Reconstructing Inelasticity in IceCube using Deep Neural Networks

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Massachusetts Institute of Technology

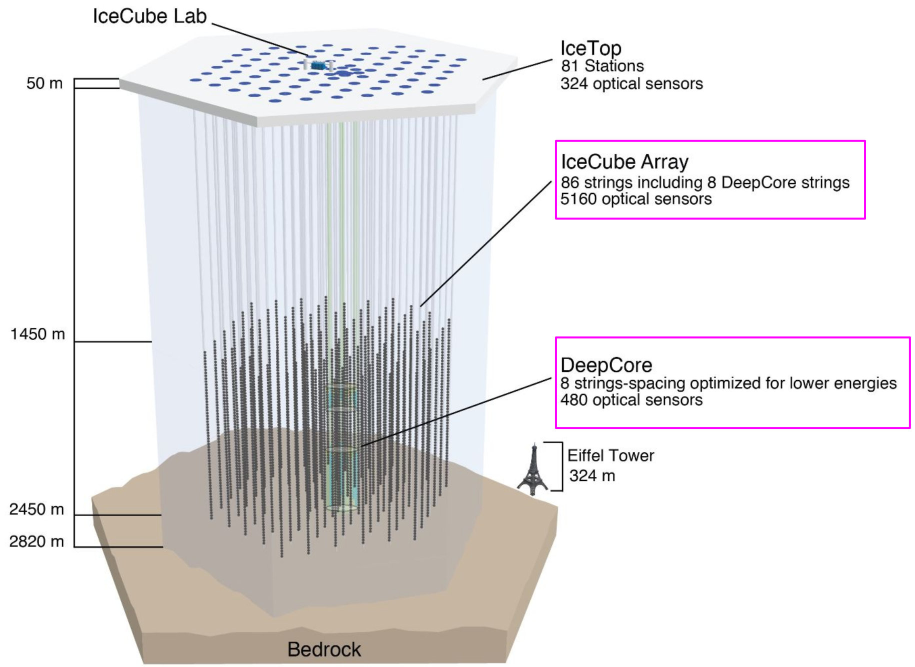
IceCube
South Pole Neutrino Observatory

Overview

1. The IceCube Neutrino Observatory
2. Neutrino Fluxes and Interactions
3. An Approach to Machine Learning in IceCube
4. Inelasticity Reconstruction

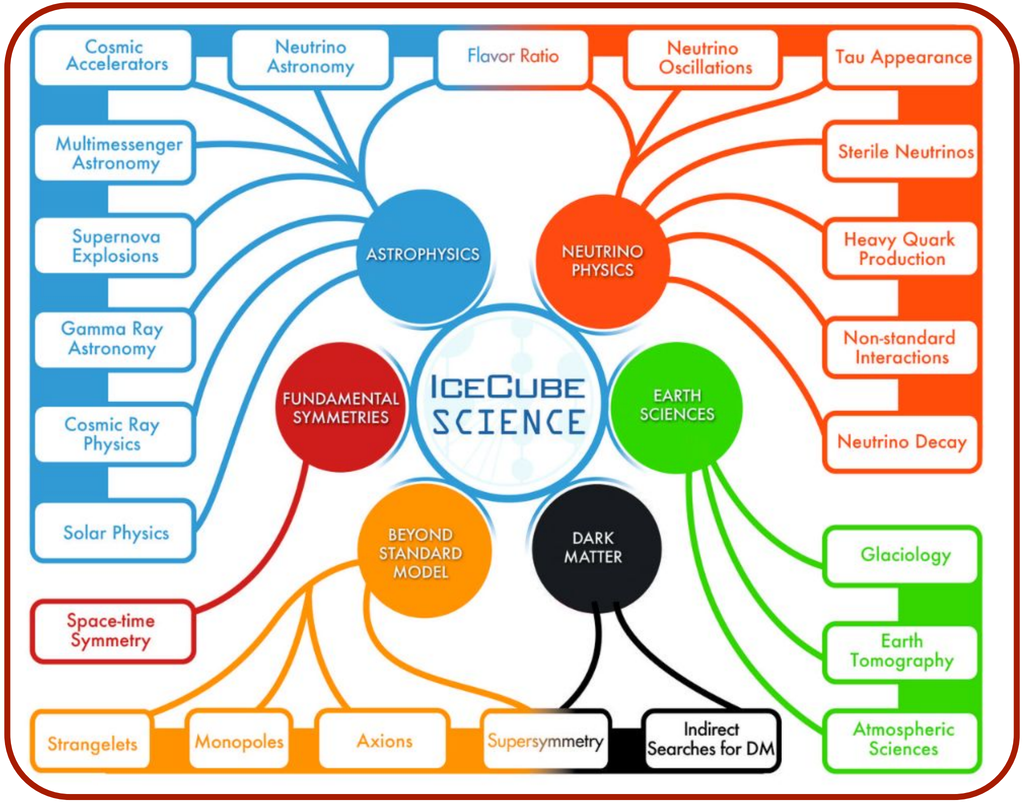
The IceCube Neutrino Observatory

- IceCube is a cubic kilometer of instrumented ice at the South Pole
- There are 5160 digital optical modules (DOMs) that detect Cherenkov light from charged particles passing through the ice
- For neutrino interactions, these are charged particles resulting from hadronic showers and outgoing charged leptons



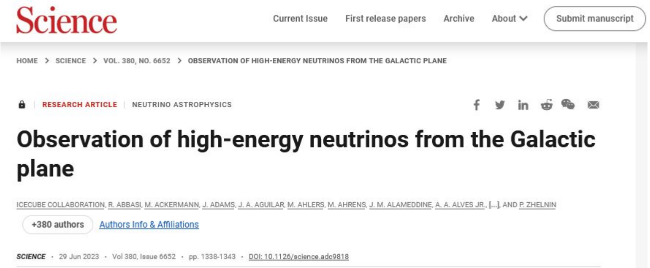
IceCube Science

- The results from our analyses rely strongly on our ability to reconstruct neutrino energies, directions, and particle identification
  - In recent years, these reconstructions have improved greatly with the introduction of machine learning tools



Recent IceCube Result: Galactic Plane

- One of the biggest results from IceCube this year
    - Identification of neutrinos originating from the galactic plane at 4.5**σ**
- Analysis relied on many DNN-based reconstructions and hybrid methods
    - **See Mirco Huennefeld's talk from the 2020 NPML for a good overview**
    - I will discuss some of these tools later


Science
Current Issue First release papers Archive About Submit manuscript
HOME > SCIENCE > VOL. 380, NO. 6652 > OBSERVATION OF HIGH-ENERGY NEUTRINOS FROM THE GALACTIC PLANE
RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

ICECUBE COLLABORATION, R. ABBASI, M. ACKERMANN, J. ADAMS, J. A. AGUILAR, M. AHLERS, M. AHRENS, J. M. ALAMEDDINE, A. A. ALVES JR., [...], AND P. ZHELNIN
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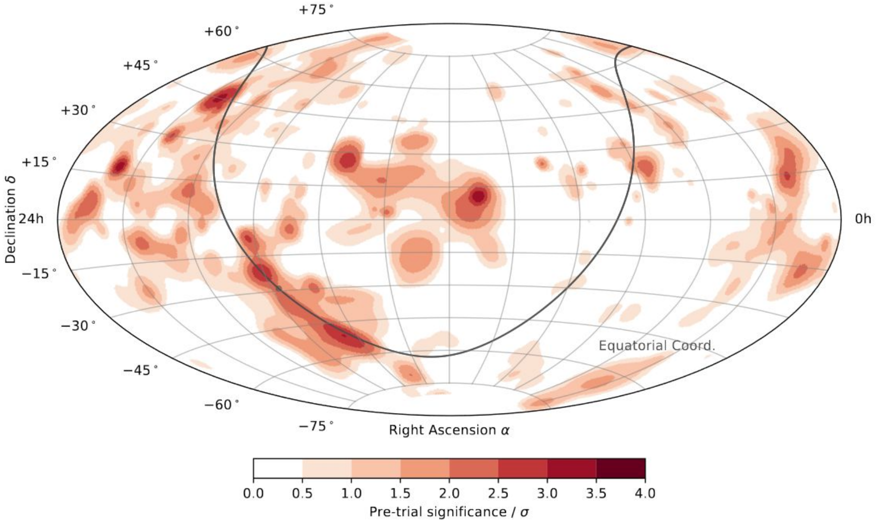
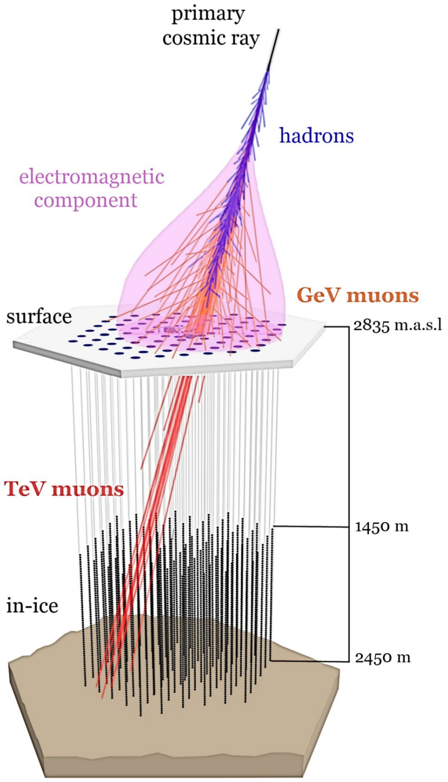


Science 380, 1338-1343 (2023)

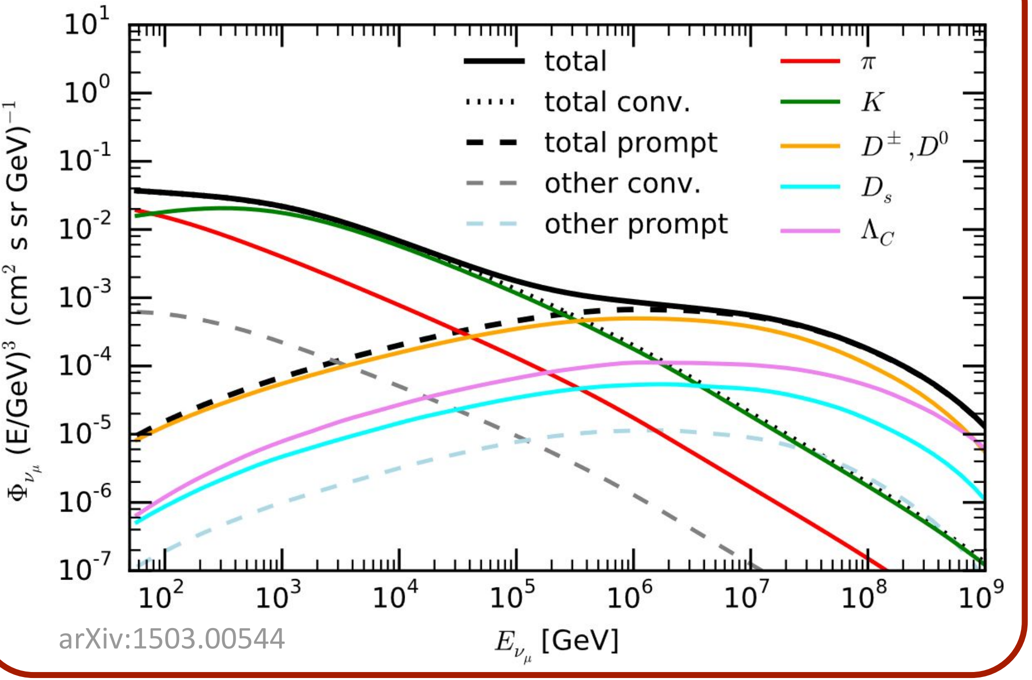
Atmospheric Muons

- Cosmic rays interact with the atmosphere, producing a large number of secondary particles
- Only muons and neutrinos are able to make to the detector below the ice
  - These atmospheric muons are a large background for many of the neutrino physics analyses
  - The detector triggers on atmospheric muons at a rate of about 3kHz (*Astropart. Phys. 78 (2016)*)
    - Example: neutrino rate in the 2020 sterile neutrino analysis: 1.3 mHz (*Phys. Rev. Lett. 125, 141801*)



Atmospheric Neutrino Flux

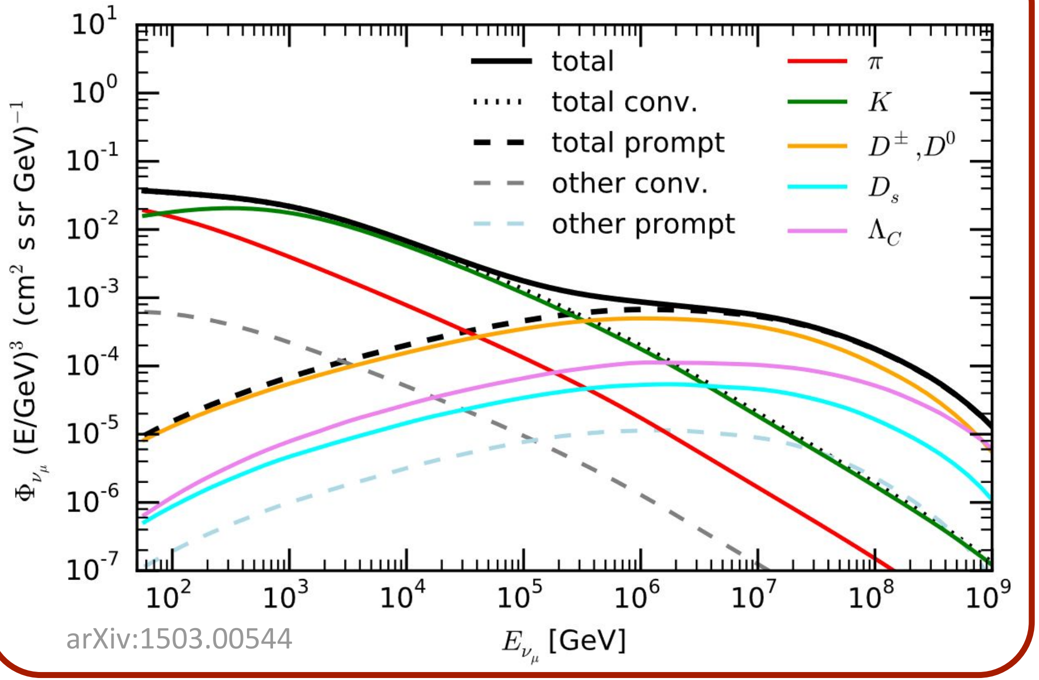
- Most neutrinos observed in IceCube come from the conventional atmospheric flux
- These neutrinos mostly originate from pion and kaon decay-in-flight
- Note the factor of E^3!



arXiv:1503.00544

Atmospheric Neutrino Flux

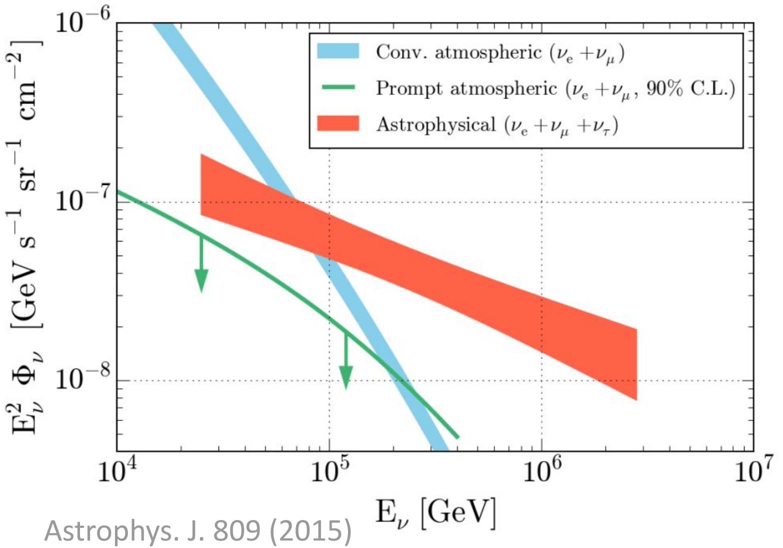
- The prompt atmospheric flux primarily comes from $D^{\pm/0}$/D_s meson and Λ baryon decays
  - Simply called “prompt” based on the decay times of these particles
- The prompt component overtakes the conventional component at the highest energies



arXiv:1503.00544

Astrophysical Neutrino Flux

- Above ~200 TeV, the diffuse astrophysical flux begins to dominate over the atmospheric flux
    - Diffuse meaning isotropic, neutrinos originating from high energy astrophysical events
    - Origins of these neutrinos are not completely known
- Point Sources:
    - TXS 0506+056
    - NGC 1068
- A fraction also originates from the galactic plane

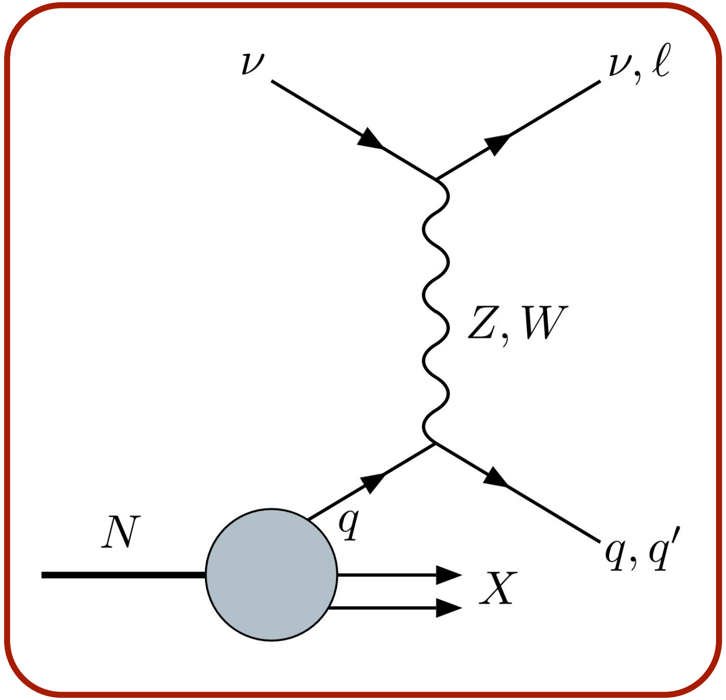


Astrophys. J. 809 (2015)

Neutrino Deep Inelastic Scattering

- In neutrino deep inelastic scattering (DIS), a neutrino exchanges a W or a Z boson with a quark
  - W boson (CC) $\longrightarrow$ Charged lepton + hadrons out
  - Z boson (NC) $\longrightarrow$ Neutrino + hadrons out
- Inelasticity, labeled y, is the fraction of energy imparted into the hadrons:

$$y = \frac{E_{\text{had}}}{E_{\nu}}$$



Neutrino Deep Inelastic Scattering

- The cross section in terms of the structure functions is given by

$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi\left(1+Q^2/M_{W,Z}^2\right)^2}\left[\begin{array}{c}\frac{y^2}{2}2xF_1(x,Q^2)+\left(1-y-\frac{Mxy}{2E}\right)F_2(x,Q^2)\\ \pm y\left(1-\frac{y}{2}\right)xF_3(x,Q^2)\end{array}\right]$$

- +y for neutrinos, -y for antineutrinos
- The structure functions depend on the parton distribution functions

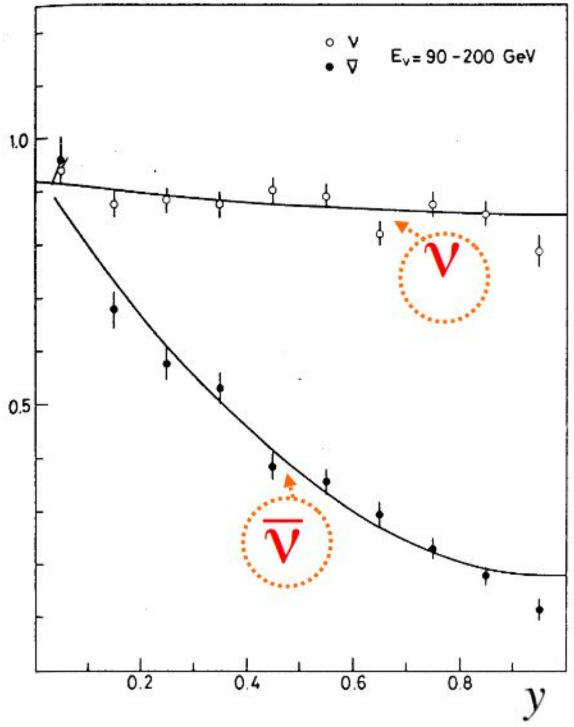
$$F_2(x,Q^2) = 2\sum_{i=u,d,\ldots}\left(xq(x,Q^2)+x\overline{q}(x,Q^2)\right)$$

$$xF_3(x,Q^2) = 2\sum_{i=u,d,\ldots}\left(xq(x,Q^2)-x\overline{q}(x,Q^2)\right)$$

Neutrino Deep Inelastic Scattering

- An interesting feature of DIS is that neutrinos and antineutrinos have differently shaped distributions with respect to inelasticity
  - Note: y-axis of this plot is proportional to the cross section
- These cross sections are very well understood
  - Uncertainty of DIS cross sections ~several %
- This will come up again later!

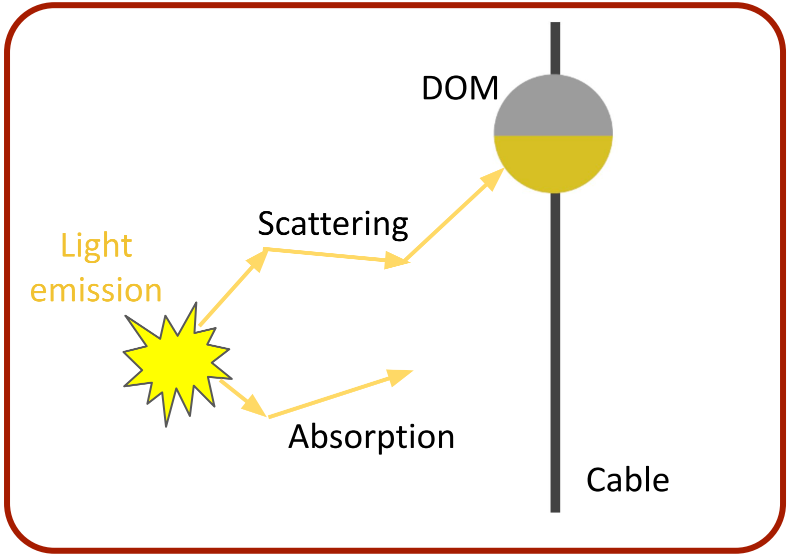
•CDHS measured y distribution

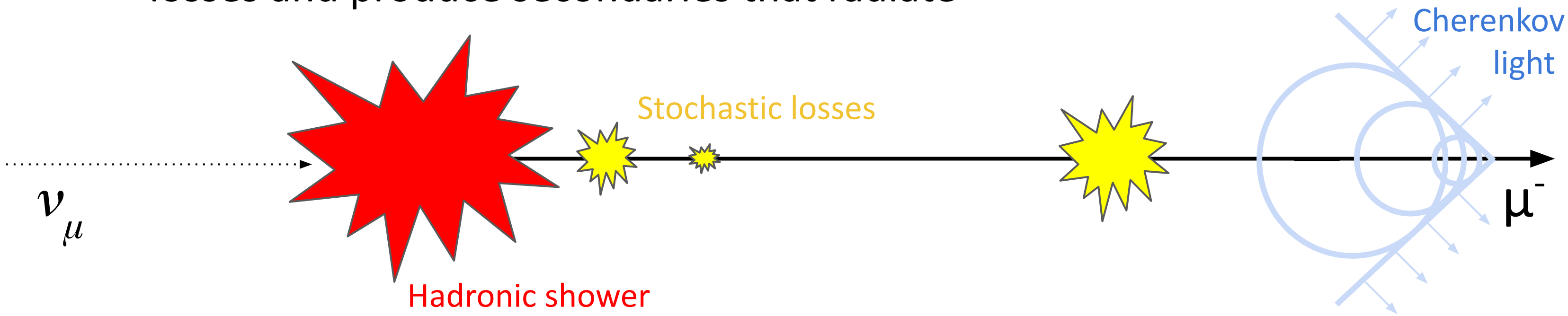


J. de Groot et al., Z.Phys. C1 (1979) 143

Light Detection

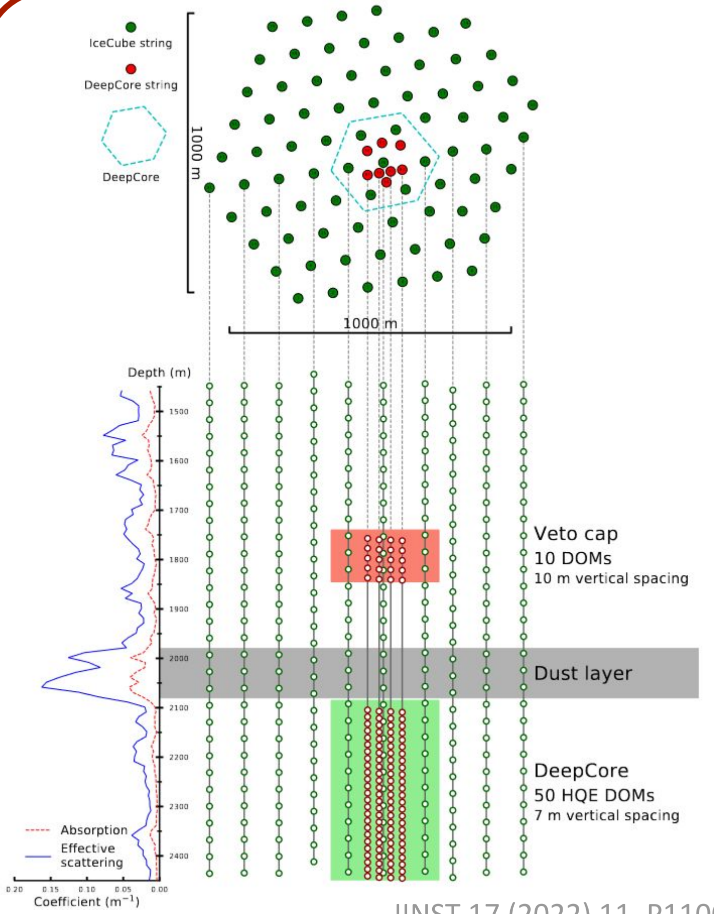
- Charged particles in the ice can produce Cherenkov light
- The light propagates and scatters until hitting a DOM or absorbed
- At high energies, muons undergo stochastic losses and produce secondaries that radiate





The Dust Layer

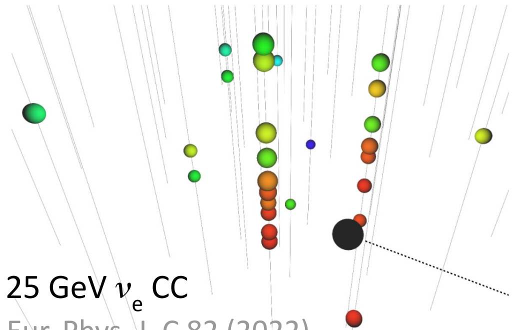
- The ice below the South Pole is typically very transparent, allowing us to observe many of these events
  - However, scattering in the ice obscures the typical Cherenkov rings people would expect
- Additionally, about half-way down the detector, there is an additional layer of dust
  - A region of higher absorption and scattering



JINST 17 (2022) 11, P11003

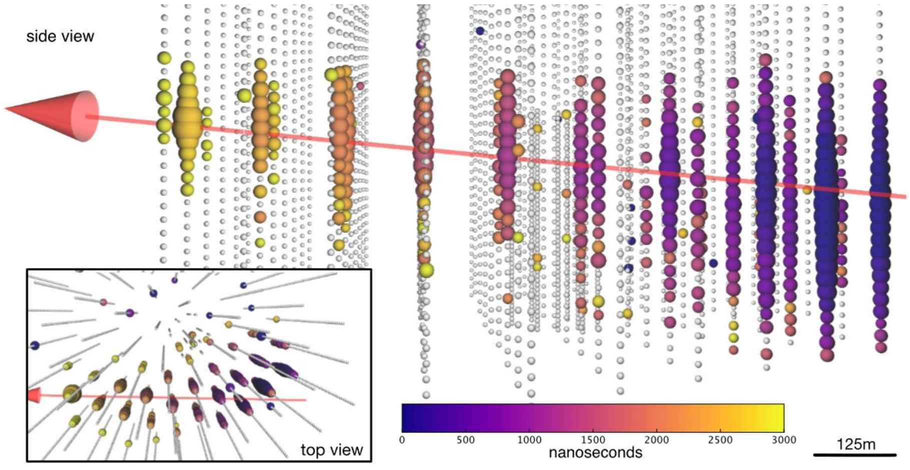
IceCube Events

- IceCube detects events with energies varying over several orders of magnitude
  - ~GeVs to ~10 PeV
- The shape and size of these events vary greatly
  - Only DeepCore can really resolve events < 100 GeV (top right)
- ν_e CC, ν_τ CC, and NC interactions look spherical (showers/cascades)
- ν_μ CC are extended (tracks)



25 GeV ν_e CC

Eur. Phys. J. C 82 (2022)



IceCube-170922, 290 TeV ν_μ CC

Science 361, eaat1378 (2018)

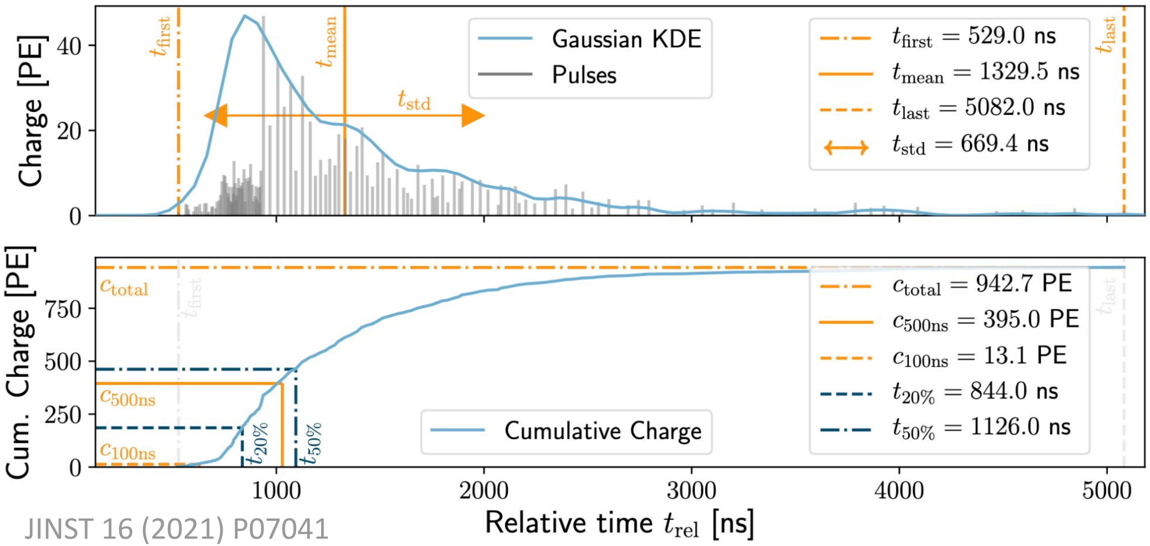
Shaping IceCube Data

Complication of geometric information and dimensionality:

- Time-series data from DOMs
  - DOMs can have small or very large numbers of pulses
  - For use in a CNN, we need a fixed-length input for each dOM
- Spatial layout of the main array strings
  - Simply mapping the hexagonal geometry to a rectangular array throws away useful geometric information
- DeepCore strings
  - Do not follow the geometrical pattern of the main array strings
  - DeepCore contains a lower and an upper sub-array, which are separated by a layer of dust in the ice

PMT Pulses to Features

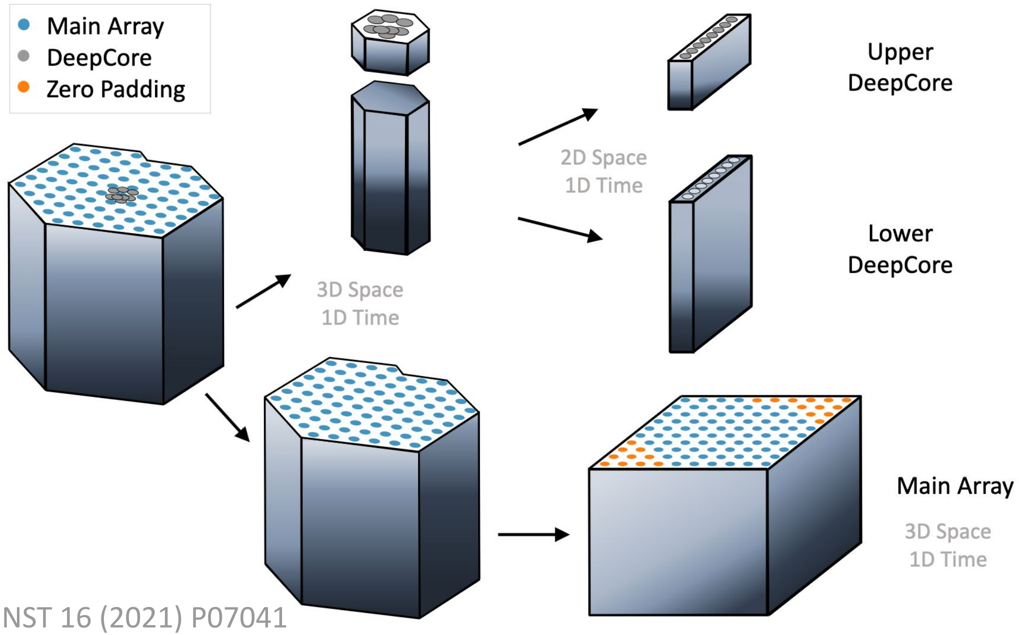
- Pulse data from PMTs are reduced with summary statistics



JINST 16 (2021) P07041

PMT Pulses to Features

- The DeepCore upper and lower arrays are separated out from the main array
- The IceCube main array is mapped to a zero-padded rectangular array
    - Geometry will be handled by modified convolutions

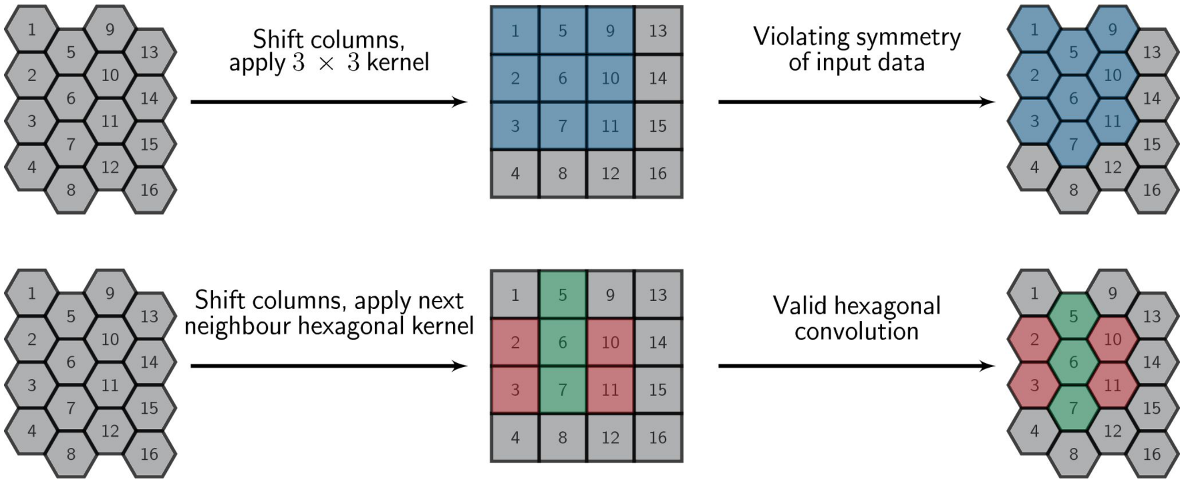


JINST 16 (2021) P07041

Hexagonal Convolutional Layers

- Hexagonal convolutions are used to leverage the near-symmetric properties of the IceCube detector
  - Reduces the geometric mismatch when embedding onto the square grid
- This is not an exact symmetry as the spacings between detector strings are not even
- There are several available tools for hexagonal convolutions:
  - hexaconv: https://github.com/ehoogeboom/hexaconv
  - TFScripts: https://github.com/icecube/TFScripts (used in this work)
  - HexCNN: https://arxiv.org/abs/2101.10897
  - hexagdly: https://github.com/ai4iacts/hexagdly

Example: Hexagdly Implementation



Astroparticle Physics 105 (2019): 44-53

See also: https://github.com/ai4iacts/hexagdly/

Example: TFScripts Implementation

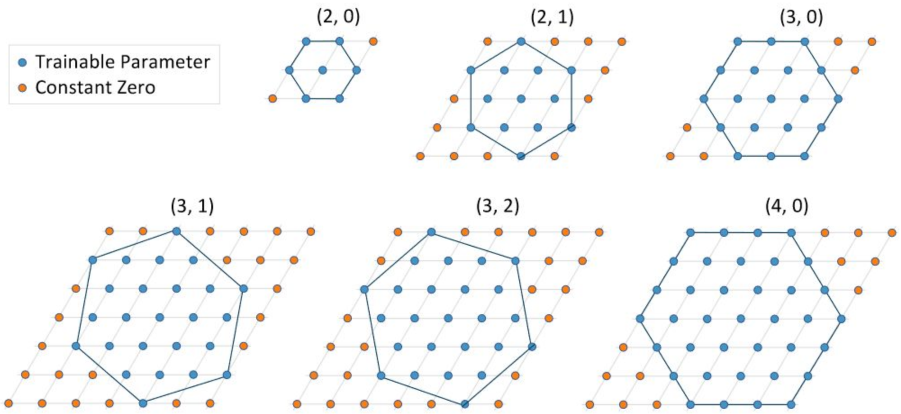


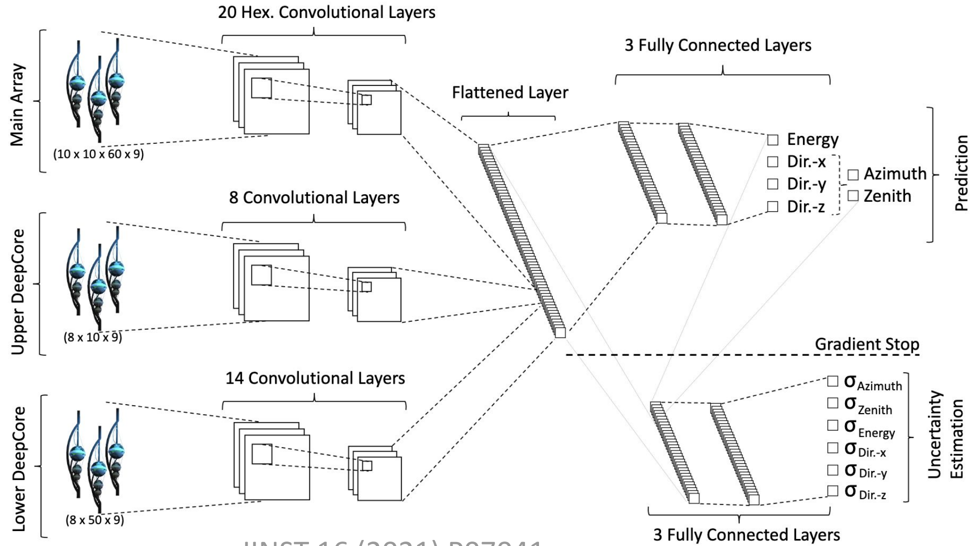
Figure 7: An hexagonally shaped kernel can be defined by a tuple of size s and orientation o: (s, o). For an axis aligned hexagon (orientation $o = 0$), the size parameter s defines the number of points along an edge of the hexagon.

JINST 16 (2021) P07041

See also: https://github.com/icecube/TFScripts

Neural Network Architecture

- Components of the detector are fed through different sequences of convolutional layers, later flattened and combined
- A sub-network is used to estimate the uncertainty on the prediction
  - A gradient stop is used so the uncertainty estimation does not backprop to the main network



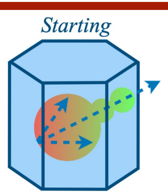
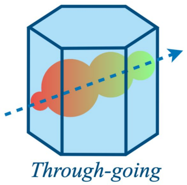
JINST 16 (2021) P07041

See also: https://github.com/icecube/dnn_reco/

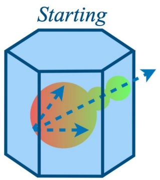
Event Topologies

- We are interested in CC muon (anti)neutrino interactions which produce an outgoing muon (a “track”) and a hadronic shower
- There are two types of observed event topologies:

I will be focusing on starting tracks!

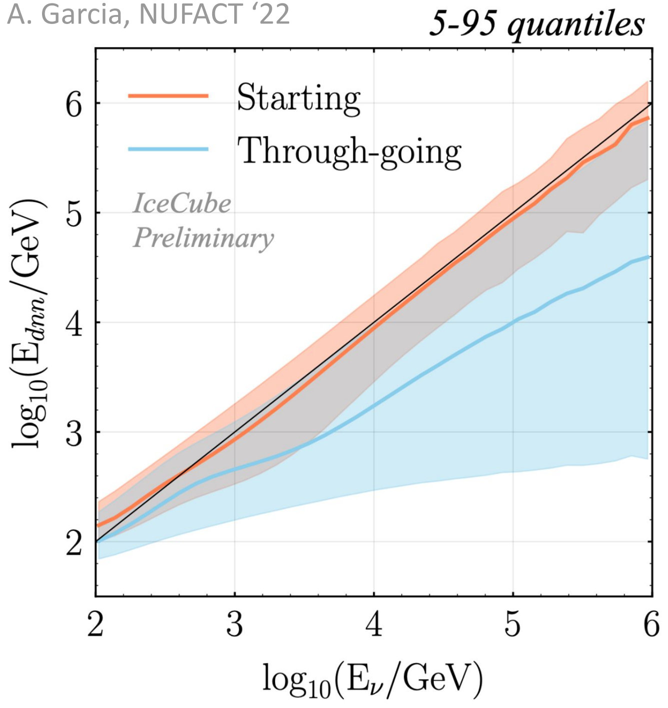
	*Hadronic shower inside detector*	*Good energy resolution*	*~20% of events*
	*Hadronic shower outside detector*	*Poor energy resolution*	*~80% of events*

Starting Tracks



- Starting tracks have an interaction vertex inside of the detector volume
  - Most of the hadronic energy is deposited in the detector
- Even though the muon leaves the detector, its energy is proportional to its stochastic energy losses
  - The combination of the hadronic shower and the muon losses allow for a far more accurate reconstruction of the neutrino energy than that of through-going events

A. Garcia, NUFACT ‘22



Training Monte Carlo Dataset

- Inelasticity can only be reconstructed if we have information about the hadronic shower at the interaction point
- To train this DNN, we use true starting track (ν_μ CC) events
  - These events are generated with energies of 100 GeV to 1 PeV with an E^{-2} power law spectrum
  - Only simple filtering and precuts are applied to this dataset
- Through-going tracks and other flavor events are not considered in the training
  - Other reconstructions and filters are used to significantly reduce these rates to negligible levels

Reconstructing Inelasticity

Approach:

- Reconstruct the energy deposited by the hadronic shower and outgoing muon separately
- Divide the hadronic energy by muon+hadronic to obtain the inelasticity

Complication:

- Hadronic shower energy is tricky–not all of it will be visible in the detector

Visible Energy

- A new variable is introduced: visible energy, which equates to an equivalent energy of a purely electromagnetic shower
- This can be calculated by multiplying the total hadronic shower energy by an energy-dependent scaling term determined by simulation:

$$E_{\text{had}}^{\text{vis}} = F_{\text{EM}}(E_{\text{had}})E_{\text{had}}$$

- For a muon, the visible energy is its kinetic energy when it enters the detector
  - Alternatively, its energy when it is created from the interaction if the vertex is within the detector

Defining Visible Inelasticity

- The visible inelasticity will be defined by using the visible hadronic energy and visible muon energy
  - This proxy for inelasticity is more correlated with the photons observed in the detector

$$y = \frac{E_{\text{had}}}{E_\nu} = \frac{E_{\text{had}}}{E_\mu + E_{\text{had}}} \longrightarrow y_{\text{vis}} = \frac{E_{\text{had}}^{\text{vis}}}{E_\mu^{\text{vis}} + E_{\text{had}}^{\text{vis}}}$$

Training Information

- Train on 3M simulated true starting track events that pass basic quality cuts
  - Labels: visible track energy, visible hadronic energy, total visible energy
- Adam optimizer, ~2M steps w/ learning rate scheduler
  - 1e-5 to 1e-3 for 1k steps
  - 1e-3 to 1e-3 for 1M steps
  - 1e-3 to 1e-7 for 1M steps
- Loss function: Gaussian Likelihood
  - Very similar to MSE, but the estimated error from the sub-network is an input to the loss function s.t. the lower the uncertainty the lower the loss
- Total number of parameters: ~1M

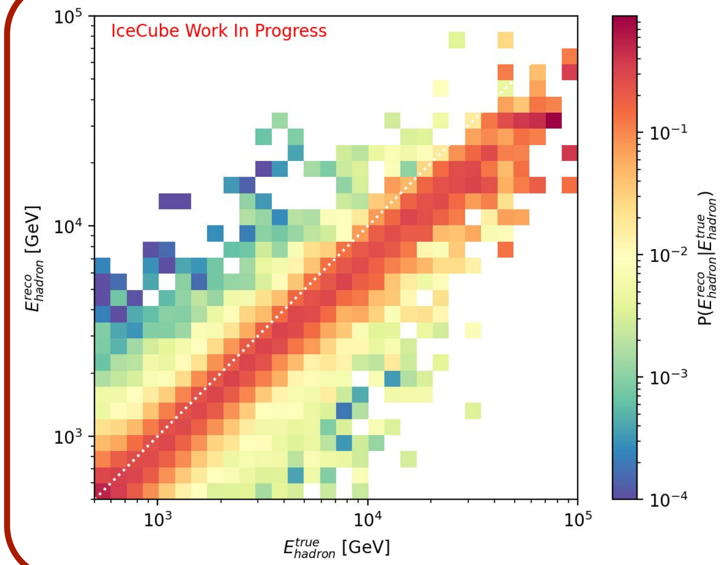
Final Level Dataset

This work uses an event selection designed for an ultra-high purity (>99.9%) muon neutrino dataset, so the performance of this reconstruction will be shown with the following filters/cuts:

- Events are generated from 100 GeV to 1 PeV with muon neutrinos/antineutrinos
- Precuts are applied to reduce the overall data rate and remove poor quality events
- Events above the horizon are cut to reduce cosmic ray muon background
- Two DNN reconstructions are applied: energy estimator and topology classifier
  - Only classified starting tracks with a reconstructed energy of 500 GeV to 100 TeV pass
- A final level BDT is applied to further reduce background events

Reconstructing Hadronic Energy

- For a starting track event, the neutrino interaction vertex is inside of the convex hull of the detector, allowing for an accurate reconstruction of the hadronic energy
- Columns are normalized to 1
  - Essentially a pdf in each column



Notes:

1. There is a bias toward predicting a lower hadronic energy, likely due the higher statistics at low energies in the training sample

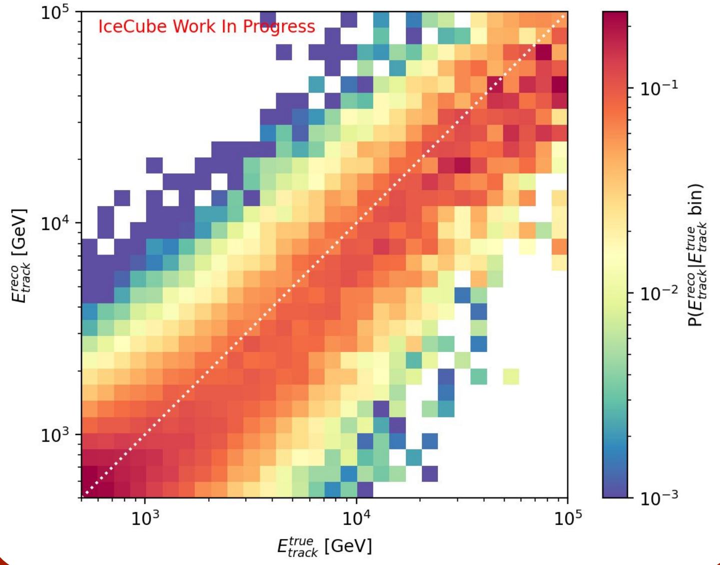
2. The higher energy region is sparse from the low MC statistics

Reconstructing Track Energy

- High energy muons leave the detector with most of their energy, making it harder to resolve their energy

Notes:

1. Again, the higher energy region is sparse from the low MC statistics

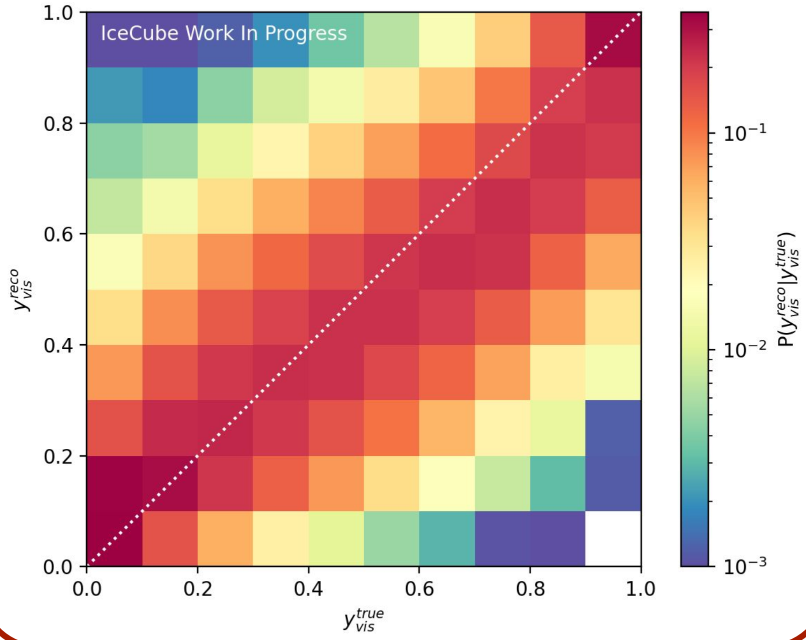


Reconstructing Visible Inelasticity

- The visible inelasticity can be calculated using the equation from before:

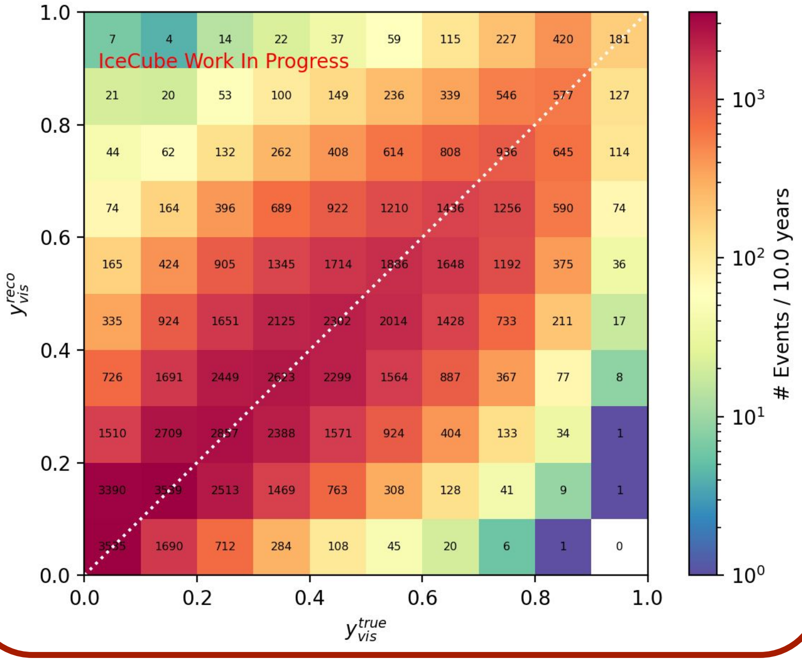
$$y_{\text{vis}} = \frac{E_{\text{had}}^{\text{vis}}}{E_{\mu}^{\text{vis}} + E_{\text{had}}^{\text{vis}}}$$

- Despite poor muon energy resolution, the ability to reconstruct the visible inelasticity is quite good



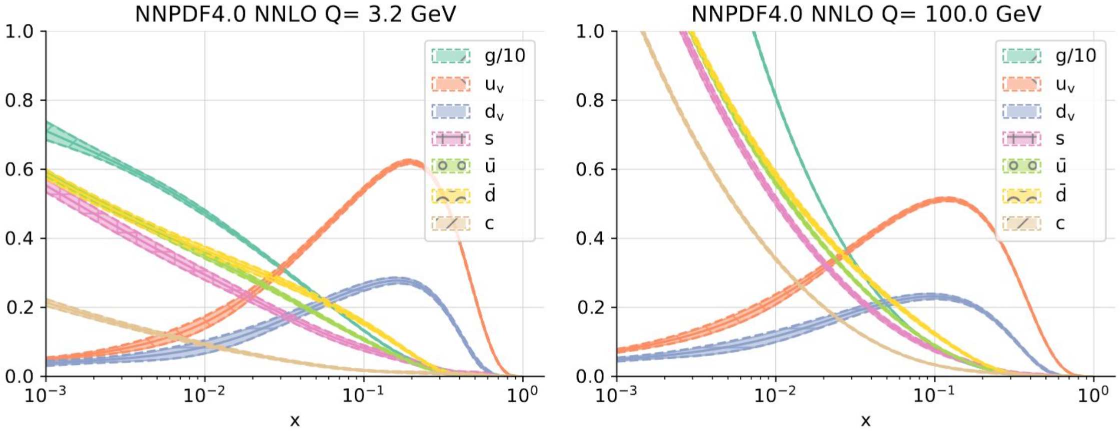
Number of Events

- Here is the same plot as the previous slide, but showing the expected number of events in 10 years
- There is a noticeable deficit at high visible inelasticity
  - This is caused by the shape of the DIS cross section as well as the precuts that try to remove events that don't look track-like



What can we do with inelasticity?

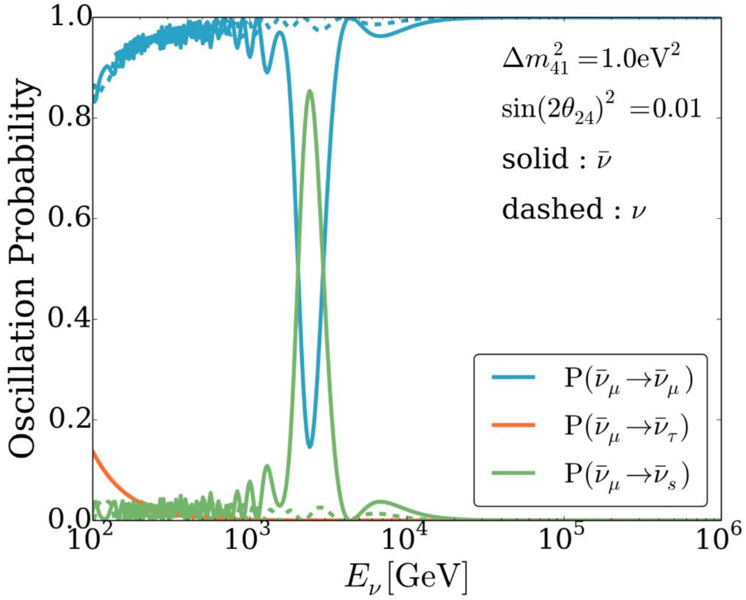
- In general, the visible inelasticity is sensitive to any interaction that looks more shower-like than track-like
  - Tau decays that produce final-state muons will look more shower-like
- Also sensitive to the production of heavy quarks in the hadronic showers
  - Primarily charm production → produces a flatter y distribution



Eur. Phys. J. C 82 (2022) 5, 428

What can we do with inelasticity?

- As mentioned earlier, the cross section as a function of inelasticity differs between neutrinos and antineutrinos
  - This can be used for the statistical separation of nu and nubar
- One such application is to improve predictions on the atmospheric nu/nubar ratio
  - This can improve searches for signals that differ w.r.t. neutrinos and antineutrinos
  - e.g. sterile neutrino oscillations with matter effects



Prog. Part. Nucl. Phys. 111 (2020)

Conclusions

- We have shown that deep neural networks can be effective at reconstructing the visible inelasticity of neutrino deep inelastic scattering events in IceCube
  - This method relies on separating the outgoing muon energy and the hadronic shower energy
- Improvements with regard to network architectures, hyperparameters, etc. are currently being investigated

Thank you for listening!