IceCube ν_μ Disappearance Oscillation Measurement using DeepCore and CNNs

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Photo Credit: Felipe Pedreros, IceCube/NSF

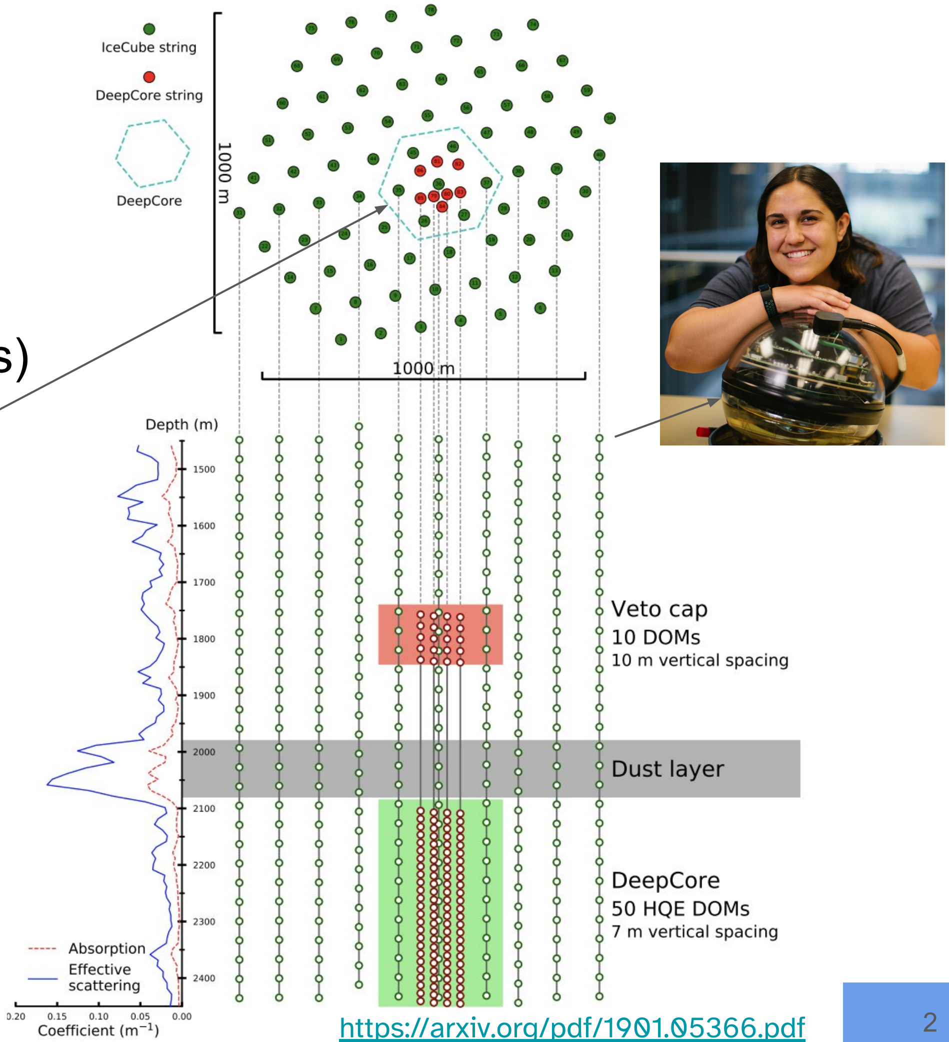
IceCube and DeepCore

IceCube:

- 1 km^3 of ice
- 5160 Digital Optical Modules (DOMs)
- Detect Cherenkov light

DeepCore:

- Center hexagon
- Densely arranged DOMs
- Higher photosensitivity
- Detects atmospheric ν from GeV - 100 TeV

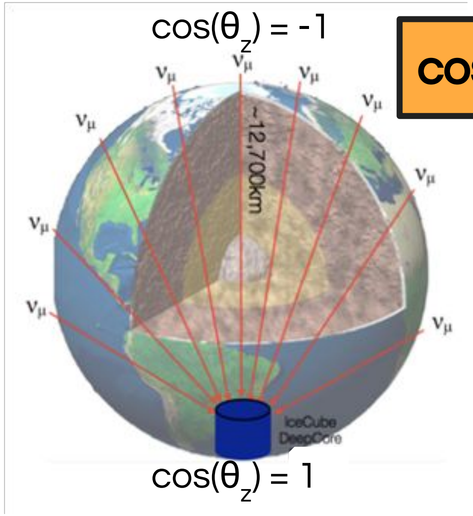


https://arxiv.org/pdf/1901.05366.pdf

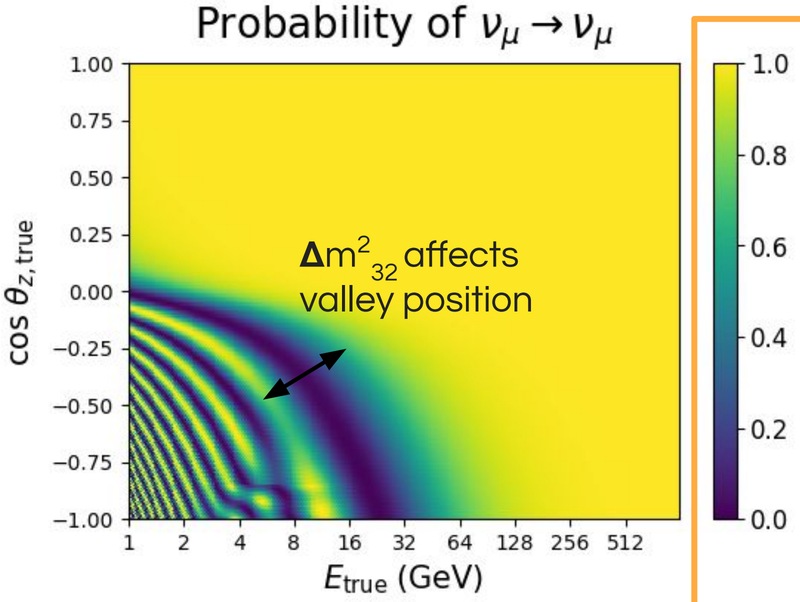
Energies & Baselines for Atmospheric Neutrino Oscillation

https://dchooz.titech.jp.hep.net/nu_oscillation.html

$$P_{\nu_\mu \to \nu_\mu}(L) \approx 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1}{4} \cdot \Delta m^2_{32} \cdot \frac{L}{E}\right)$$



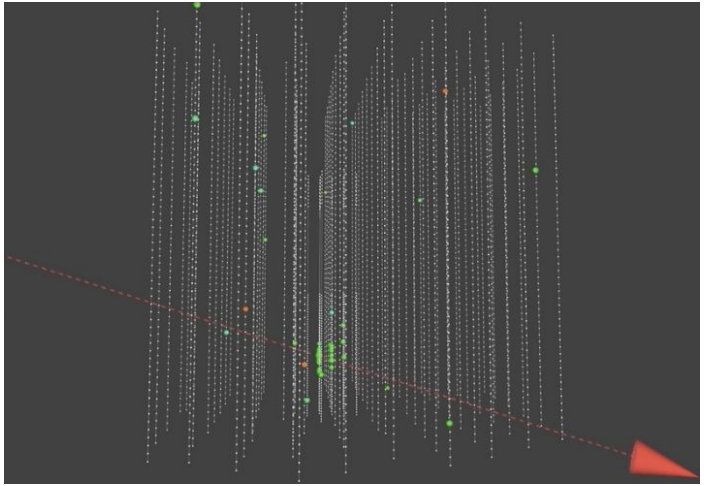
cos(θz) ~ L



$\sin^2(\theta_{23})$ affects valley depth

10-GeV Scale Events in IceCube

Typical 10 GeV scale event:

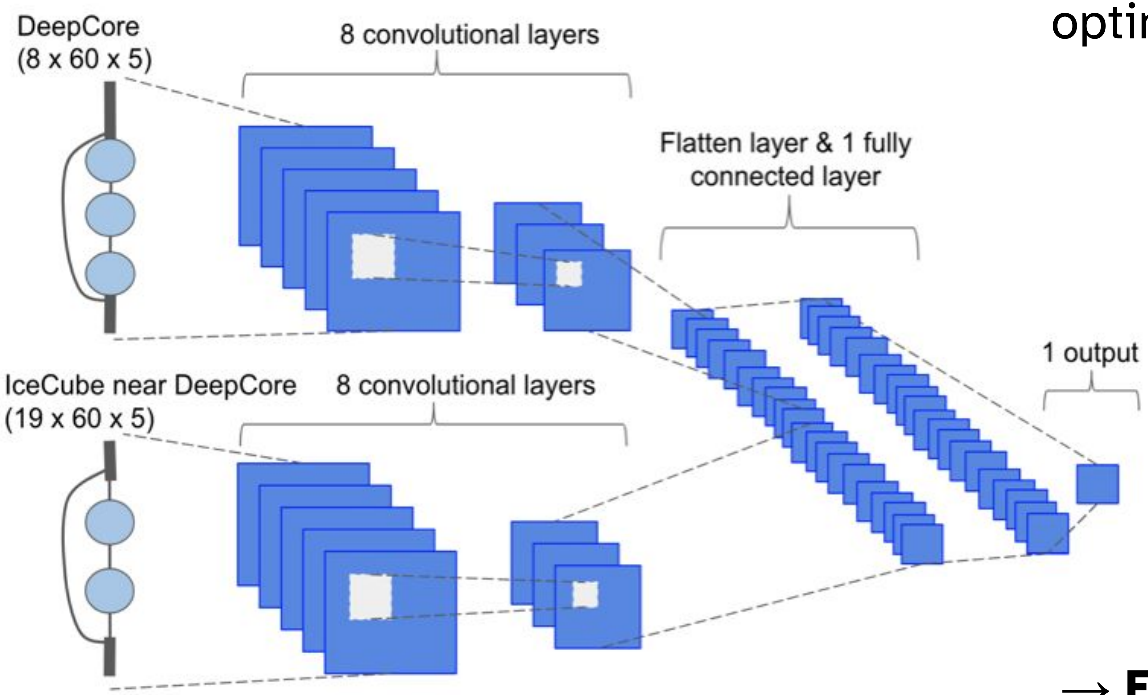


Challenging to determine

- Track or cascade (flavor)
- Direction
- Energy

- Less light produced per event → fewer DOMs record pulses
- Noise impactful: noise hits ≈ ν interaction hits
- Leverage DeepCore instrumentation
- Optimize reconstructions specifically

10 GeV-Scale CNNs



→ Five separate CNNs trained & optimized for "single" output

Regressions:

1. **Energy**
2. **Zenith**
3. Interaction Vertex
   → (x, y, and z)

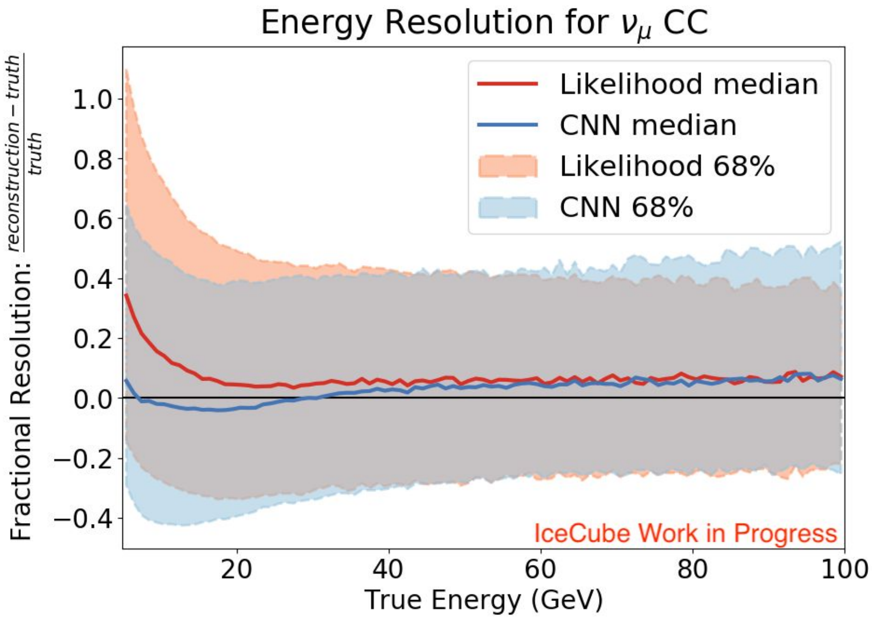
Classifications:

4. **Track vs Cascade (flavor)**
5. Atmospheric Muon vs Neutrinos

→ **Everything we need for oscillations analysis** (+ more!)

10 GeV-Scale CNNs - Energy Resolution

- Resolution comparable to LLH equivalent
- Takes ~1 ms per event to run all 5 nets



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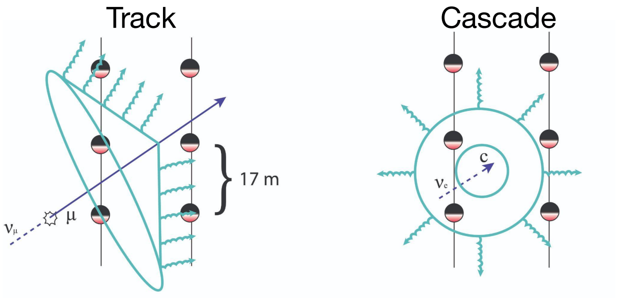
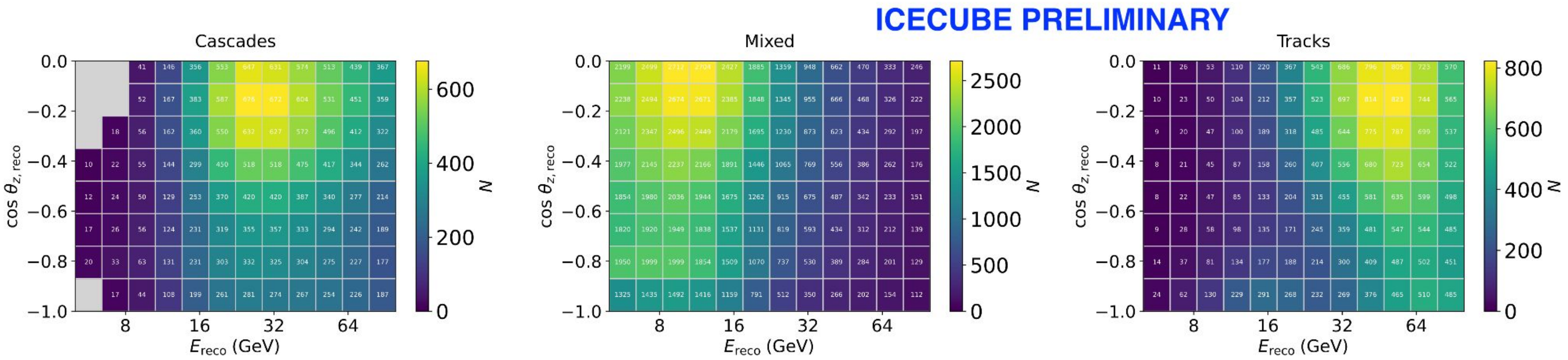
IceCube ν_μ Disappearance Analysis Procedure

1. Event selection to remove background
2. Separate in event type (flavor)
3. Bin in energy and cosine zenith



Nominal Systematics
Oscillation Weights Applied



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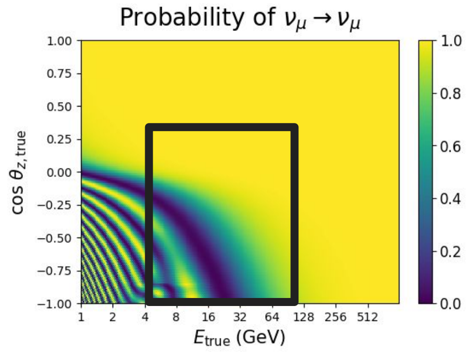

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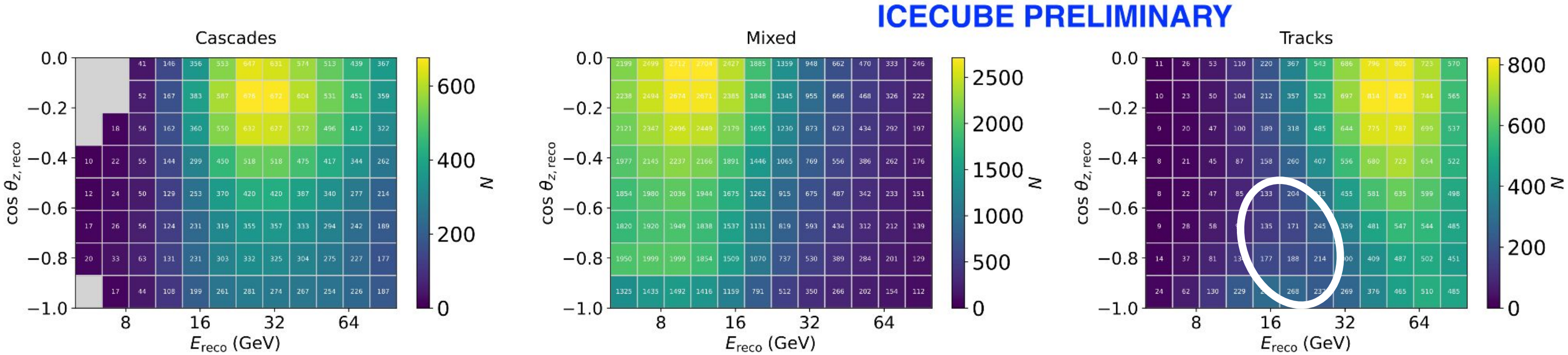
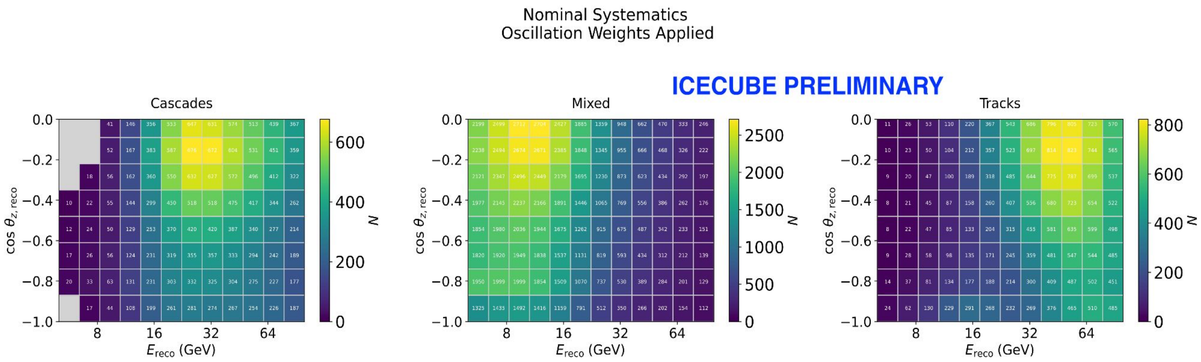
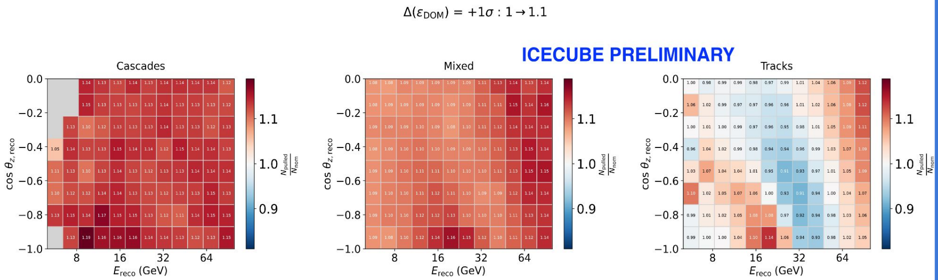


IceCube ν_μ Disappearance Analysis Procedure

4. Explore systematic effects with pulls from nominal set
5. Compare data to no oscillation hypothesis

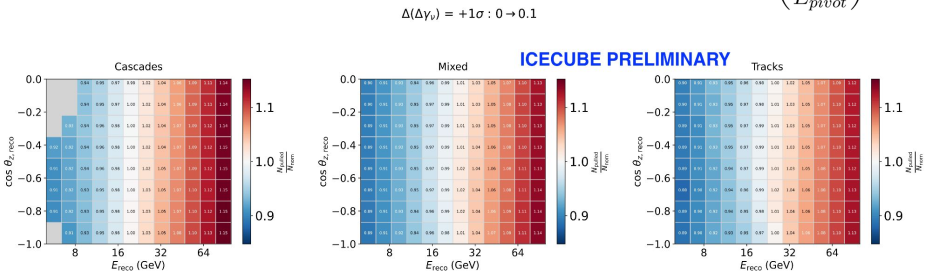


Major detector systematic: Optical Module efficiency



Systematic: neutrino flux spectral index

$$\Delta\Phi = \left(\frac{E}{E_{pivot}}\right)^{\Delta\gamma}$$



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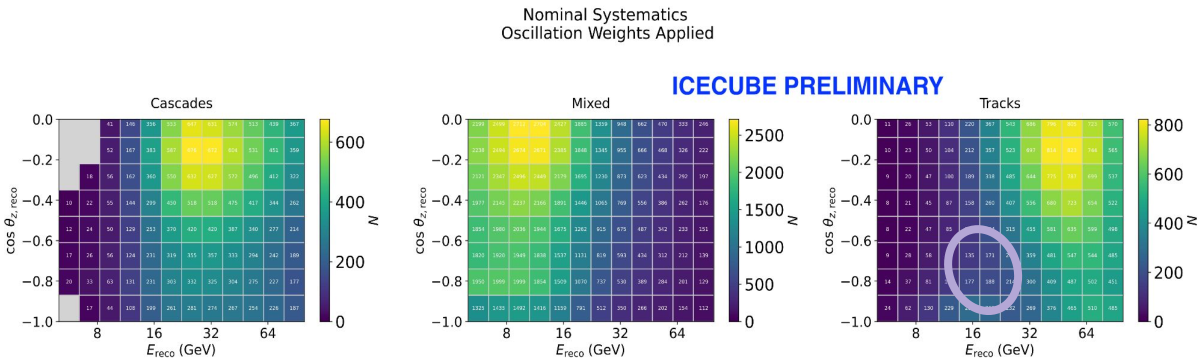
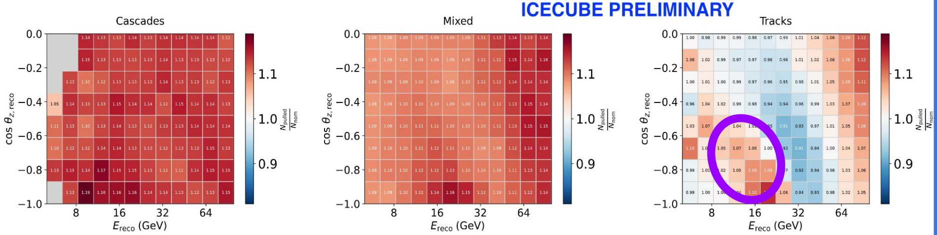


Major detector systematic: Optical Module efficiency

$\Delta(\varepsilon_{\mathrm{DOM}}) = +1\sigma : 1 \rightarrow 1.1$



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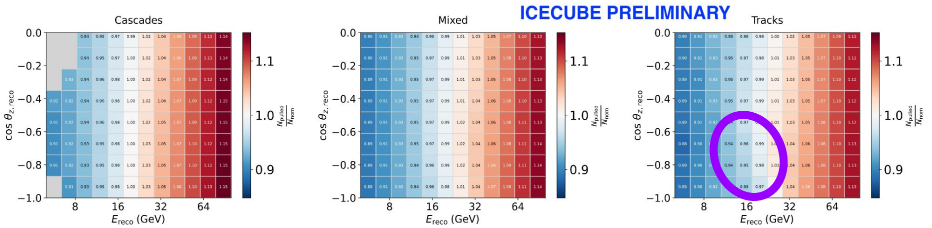

Preliminary ν_μ Disappearance Result using CNNs

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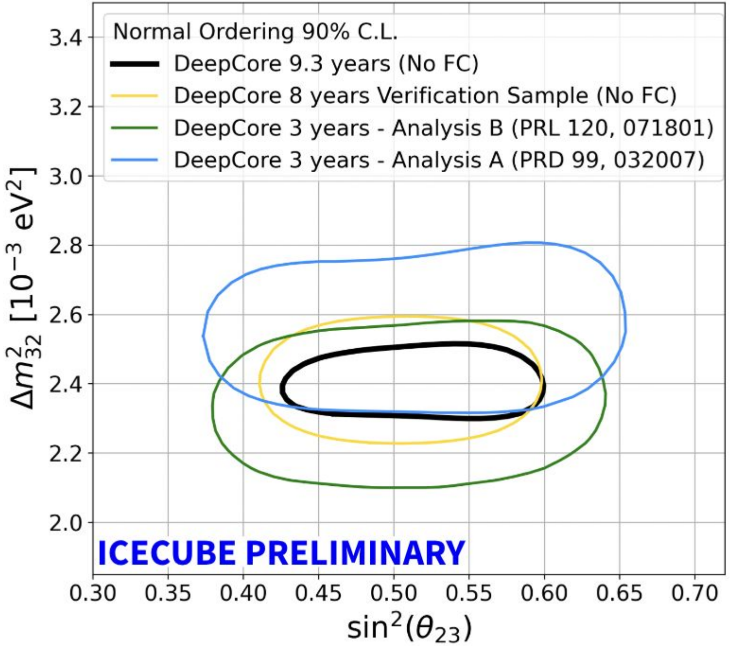
- Preliminary results: currently undergoing final checks of potential MC issue discovered after result was unblinded



✓ DeepCore 9.3 years (without Feldman Cousins) using CNNs aligns with past IceCube results

Preliminary ν_μ Disappearance Result using CNNs

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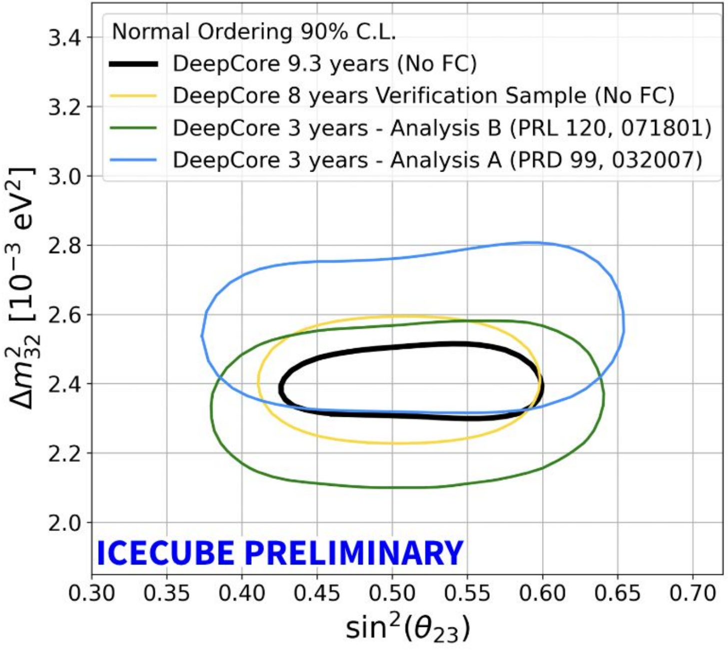
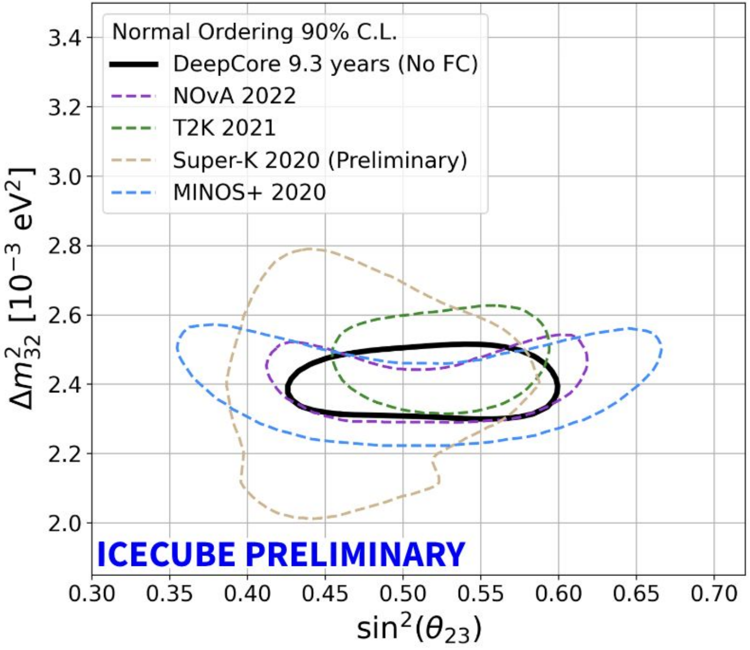
✓ Agrees with global experimental results





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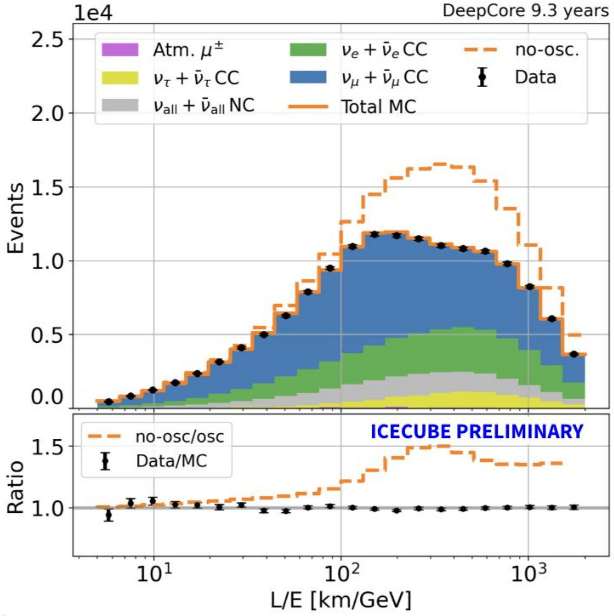
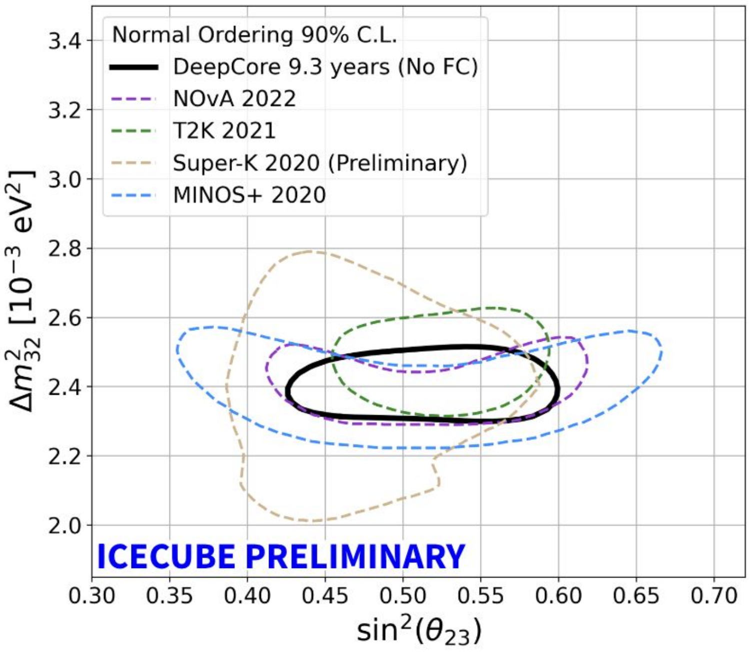
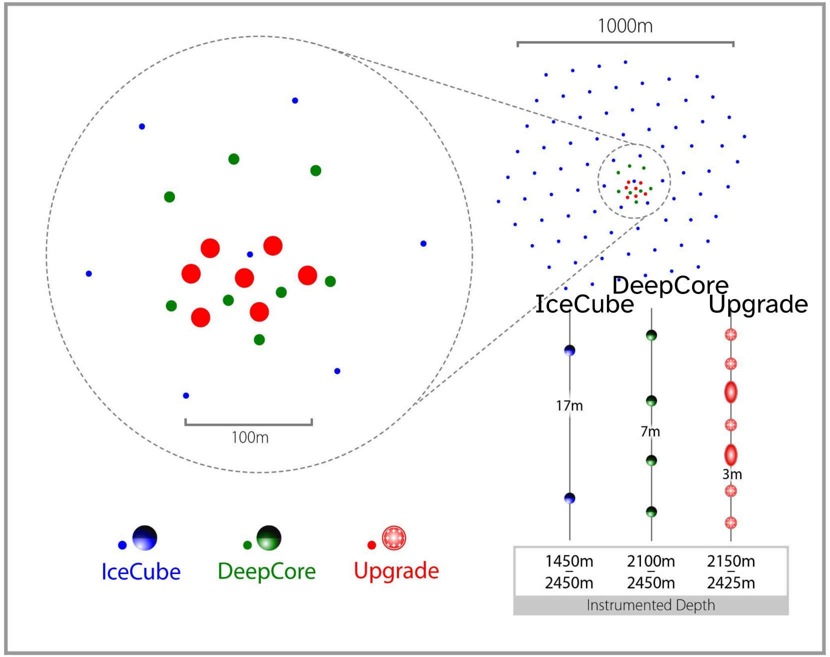
✓ Stable data/MC agreement





IceCube Upgrade

Additional high density strings + calibration:



→ Deploying 2025/26

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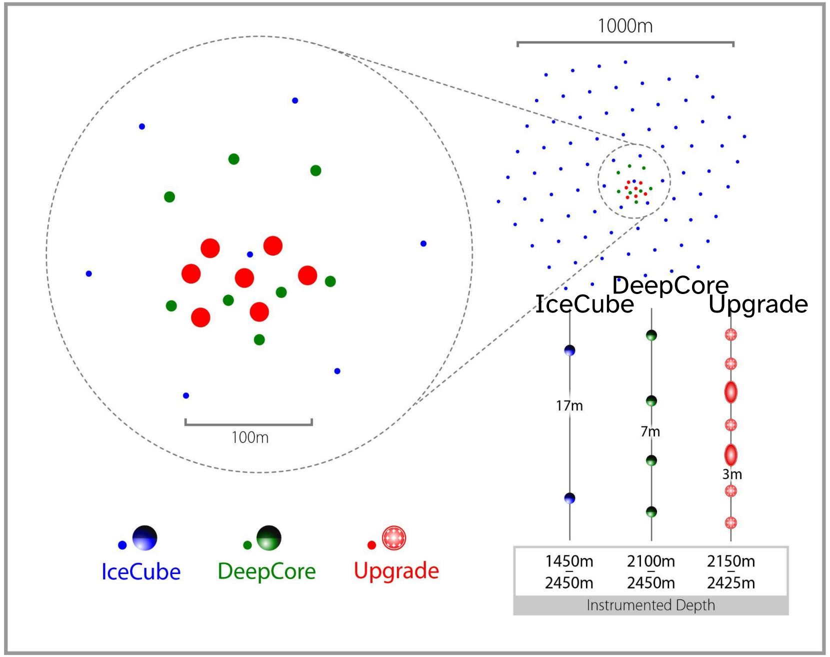

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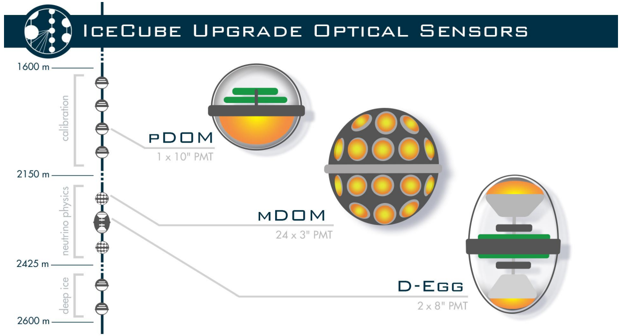
New multi-PMT designs:



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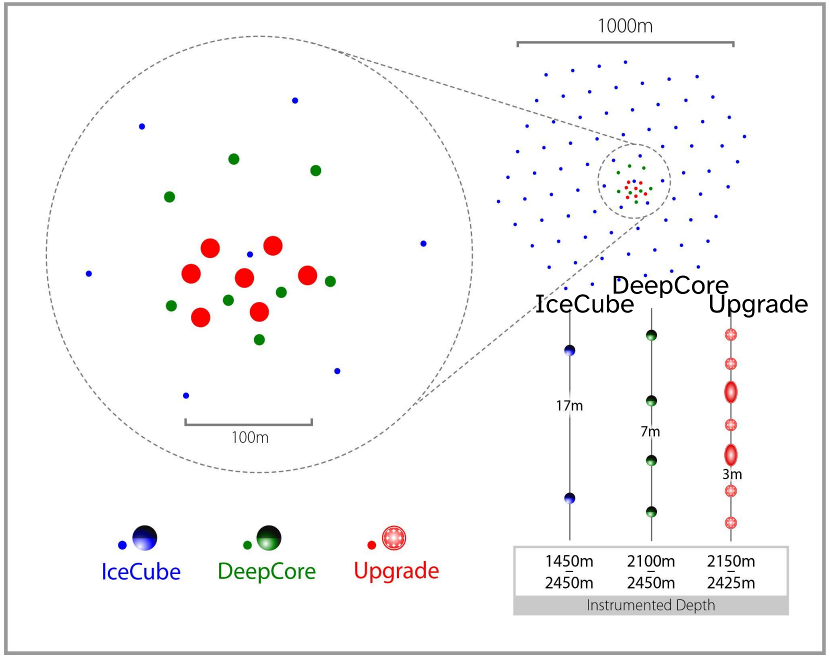

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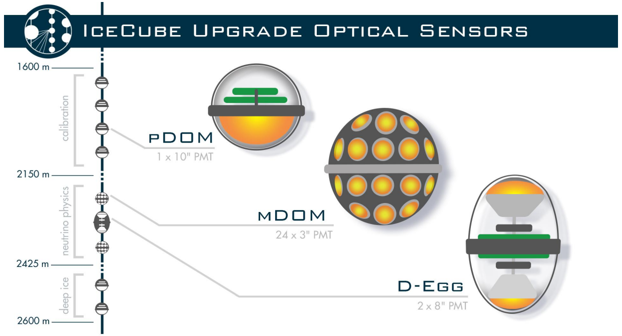
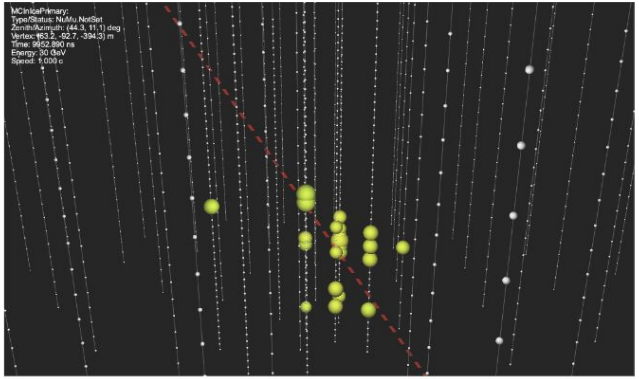


Much more detailed event view:



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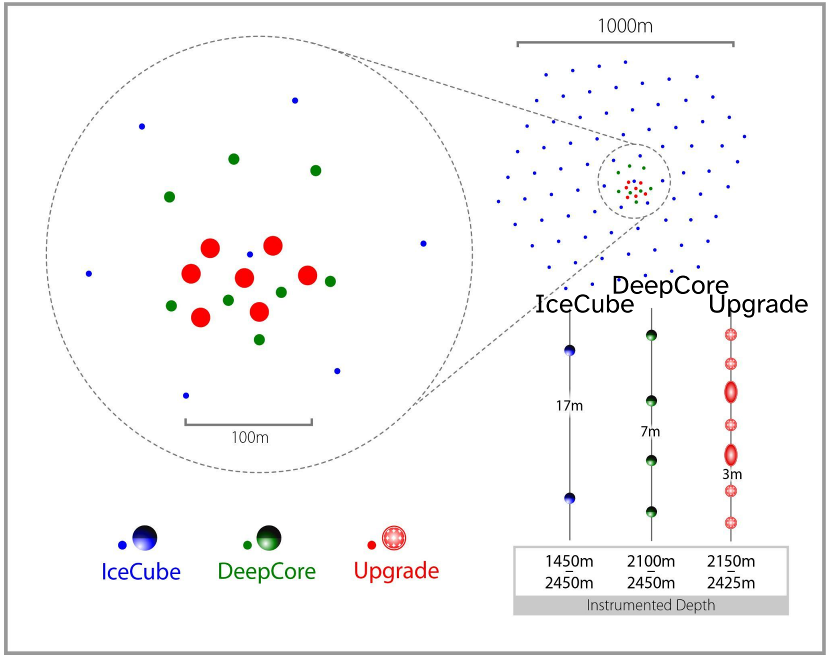

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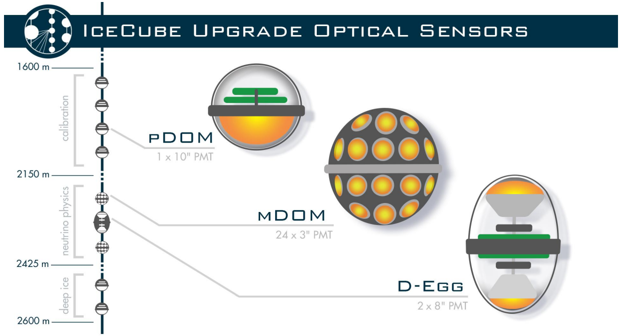

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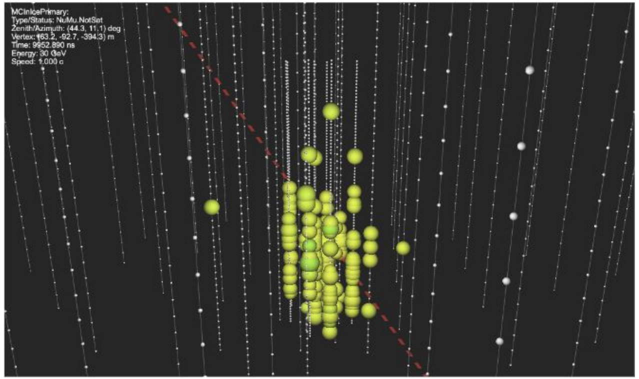

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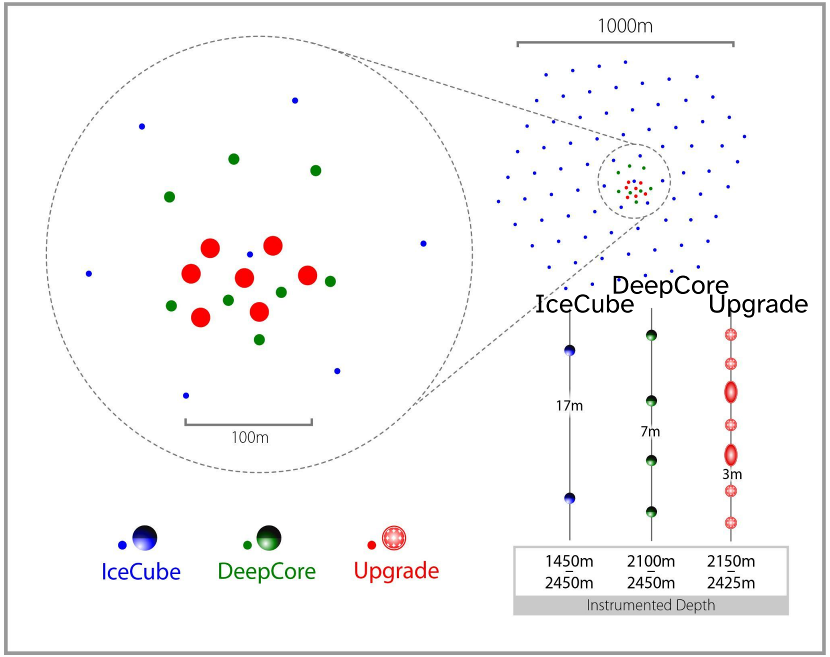

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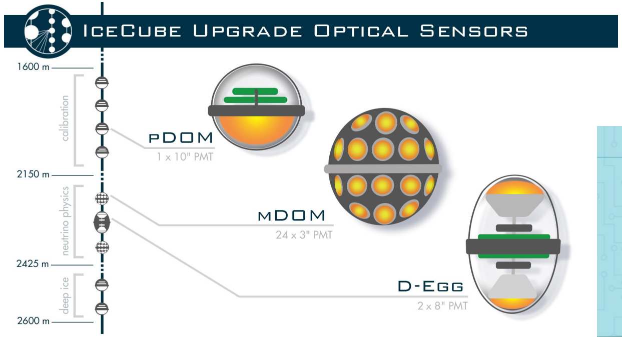
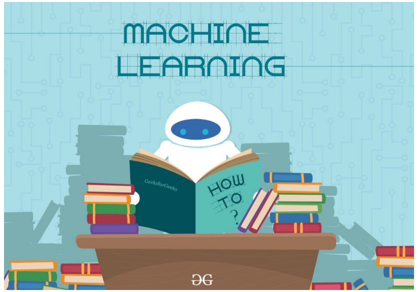


Developing ML reconstructions:



https://www.geeksforgeeks.org/machine-learning/

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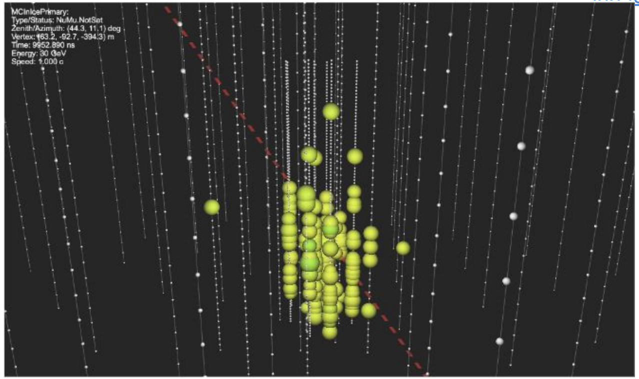

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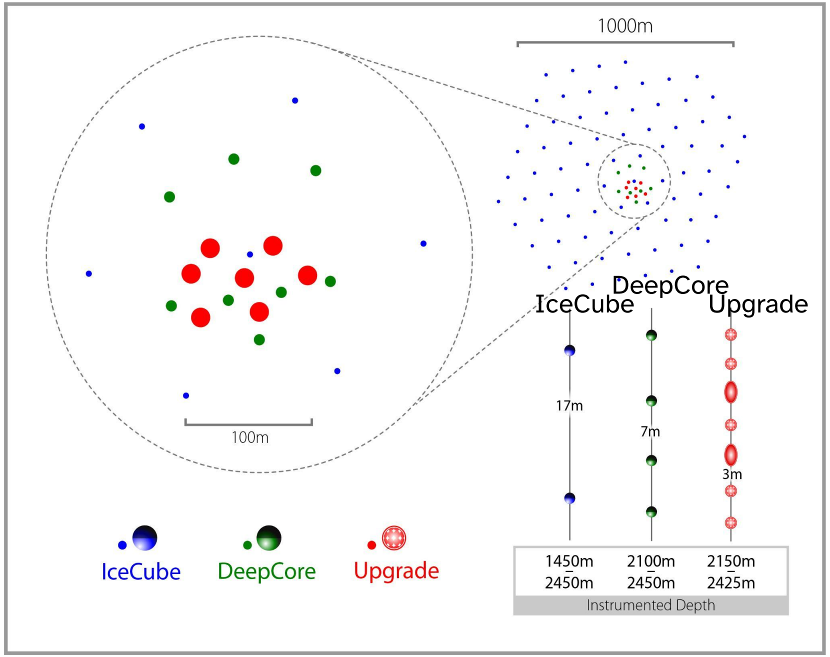

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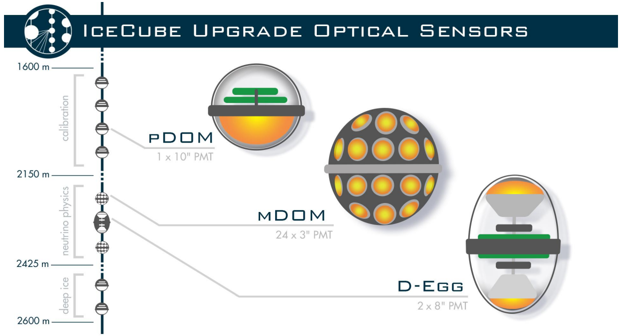

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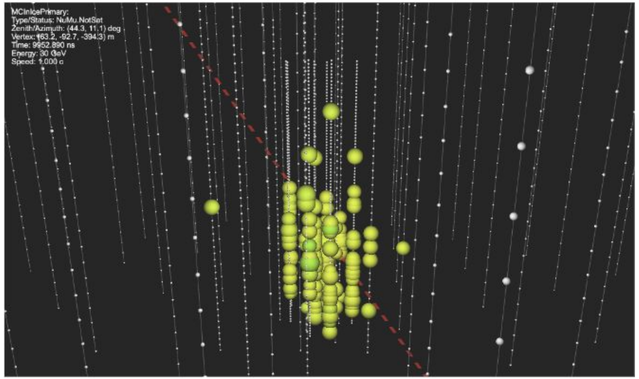

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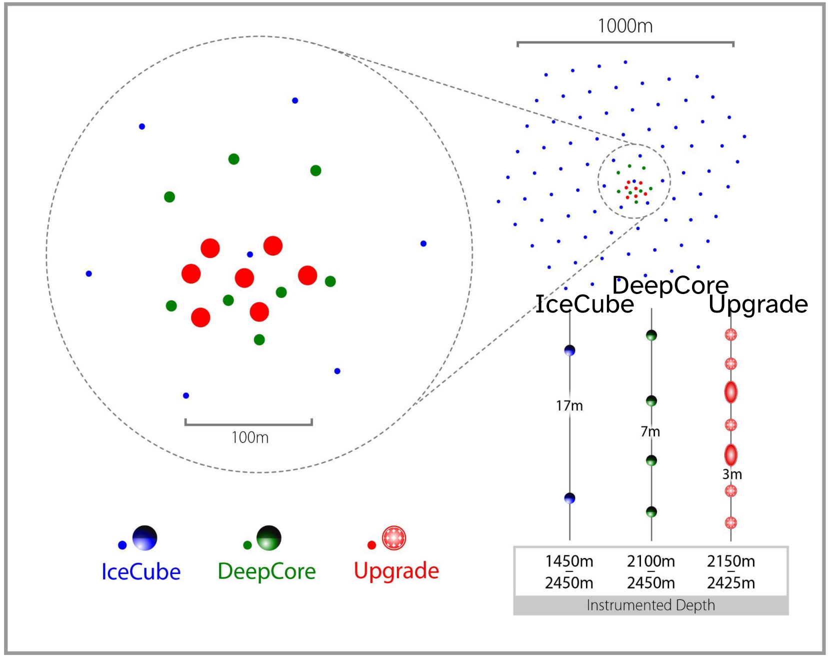

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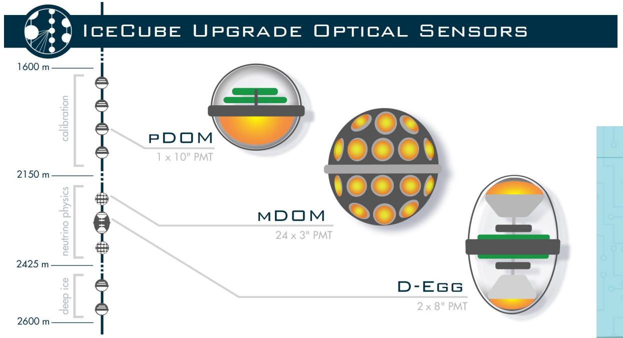

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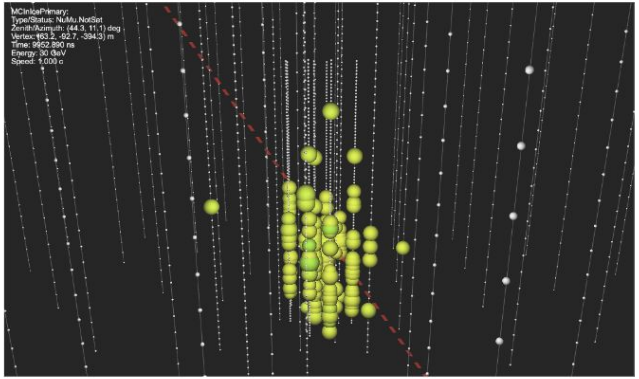
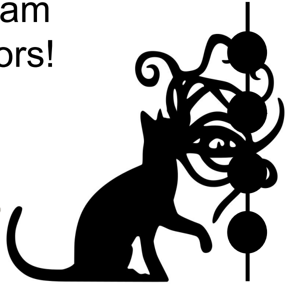


→ Expect sensitivity improvements with only 3 years of Upgrade data

Summary

- IceCube's constraints on Δm^2_{23} and $\sin^2(\theta_{32})$ agree with global experiments
- This will soon be the most sensitive measurement of oscillations using atmospheric neutrinos at the highest energies
- ML reconstruction methods have bright future in IceCube & Upgrade
- IceCube Upgrade expects further improvement in sensitivity and understanding of neutrino properties

Thanks to the FLERCNN team and our IceCube collaborators! And, as always, NSF!

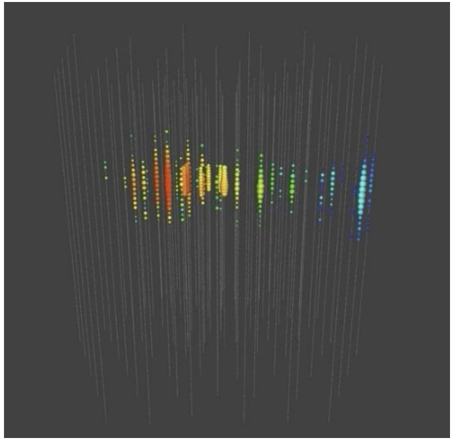


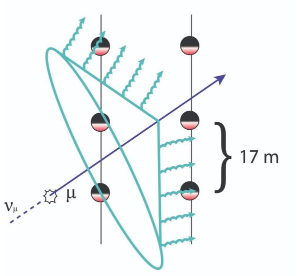
Backup

“Typical” Event Signatures in IceCube

Track-like events:

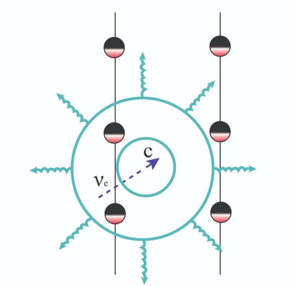
- Source: ν_μ CC
- Energy: 71 TeV

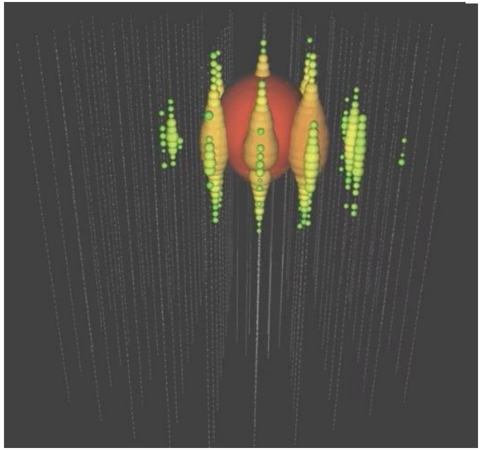




Cascade-like events:

- Source: ν_e CC, ν_τ CC, all NC
- Energy: 2 PeV





Determine:

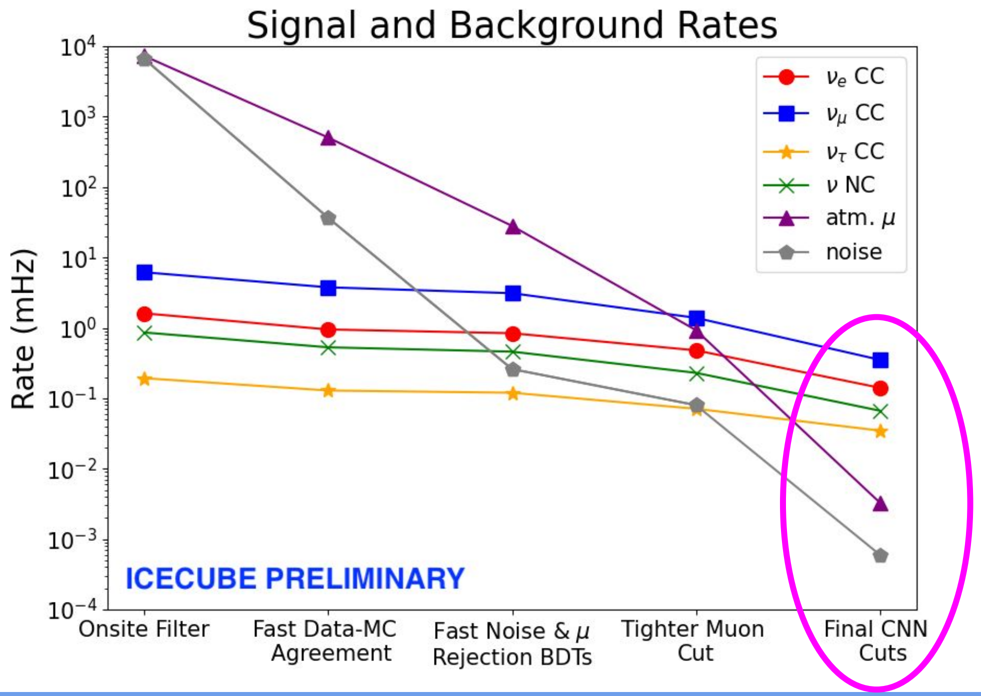
- Track or cascade
- Direction
- Energy

→ Can make a “picture” or video, so can we use image recognition?

- Yes! Successful convolutional neural network for reconstructing high energy cascade events in IceCube: arXiv:2101.11589v1

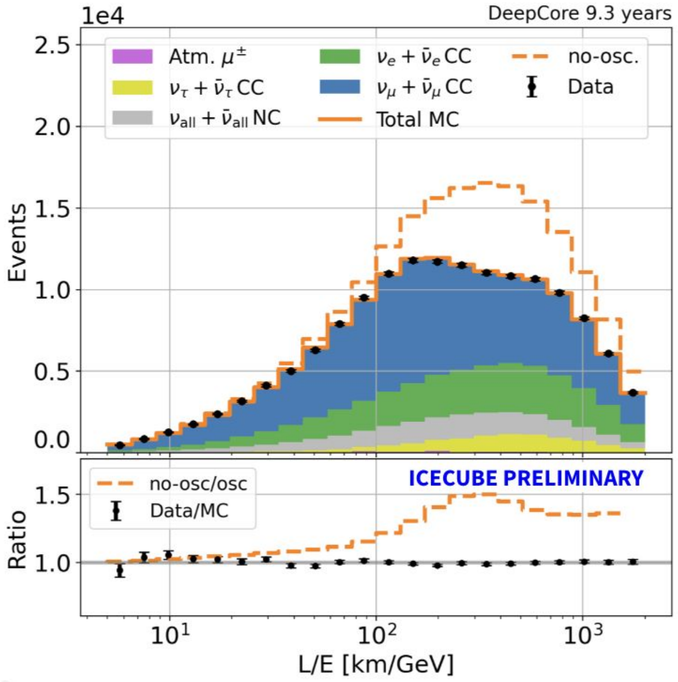
Event Selection and Background Removal

Goal: remove atmospheric muons and pure noise

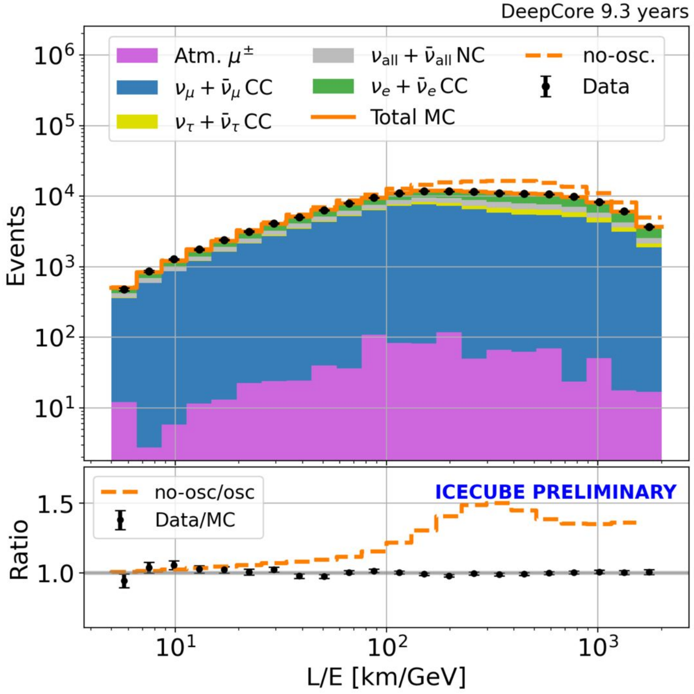


- ✓ Largest rate for ν_μ (🟦) → important for ν_μ disappearance analysis
- ✓ μ and noise rates are orders of magnitude lower

Data and MC Agreement Muons



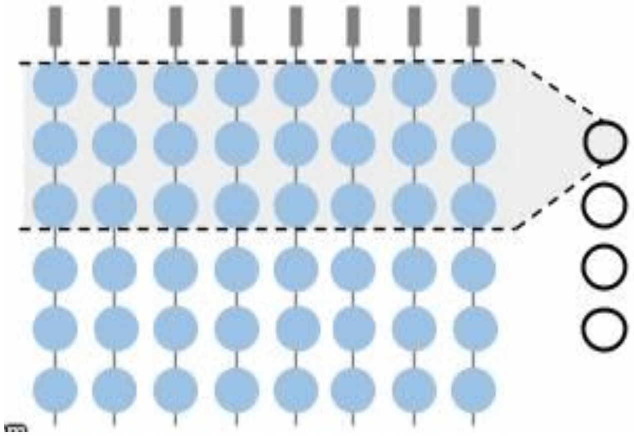
Log scale to show muons

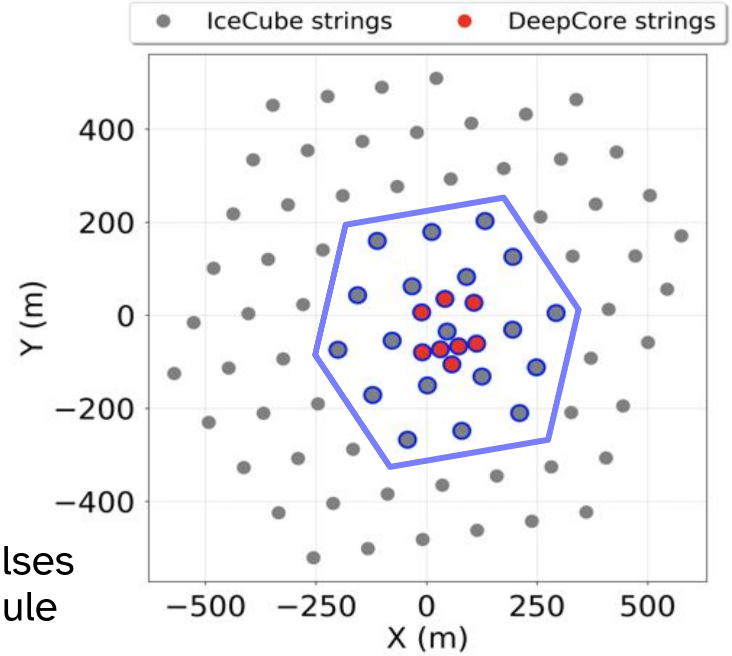


CNN Input Features

→ Only use DeepCore & nearby IceCube strings (kernel in depth only)

→ Noise cleaning applied & hit time within [-500, 4000] ns





Inputs: 5 variables summarizing all pulses hitting optical module

- Sum of charge
- Time of first hit
- Time of last hit
- Charge weighted mean of times
- Charge weighted σ of times

CNN Significantly Improves Reconstruction Time

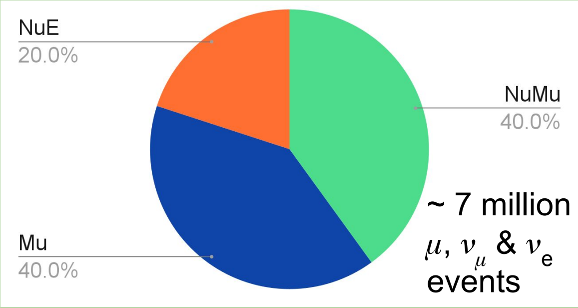
	Average time (s) per event	Events per day per single core	Time for full sample assuming 1000 cores
Current Likelihood-based method on CPU	40	2,000	~ 46 days
CNN on CPU	0.29	300,000	~ 8 hours
CNN on GPU	0.0011	80,000,000	~ 2 minutes

- 6000x runtime improvement possible in serial!
- Having access to computer clusters, can parallelize the process
  - Both GPU & CPU parallelization possible for CNN
- **Full sample: O(10^5) data events and O(10^8) Monte Carlo simulation events**

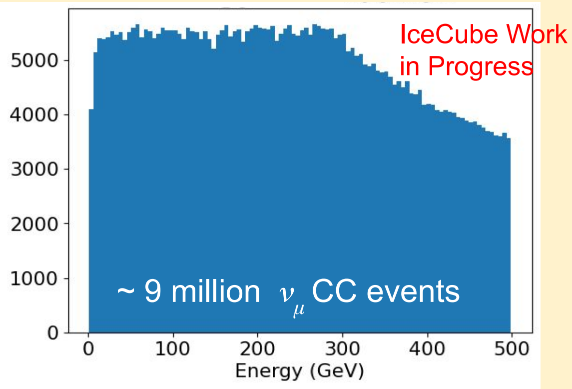
Training Samples Optimized per Variable

- ❖ Generate GENIE samples for training the CNNs
  - ➢ Unbiased in **target variable**
- ❖ Create 4 samples uses to train 5 networks
- ❖ All networks use same architecture

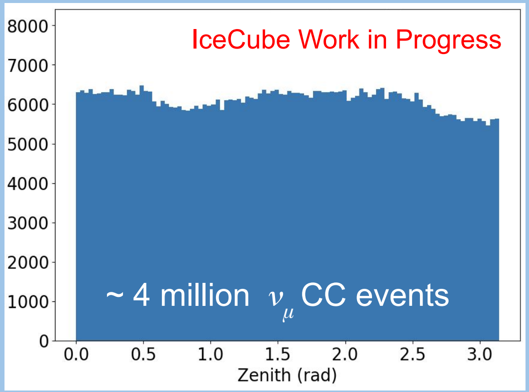
Atmospheric Muon Background vs Neutrino Training Sample



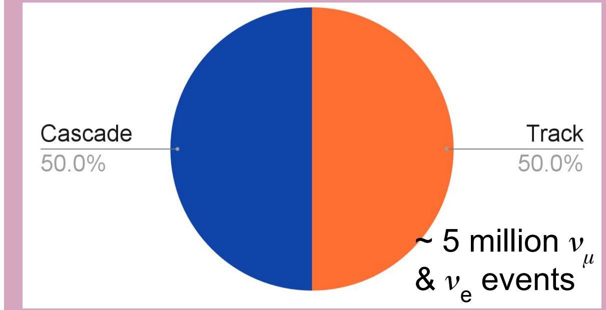
Energy (& Vertex) Training Sample



Zenith Training Sample



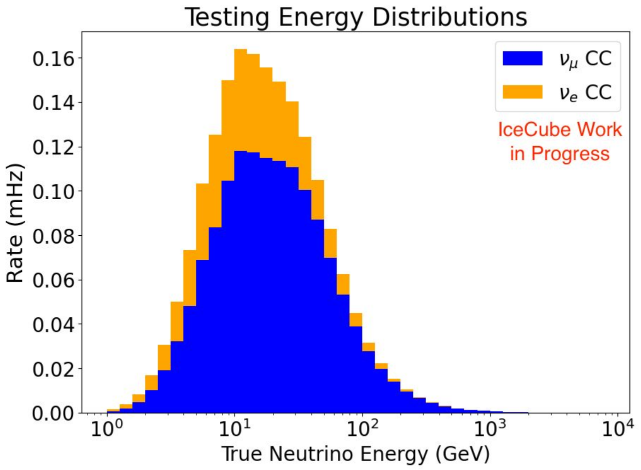
Track vs. Cascade Training Sample

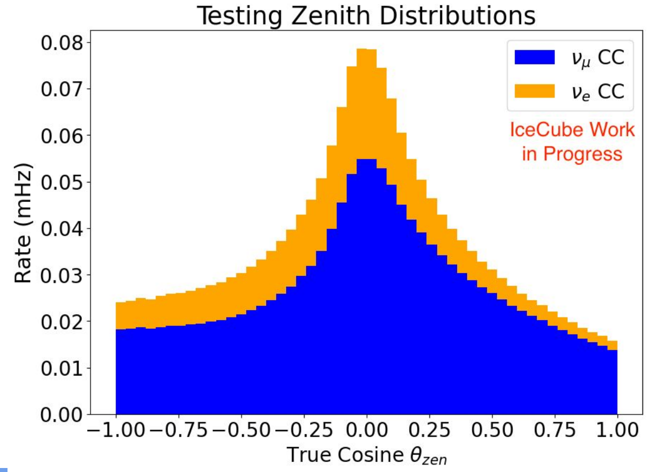


Resolution: Testing Samples

→ Testing sample with atmospheric flux, cross section, & oscillation model weights applied
→ Distributions expected to be similar to data
→ Separate testing samples for ν_μ CC & ν_e CC

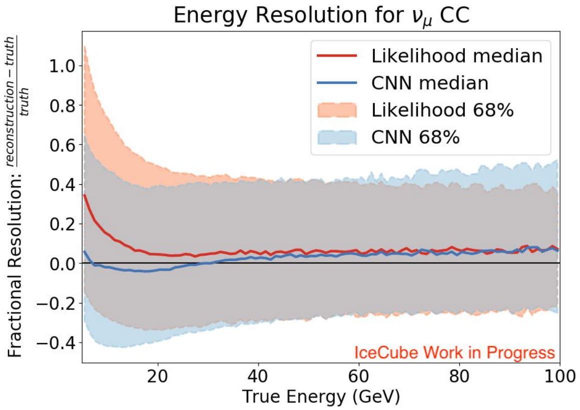
Compare to current likelihood-based reconstruction

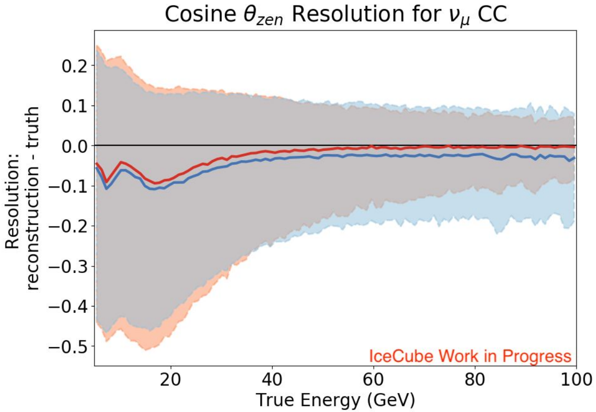


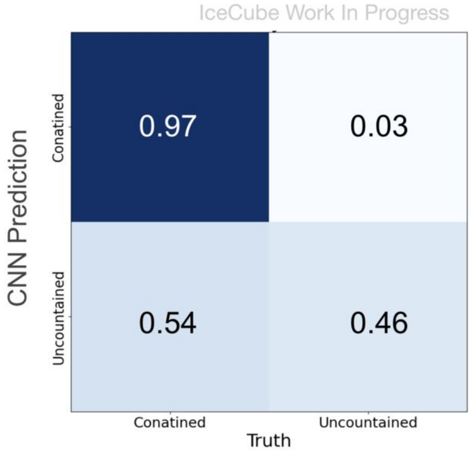


Resolution: Regression Networks

- Tested on MC with expected data distribution (flux, oscillations, etc.)
- Comparable to current likelihood-based reconstruction method







→ CNN best at lowest energy (where majority of events are)
→ Comparable at higher energy

→ CNN comparable throughout
→ Potential tracks leaving CNN input volume at high energies

→CNN starting vertex containment cut
→ Helps sample resolution