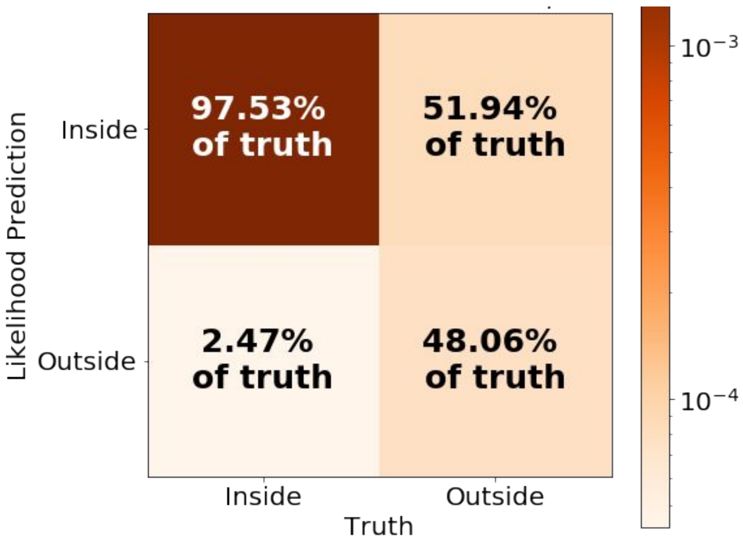




Performance: Vertex

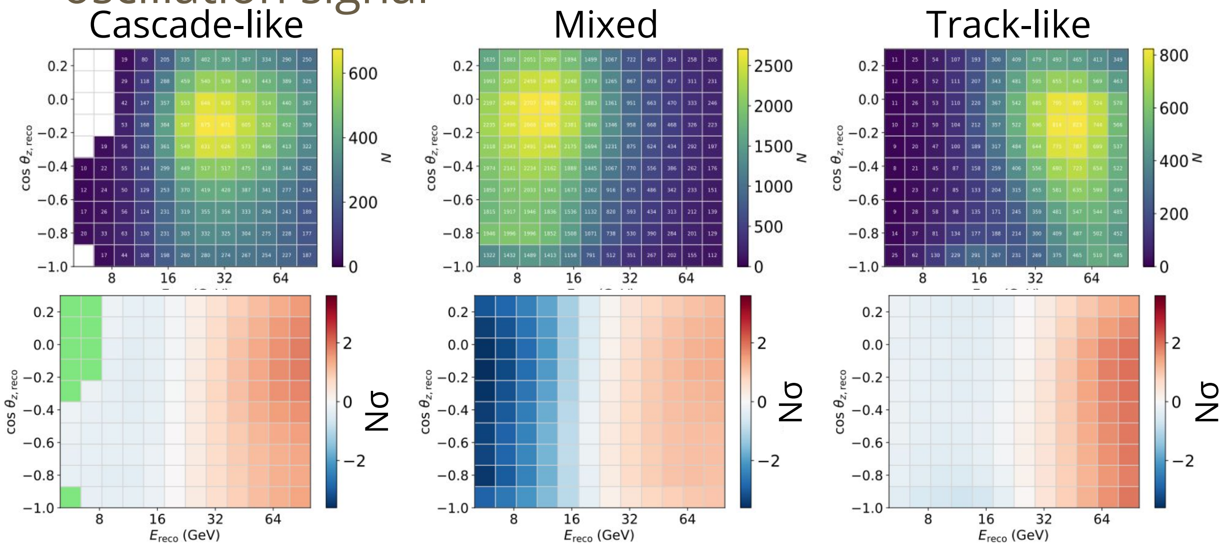
Efficiency matrixes





Systematic Effect: Neutrino Flux Model

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



IceCube Work in Progress

Fit for spectral index among other model systematics

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

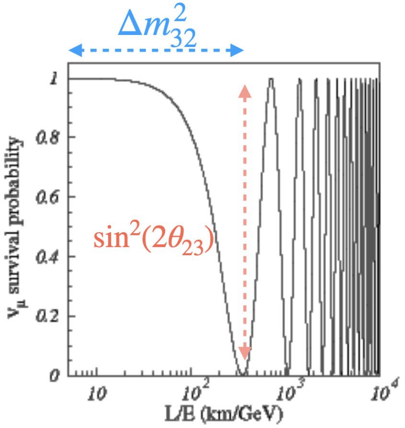
Flux model systematic: Neutrino flux spectral index changed by +1**σ**

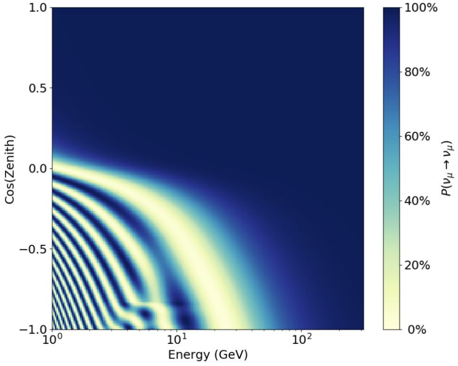
Physics Motivations: Neutrino Oscillations

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^{PMNS} \times \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

- Neutrino flavor eigenstates are superpositions of mass eigenstates.
- Relations described by PMNS matrix.

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





- Most parameters are well measured.
- Some parameters need to be better measured: θ_{23} and Δm^2_{32}

IceCube Oscillation Results

Main results + current projection on sensitiv
Kayla's plenary on Monday

We'll show an alternative way of doing numu
convolutional neural networks: 6000 times f
portable for the future expriment, the Upgra