Reconstructing Neutrino Energy using CNNs for GeV Scale IceCube Events

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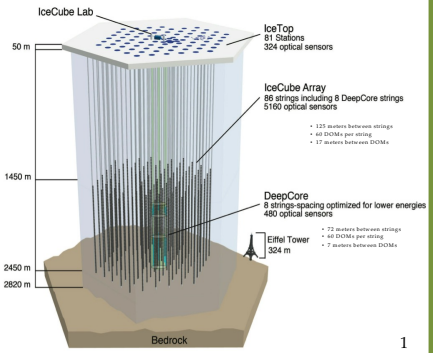
Catching Elusive Neutrinos

Using the IceCube Neutrino Observatory

- Instruments km^3 of Antarctic ice [1]
- 5160 optical modules in hexagonal array
- Detects atmospheric and extragalactic neutrinos

Detecting neutrinos:

- Digital Optical Modules (DOMs) use PMTs to detect photons from Cherenkov radiation
  - Record pulse times
  - Record pulse charge
- Use to reconstruct neutrino interaction & its properties such as incident energy and direction



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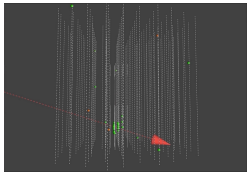
Challenge: IceCube's Low Energy Events

- CNN successfully implemented in IceCube at TeV scale [2]
- Only a few DOMs hit per event for GeV scale events
- Example of 12 GeV event in IceCube
  - Colored dots shows time DOM was hit
  - Size of dots shows amount of charge DOM recorded

Why do we care? → Interesting physics at the GeV scale like neutrino oscillations!



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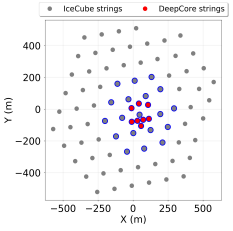
Goal: Apply convolutional neural network (CNN) on on low energy IceCube events (5-200 GeV) to improve the reconstruction speed and resolution of the neutrino's energy.

Focusing CNN on Low Energy Events

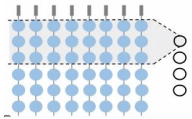
DeepCore, the densely instrumented center of IceCube, is already optimized for low energies [1]

- Focus CNN on DeepCore strings & nearby IceCube strings
- Use hits near DeepCore event trigger: time window [-500, 4000] ns



Inputs: 5 variables that summarize 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



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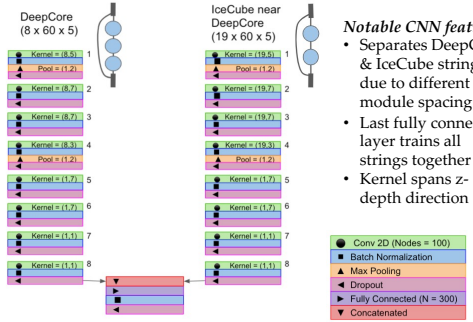
CNN Architecture for Low Energy Neutrino Reconstruction



Notable CNN features:

- Separates DeepCore & IceCube strings due to different module spacing
- Last fully connected layer trains all strings together
- Kernel spans z-depth direction

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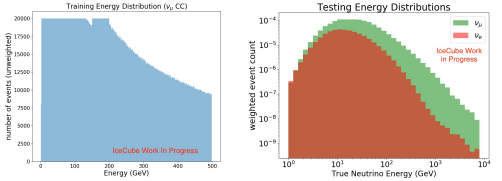
Training Sample

→ Mostly uniform energy training sample in region of interest for unbiased training
→ No weights for training
→ Only training with ν_μ CC

Testing Samples

→ Distribution expected to be similar to data
→ Atmospheric flux & oscillation model weights applied
→ Testing on ν_μ and ν_e CC



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Reconstruction Speed Improvement

✓ Reconstructs 10^5 times faster!
✓ Will take hours instead of weeks to reconstruct high statistics atmospheric neutrino sample

Method	Average Time per Event (seconds)	Events per Day per Single Core
CNN on GPU	0.0077	11,000,000
CNN on CPU	0.27	320,000
Likelihood-Based	40	2,100

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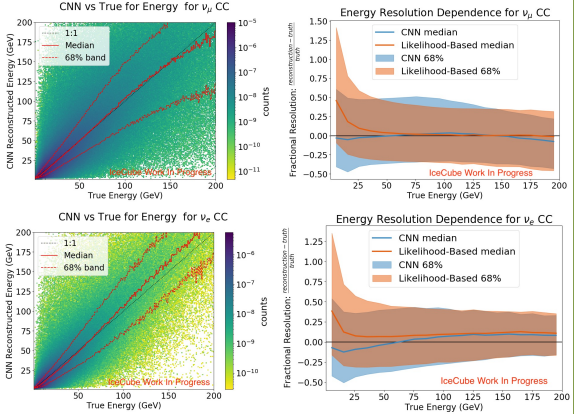
CNN Resolution Performance Comparison

✓ Reconstruction at low energy < 50 GeV shows improvements
✓ Resolution at > 50 GeV is comparable to current likelihood-based method [3], both in median and 68% containment



CNN reconstructed energy performance for ν_μ (top) and ν_e (bottom) CC events. The median line follows the ideal 1:1 line closely for most energies, indicating a good average reconstruction.

Fractional resolution as a function of true neutrino energy performance for ν_μ (top) and ν_e (bottom) CC events. CNN best at low energies, where majority of data sample is expected.

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Conclusion and Future work

✓ CNN significantly accelerates processing time while maintaining or improving the reconstruction performance
✓ CNN shows promising robustness against systematics
✓ Other applications for CNN in progress [Shiqi Yu's poster]

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References & Acknowledgments

[1] IceCube Collaboration, M. G. Aartsen *et al.* JINST 12 no. 03, (2017) P03012.
[2] IceCube Collaboration. PoS ICRC2017 (2017) 1057.
[3] M. Leuermann. PhD RWTH Aachen University. 2018. DOI 10.18154/RWTH-2018-231554

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