MICHIGAN STATE UNIVERSITY

For the IceCube Collaboration

IceCube
South Pole Neutrino Observatory

Direction Reconstruction using a CNN for GeV-Scale Neutrinos in IceCube

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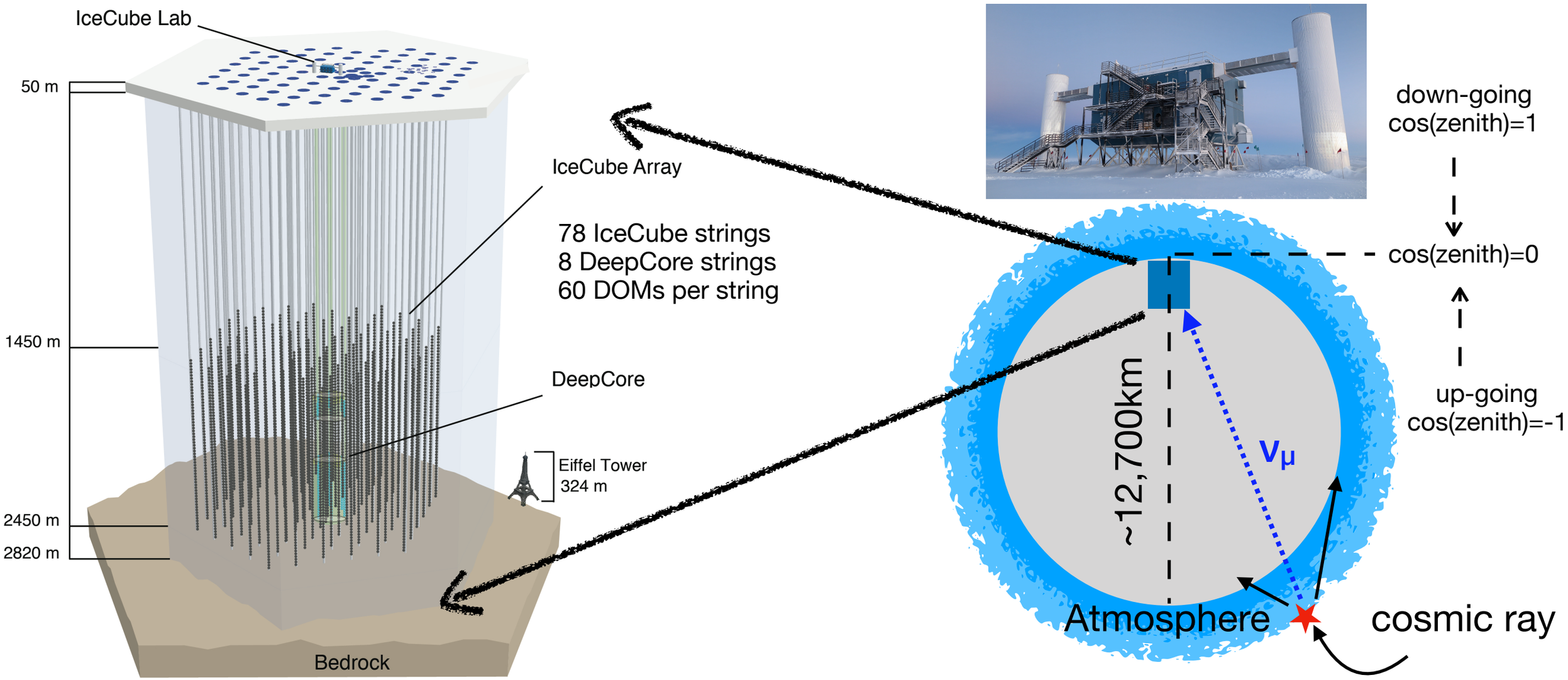
NSF

APS DIVISION OF PARTICLES & FIELDS

DPF 2021

The IceCube Neutrino Observatory



- Neutrino interactions in ice produce particles emitting Cherenkov radiation
- Digital optical modules (DOMs) detect photons: denser instrumented DeepCore detects GeV-scale events
- Abundant source of neutrinos from cosmic ray atmospheric interactions
- O(10^4) km baseline (L) inferred using arrival direction (zenith)

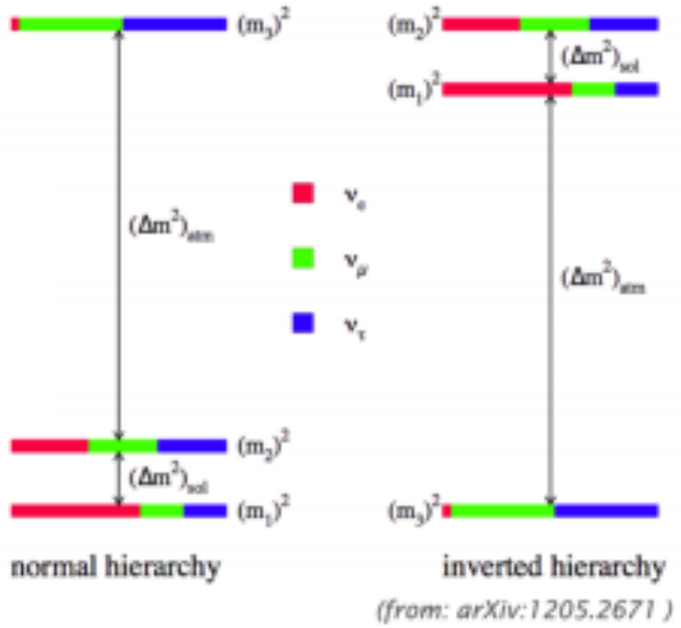
Neutrino Oscillations

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

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

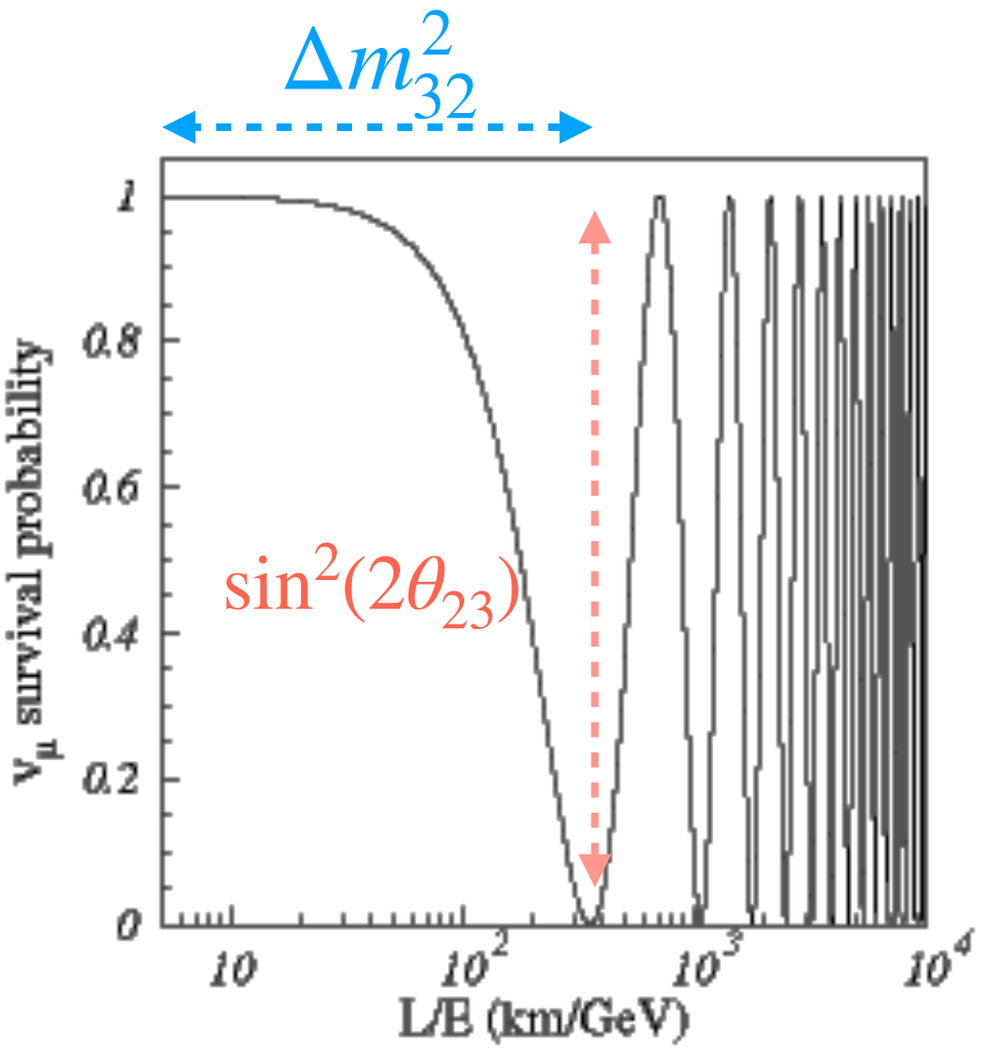
$$U^{PMNS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\,\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\,\delta_{CP}} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & 0 & \sin\theta_{12} \\ -\sin\theta_{12} & 1 & \cos\theta_{12} \\ 0 & 0 & 1 \end{bmatrix}$$

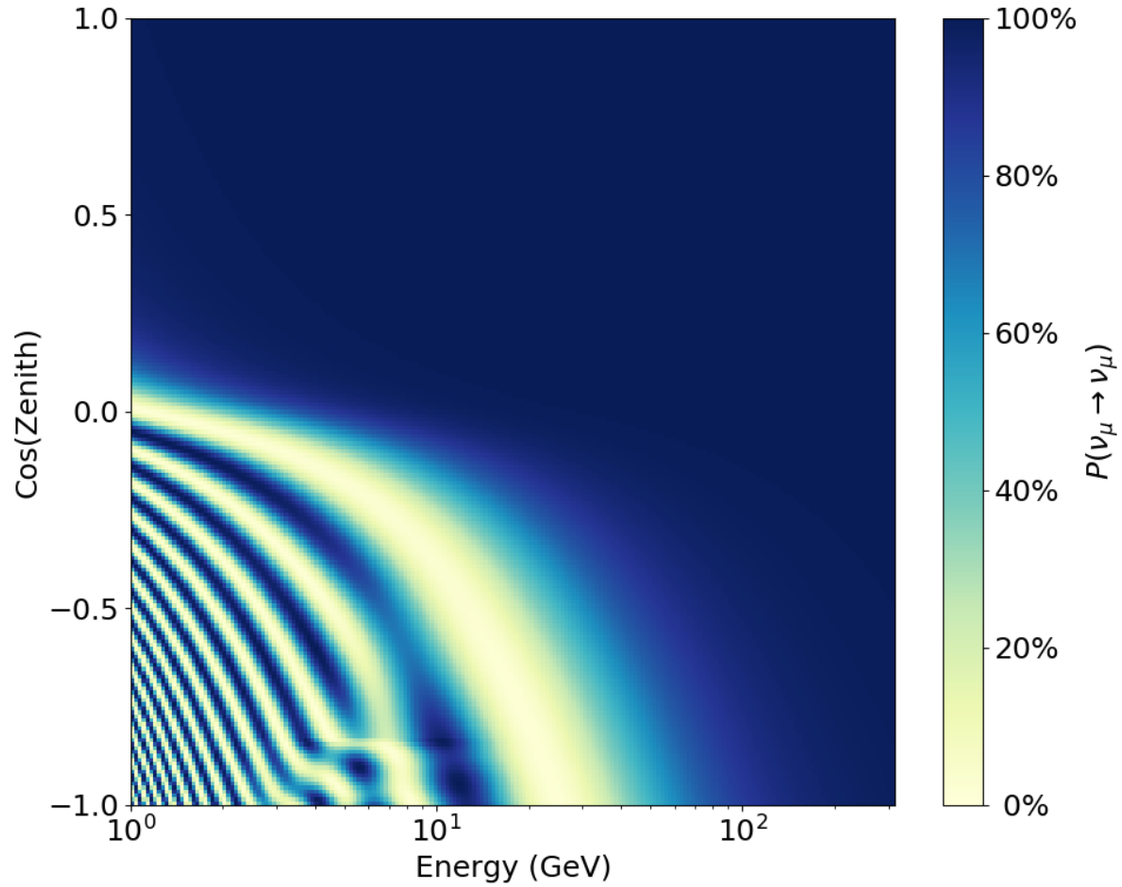
- Most parameters are well measured.
- Some parameters need to be better measured: θ_{23} and Δm^2_{32}



ν_μ Disappearance

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





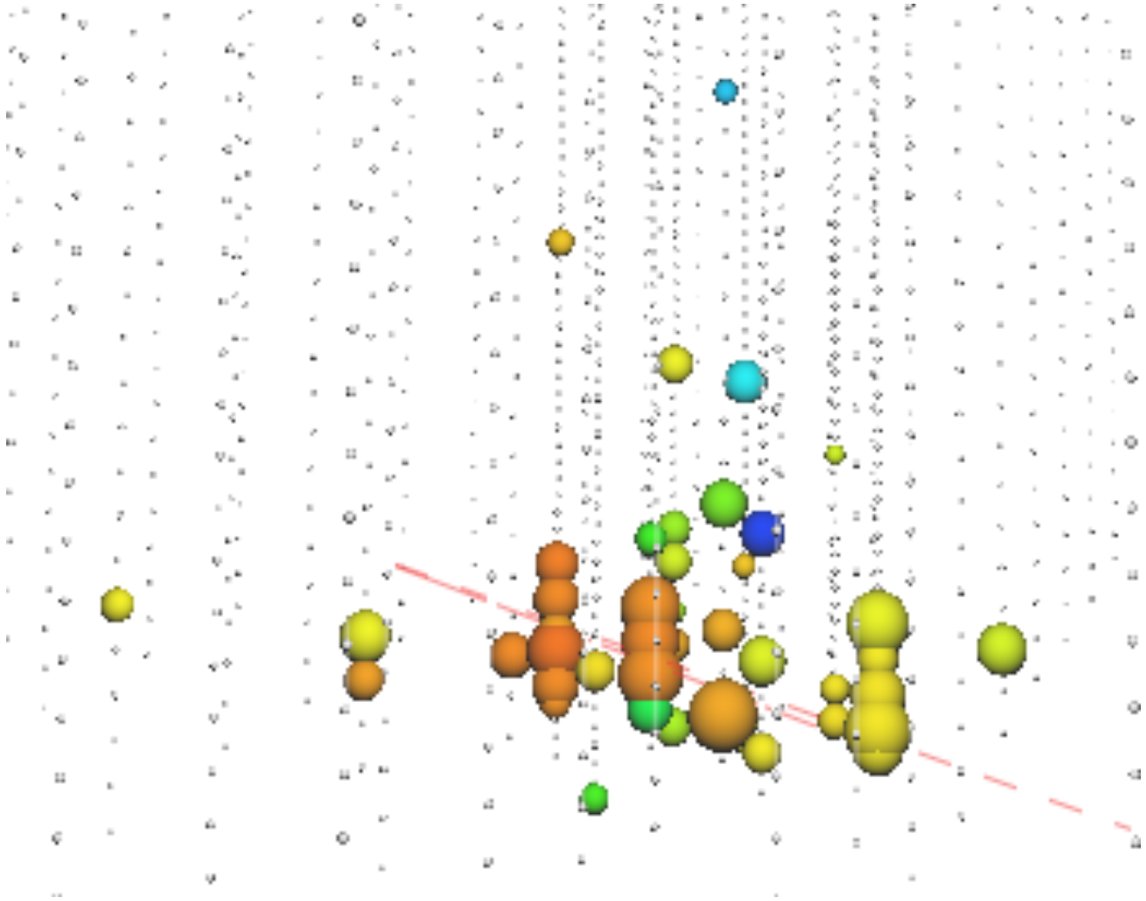
Event Display

Track-like Event:

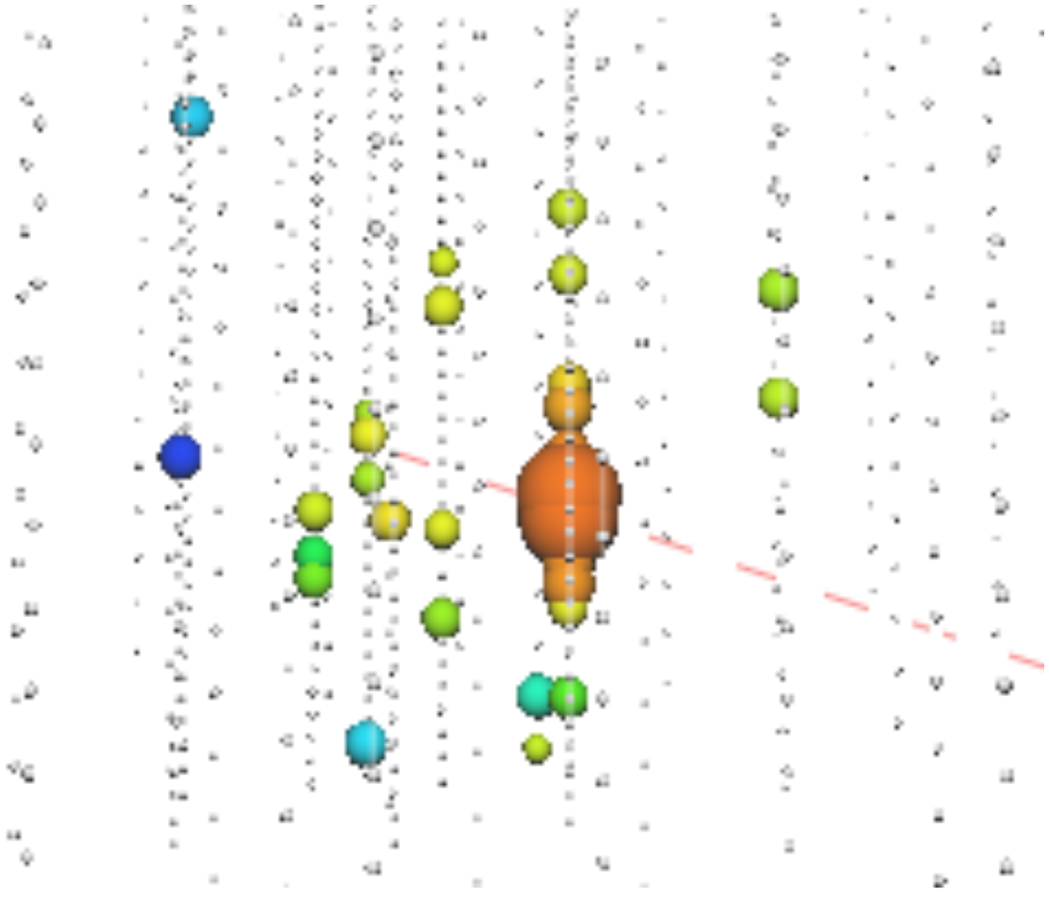
ν_μ charged-current interaction (CC) and 17% ν_τ CC

Cascade-like Event:

- Neutral current interaction
- ν_e CC and 83% ν_τ CC



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



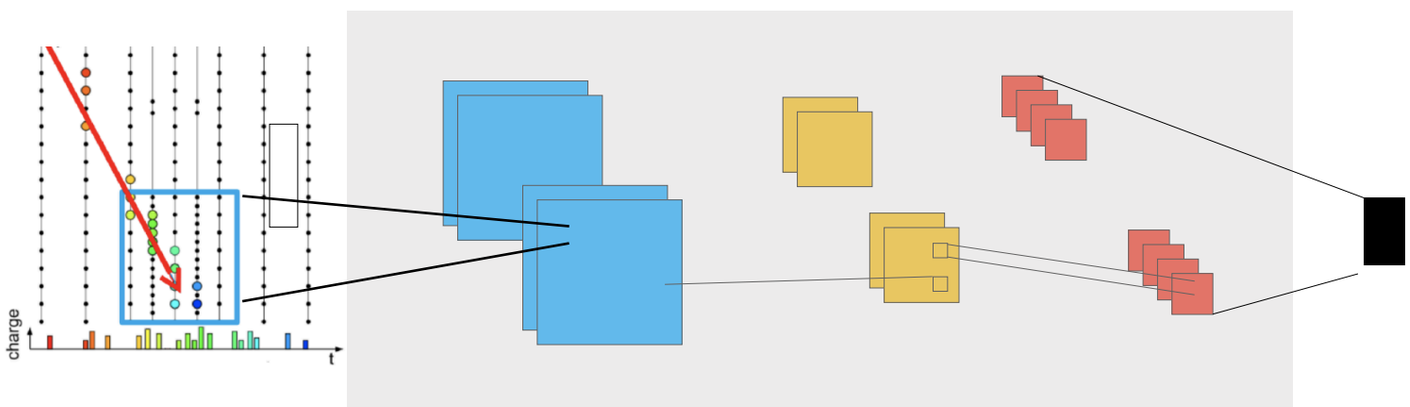
$$\nu_{e(67GeV)} \rightarrow e^-_{(57.5GeV)} + hadrons$$

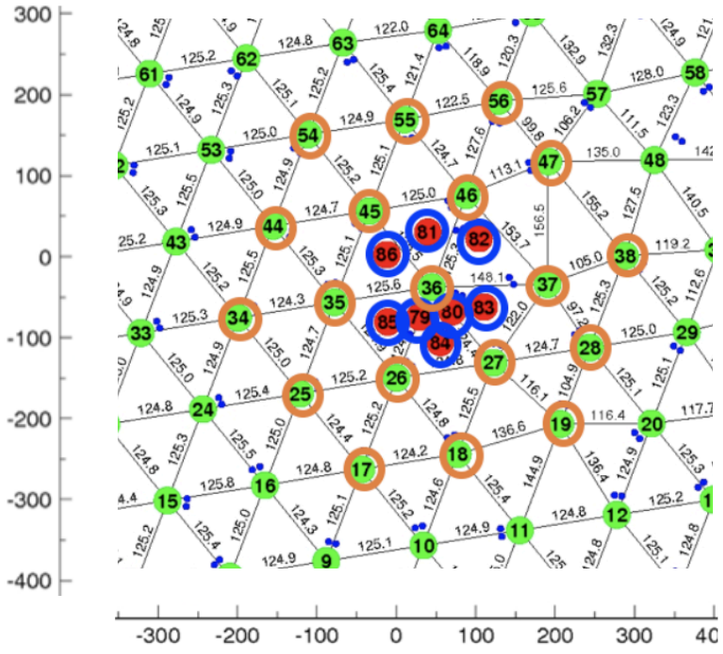
0 — 1

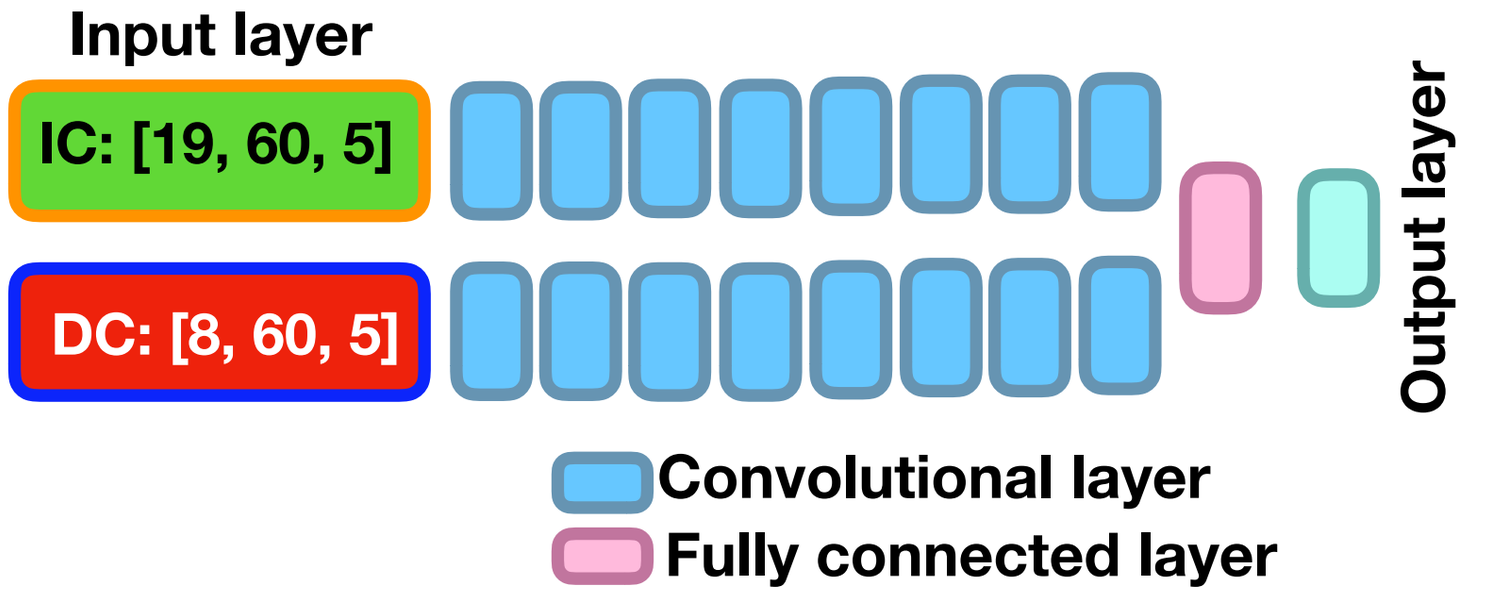
Time $[\mu s]$

Zenith Reconstruction

- **Tool:** a convolutional neural network, which extracts abstract features from the input images and predict output values
- **Output**:
  value of zenith from 0 to π
- **Input:**
  - 8 DC strings; 19 IC strings
  - 60 DOMs x 5 variables:
    sum of charges; time of first (last) hit; charge weighted mean (std.) of time

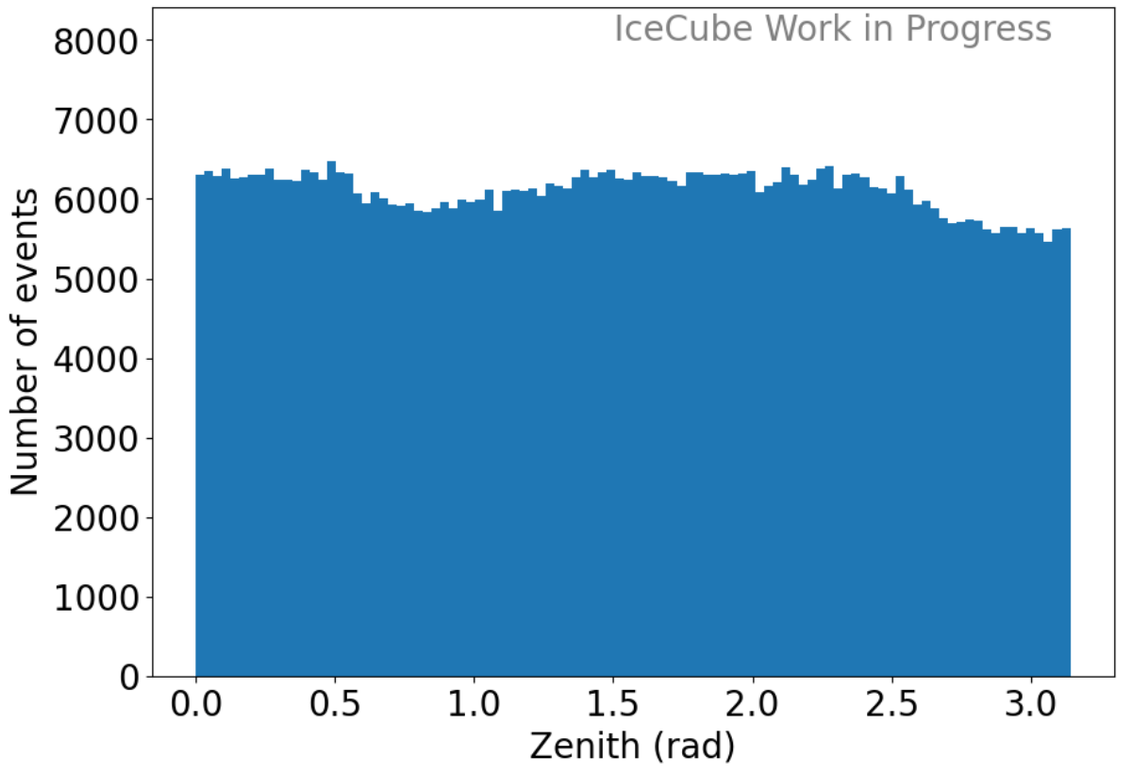


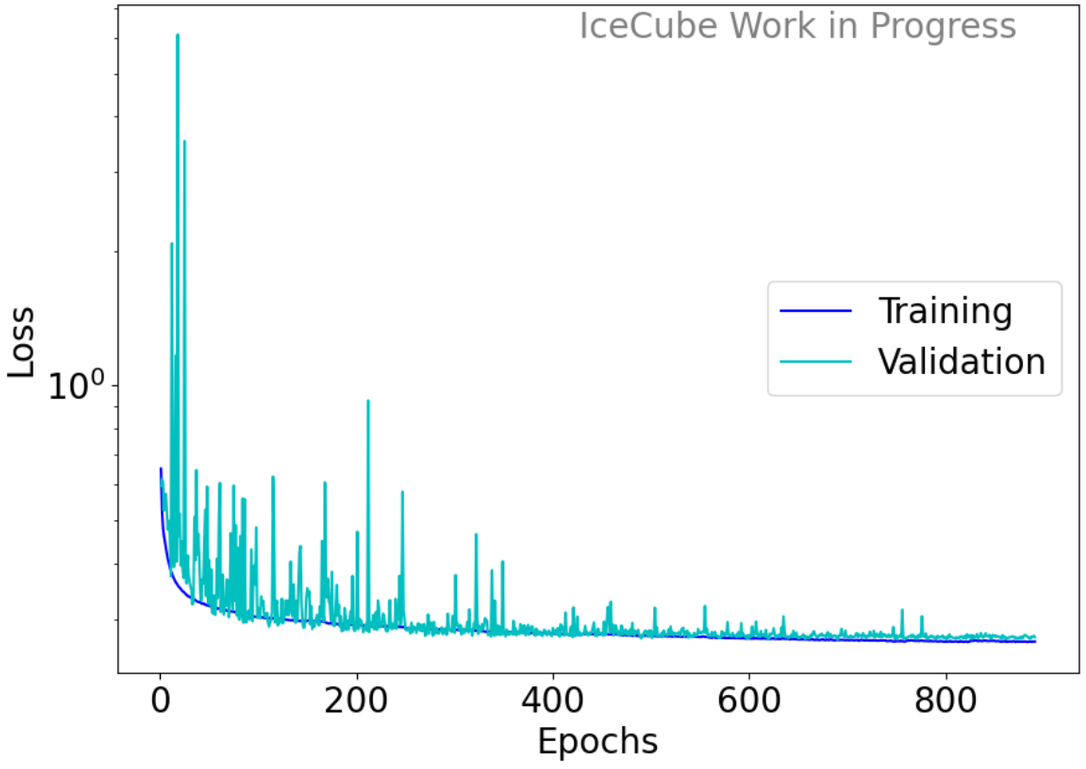




Training

- ν_μCC Monte-Carlo (MC) sample, 5-300 GeV, flat true zenith
- Approximately 5 million events: 80% training set; 20% validation set
- True vertex contained





Testing

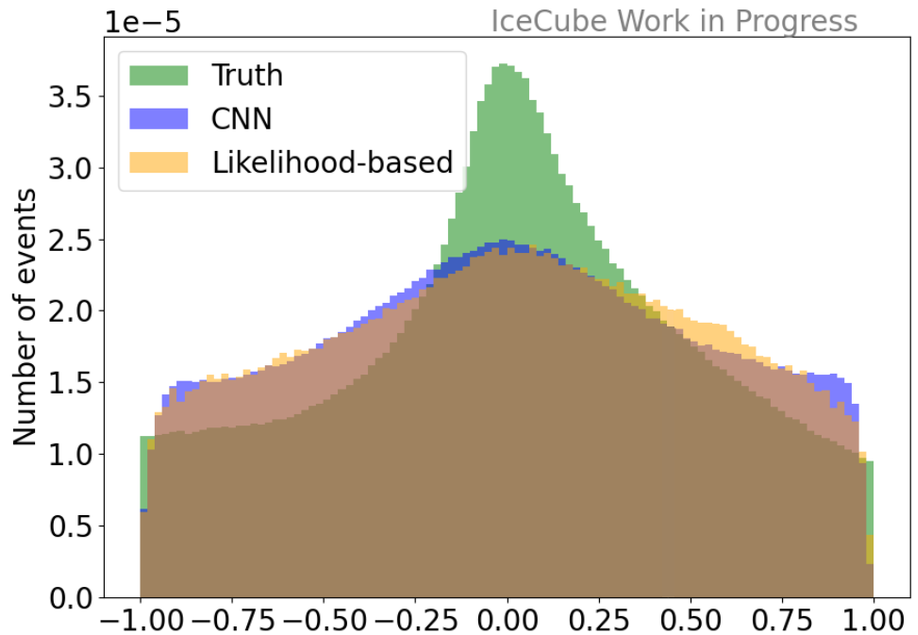
- Compare results of CNN to the current likelihood-based method (“Retro”)

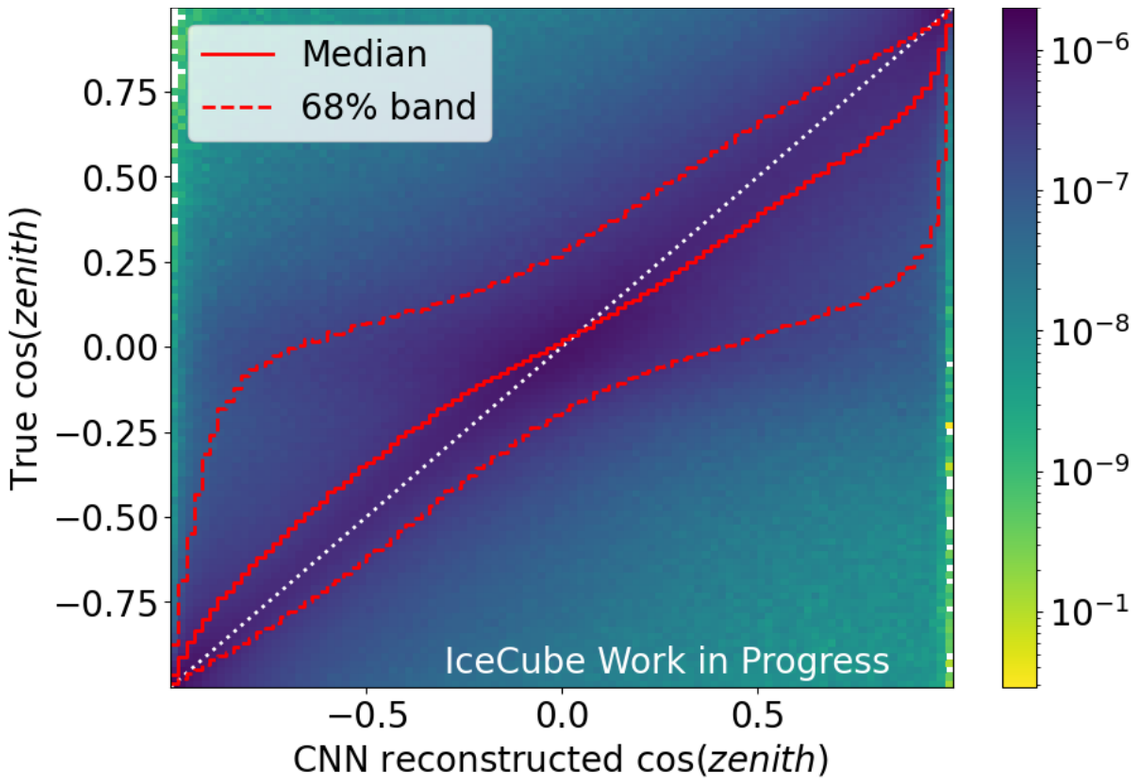
- Cuts:
  - Reconstructed energy in [5, 300] GeV
  - Reconstructed vertex is contained

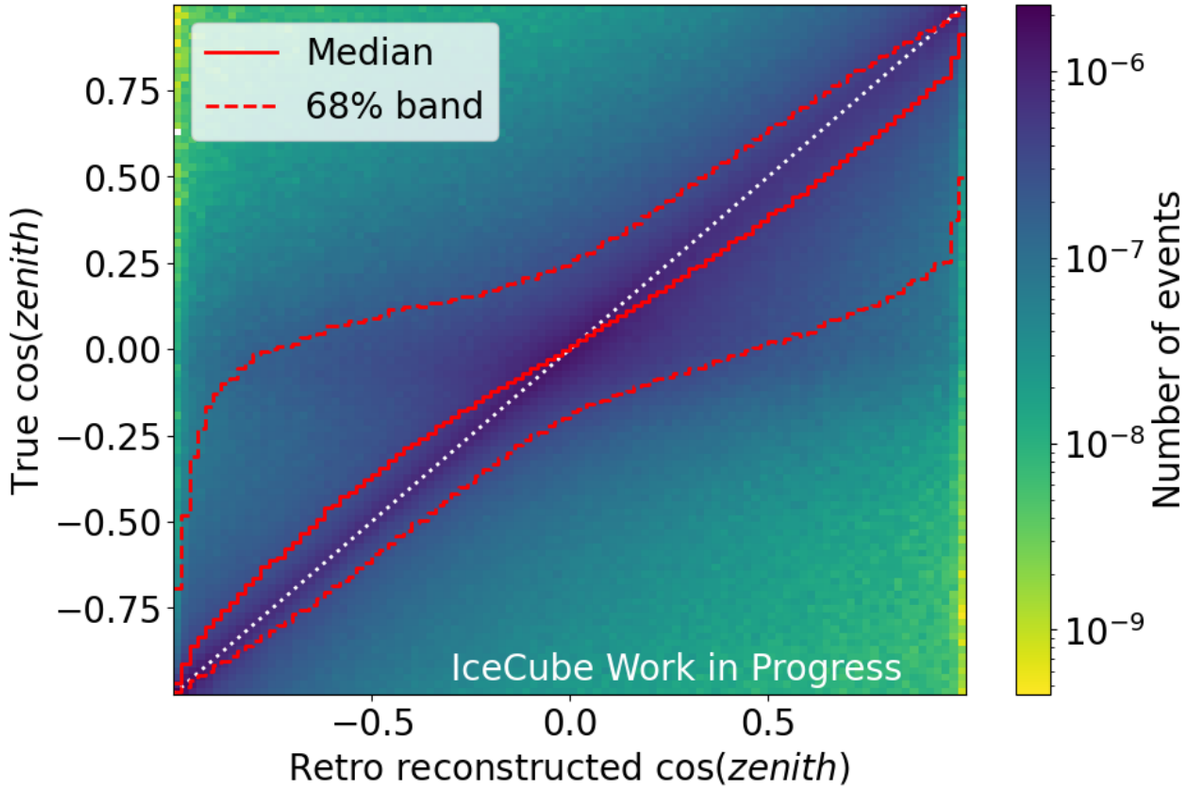
Julia talks about vertex reconstruction in next talk

Distributions of cos(zenith): True ν_μ CC

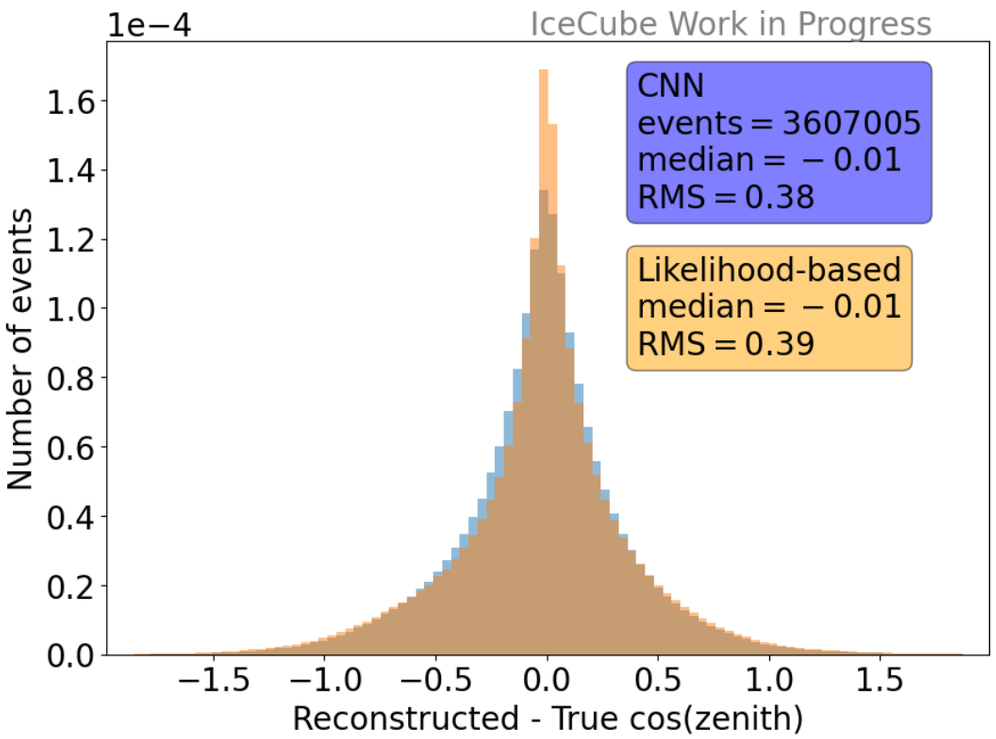
- Comparable distributions and contours
- Events smeared towards the boundaries



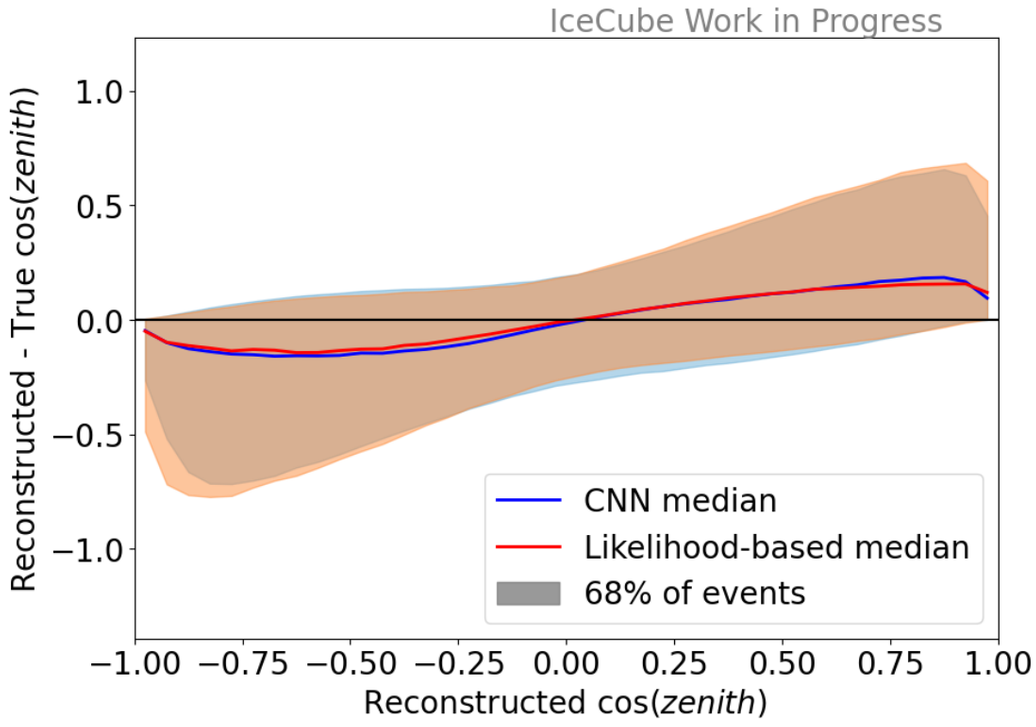


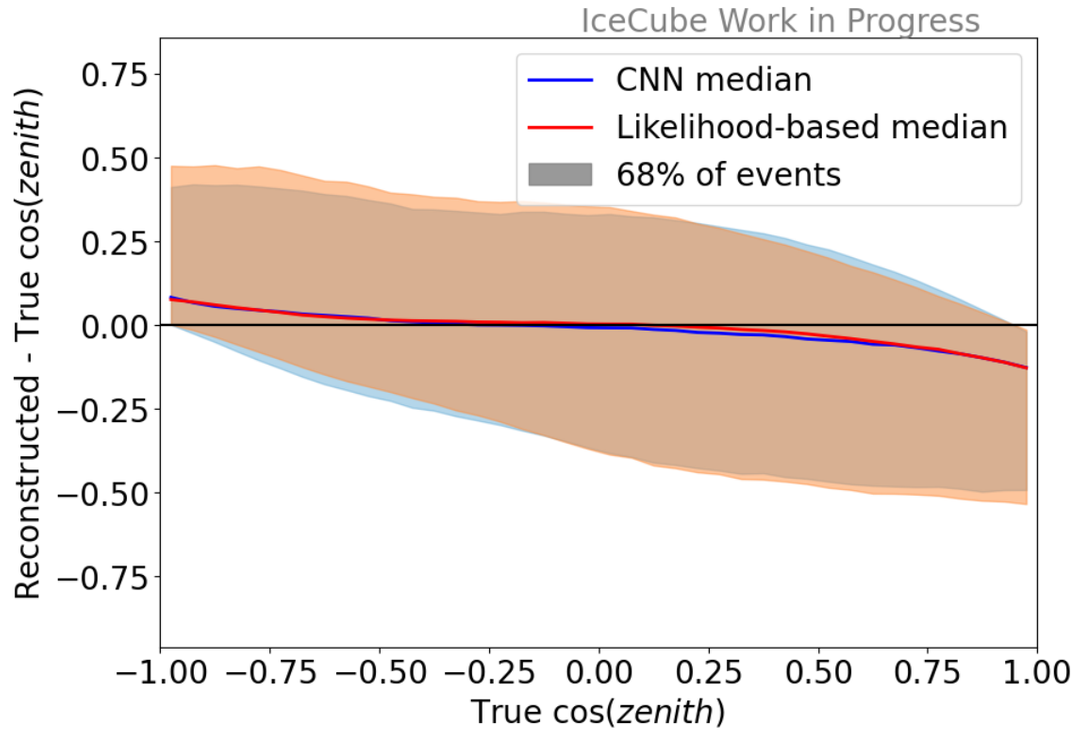


Resolution Comparison: True ν_μ CC



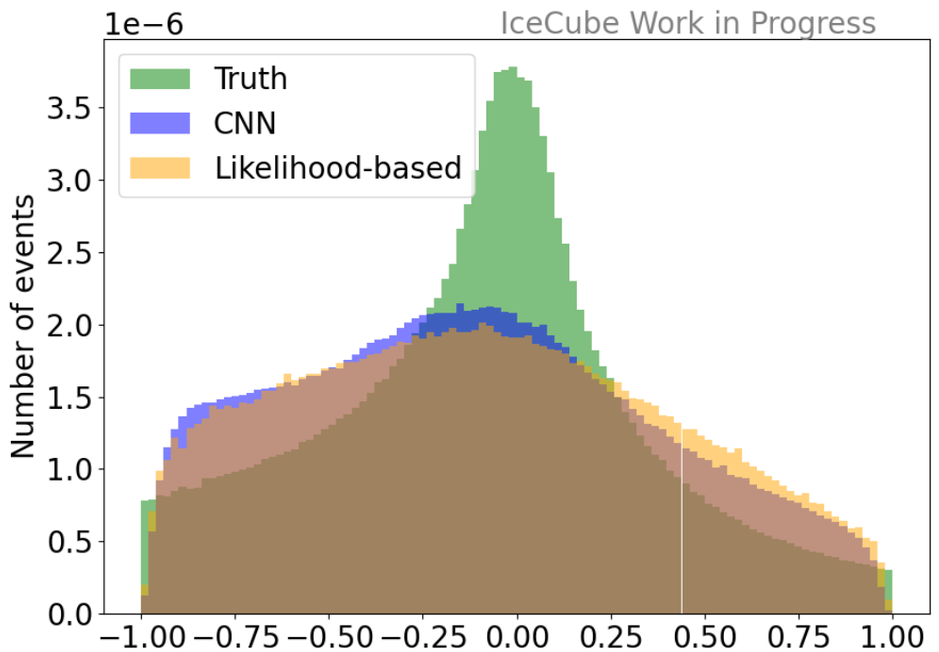
- CNN has smaller overall RMS
- Comparable to current method in bias vs. cos(zenith)

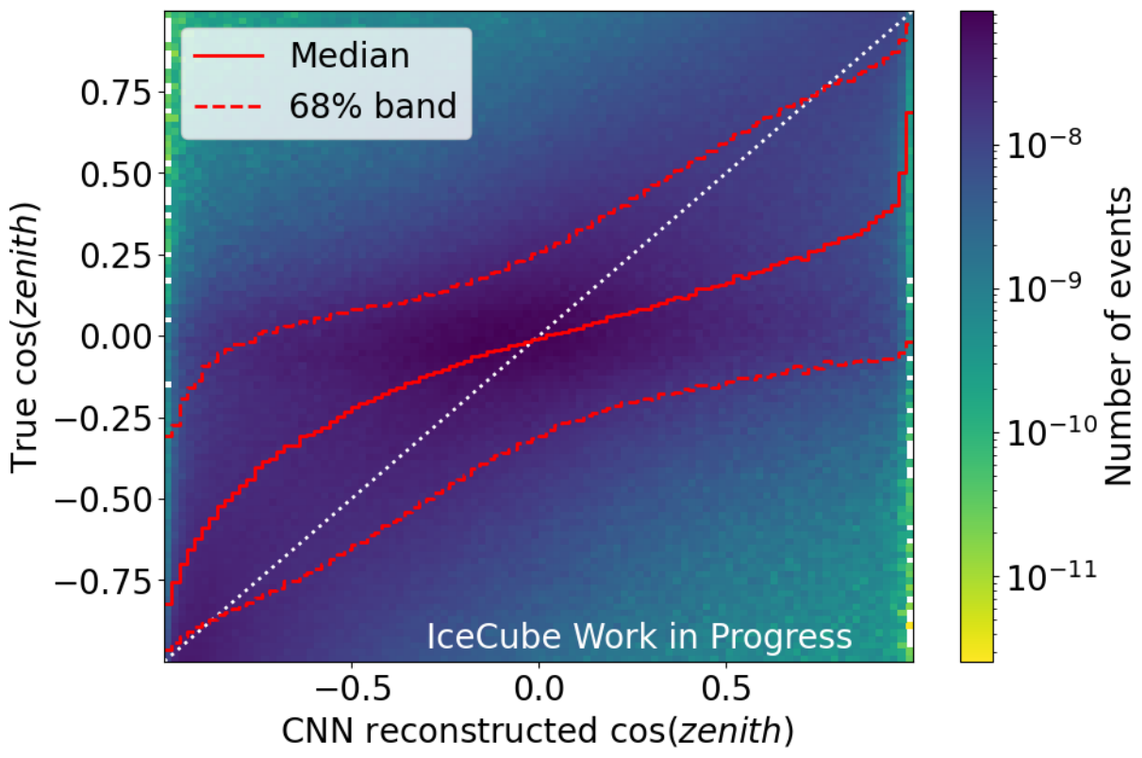


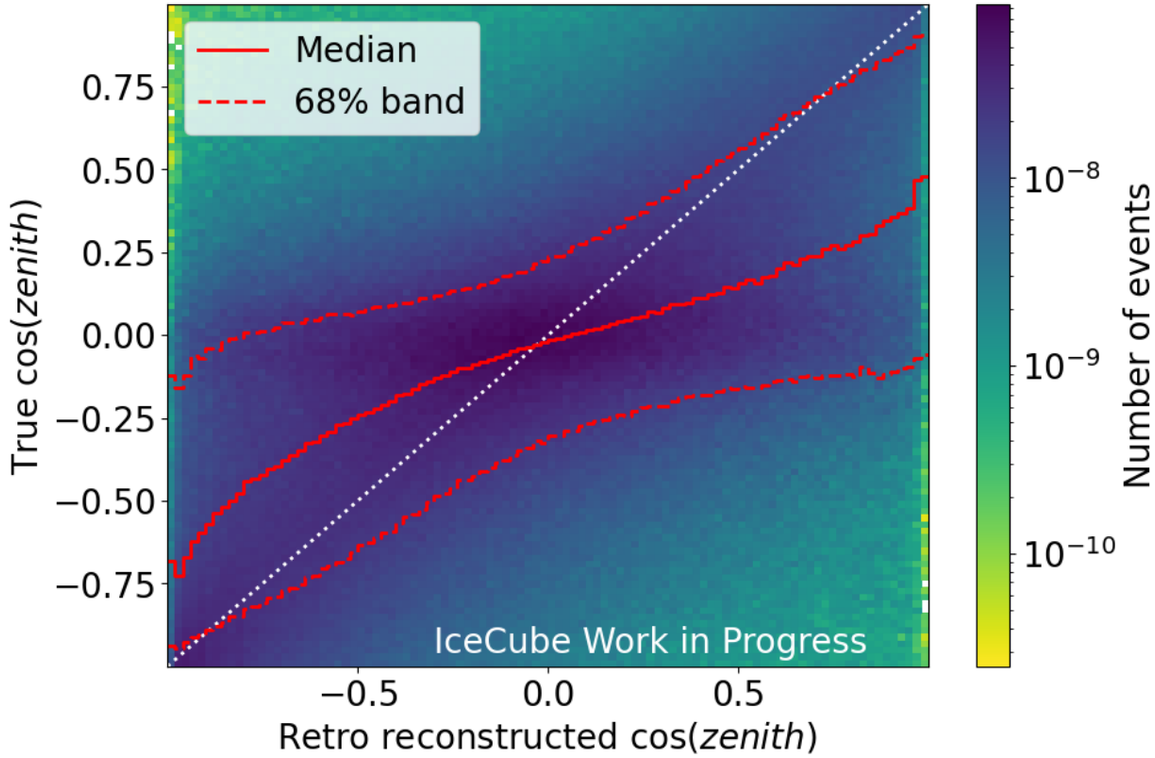


Distributions of cos(zenith): True ν_e CC

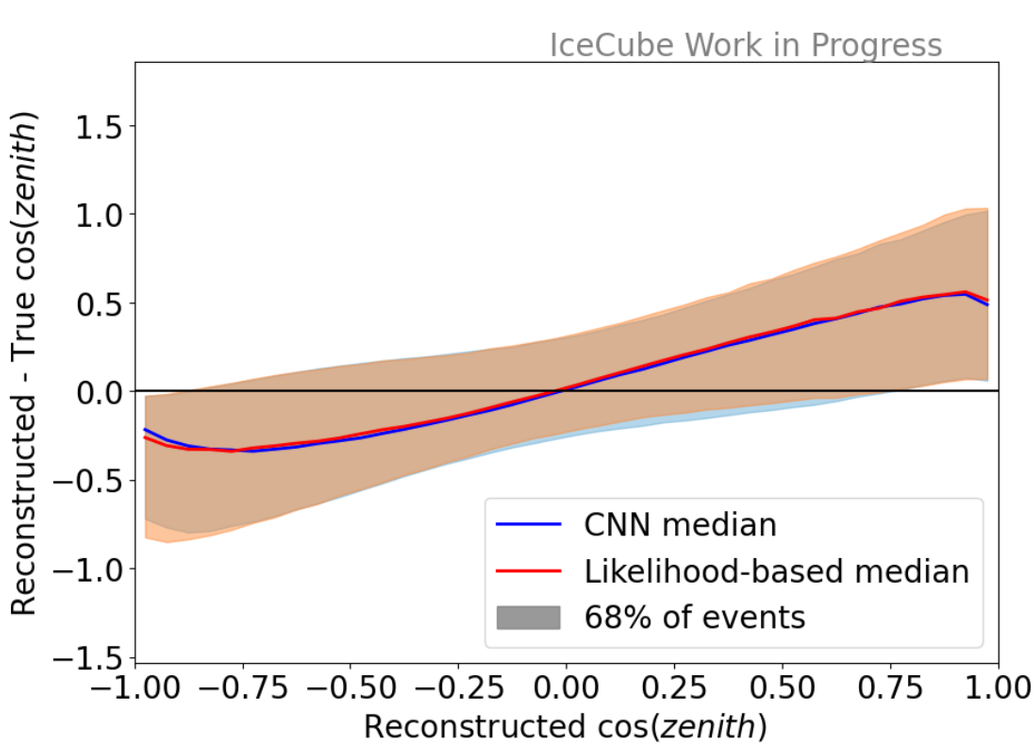
- Comparable distributions and contours
- Contours comparable but wider than those of true ν_μ CC sample





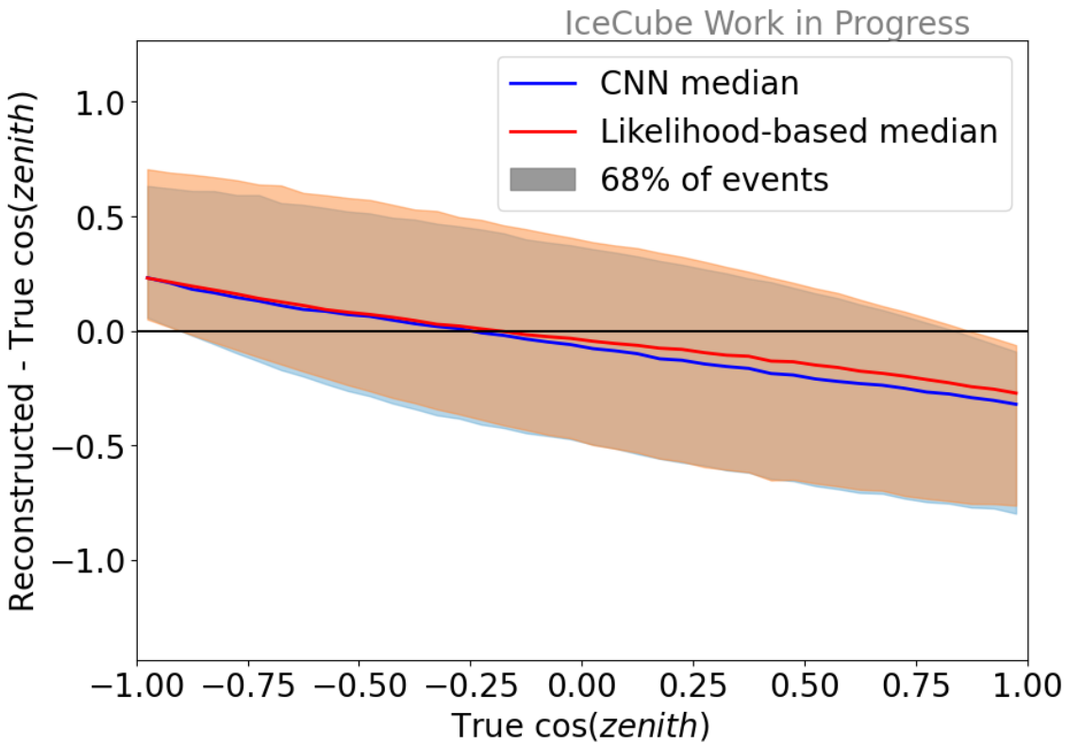


Resolution Comparison: True ν_e CC



- CNN has smaller RMS
- Larger RMS than true ν_μCC events:

  ν_eCC events harder to reconstruct
- Comparable to current method in bias vs. cos(zenith)



Summary and Future

- CNN reconstructed cos(zenith) improved overall RMS by ~2.5% for ν_μ CC sample
- Bias against true or reconstructed cos(zenith) is comparable to the current likelihood-based method
- True ν_μ CC events have better resolution than true ν_e CC events in general
- Processing speed up to 10k times faster than current method
- Investigating improvements on systematic uncertainties

10k times faster processing		
Time/Event	**GPU**	**CPU**
CNN	**0.0044**	**0.108**
Likelihood	**—**	**44.97**

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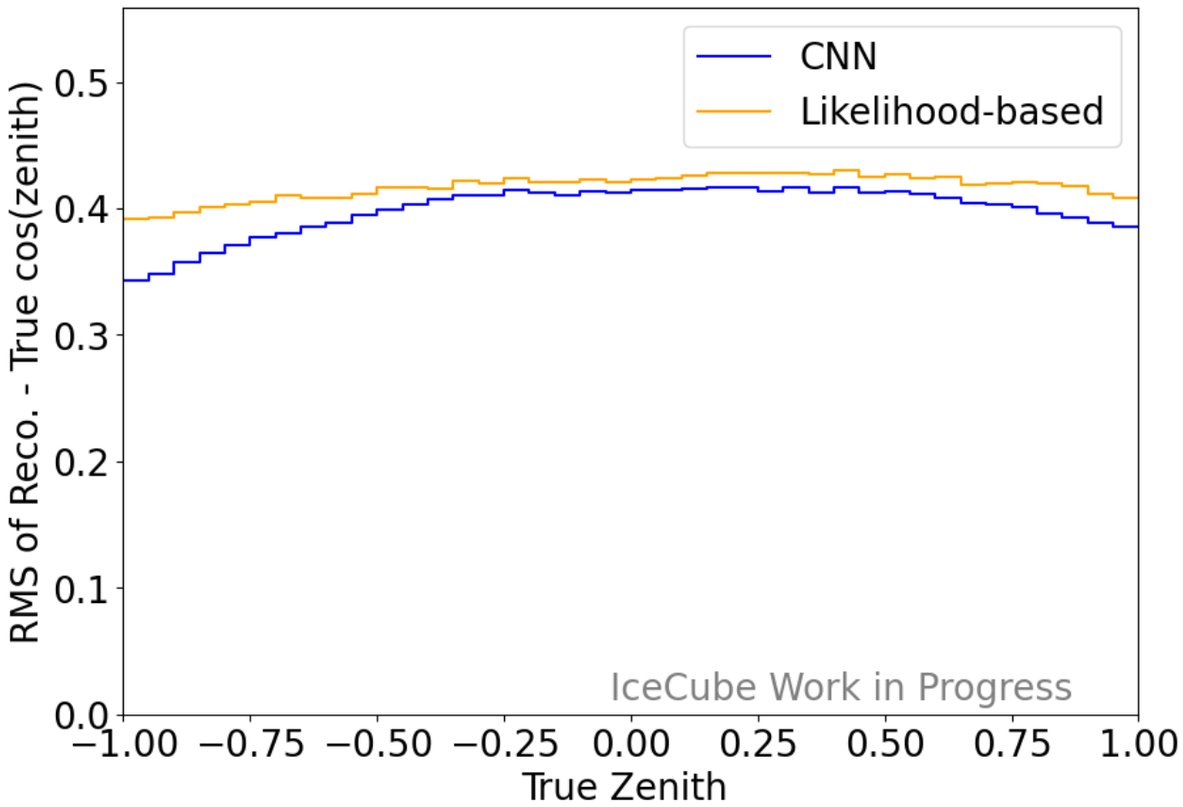
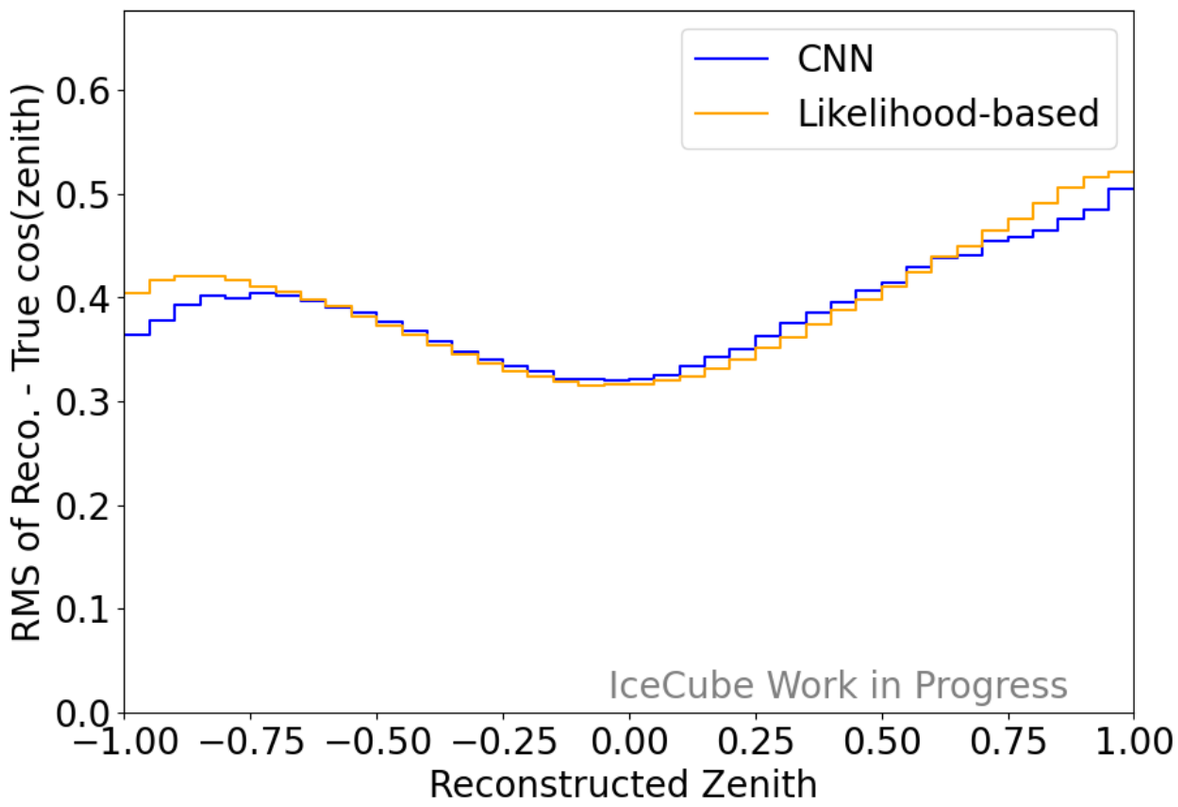
Thank You!

Backup

RMS Slices of NuE CC





RMS Slices of NuMu CC