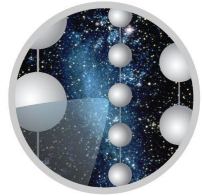


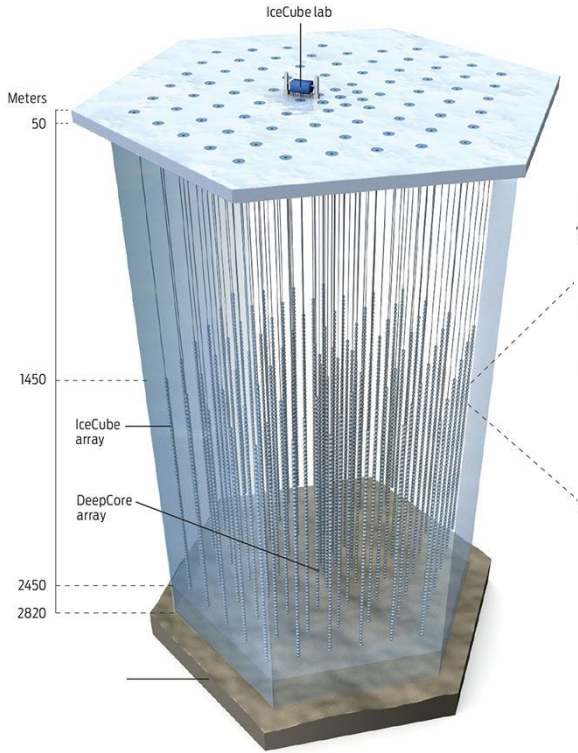
Search for astrophysical tau neutrinos using Deep Learning with IceCube

XIX International Workshop on Neutrino Telescopes

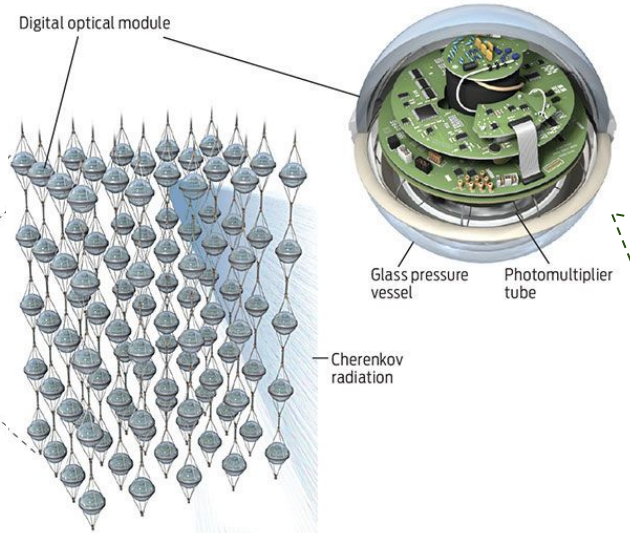
D.Pankova, A.Fienberg

25/02/2021

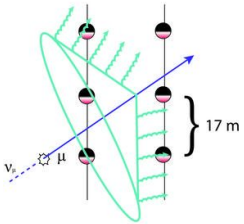
IceCube Neutrino observatory

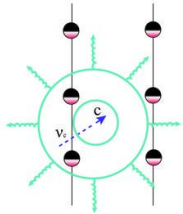


- Located at South Pole
- Volume of ~1 km^3
- ~1 km below surface

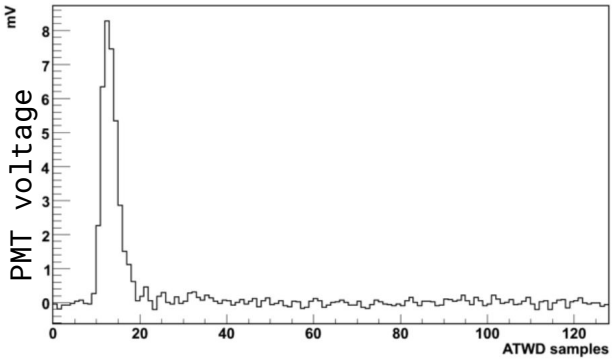


- 5160 Digital Optical Modules(DOMs)
- 86 vertical strings
- DOM Contains:
  - Photomultiplier (PMT)
  - Digitizers (ATWD, fADC)





- Neutrino interactions produce charged particles
- They emit cherenkov light, registered by the DOMs



- One Photon recording example (above)
- 128 samples
- ~3 ns sample size

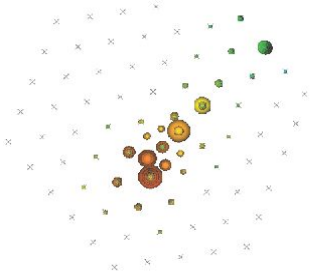
Neutrino Interaction in IceCube

Spheres: DOMs
White: recorded no light
Color: recorded light
Size: light collected

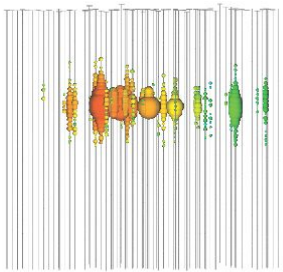
Color shows time information:

Data: (x,y,z,t,waveform)

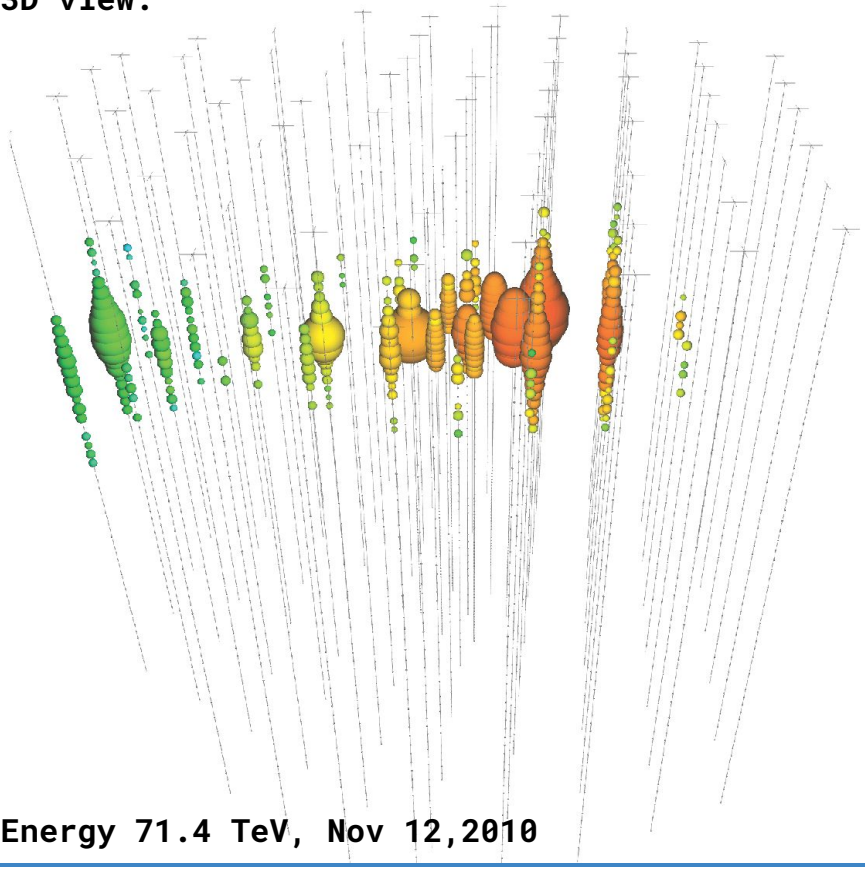
Top view:



Side view:



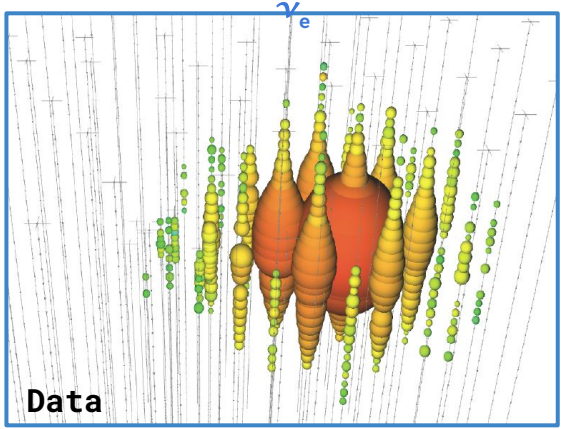
3D view:



Energy 71.4 TeV, Nov 12,2010

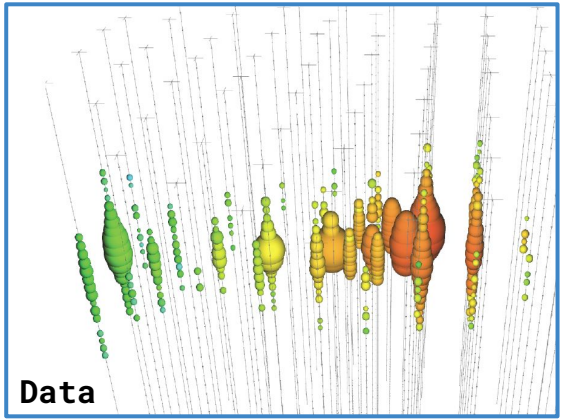
Neutrino interaction by flavor

All Neutral Current/Charged Current ν_e



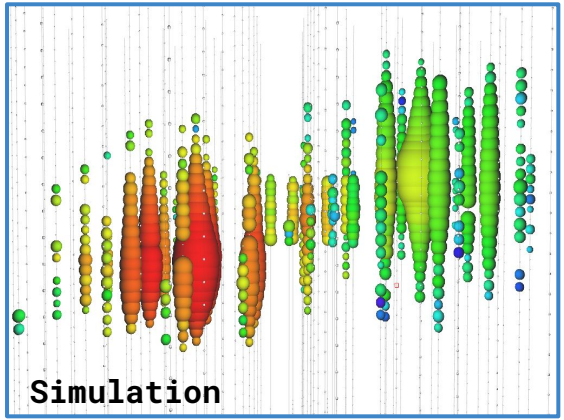
- Neutral Current interactions:
  - Hadronic cascade
- Charged Current ν_e interaction:
  - Hadronic cascade
  - Electromagnetic cascade

Charged Current ν_μ



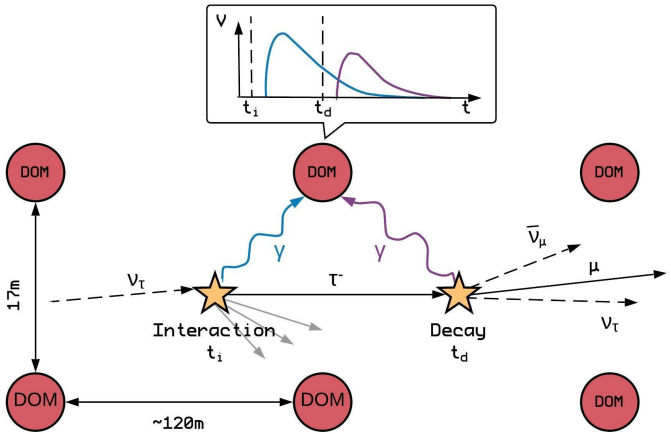
- Charged Current ν_μ interaction:
  - Hadronic cascade
  - Muon track
    - Stochastic losses

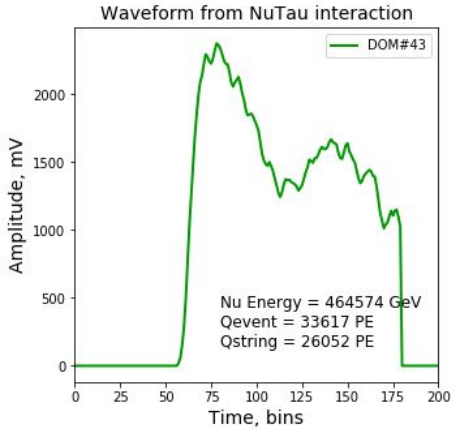
Charged Current ν_τ



- Charged Current ν_τ interaction:
  - Hadronic cascade
  - Tau meson track
  - Tau meson decay (cascade)

Types of ν_τ interactions





Charged current ν_τ interaction produces a tau meson, which decays after travelling:

$$L \sim 50m * E_{tau}/PeV.$$

(L can have large event by event fluctuations.)

Depending on E_{tau} the interaction can look like:

- **Single cascade (L ~ 1m)**:
  Cascades are fully merged.
- **Double Cascade (L ~ 10-100m):**
  Cascades separated by less than the mean interstring distance.
  - **Double Pulse**:
    Light from both cascades arrives at the same DOMs within the same recording cycle.
- **Double Bang (L > 100m)**:
  Clear spatial separation between cascades. (Rare)

Previous ν_τ searches in IceCube

From the measured flux we expect ~ 5 ν_τ events in IceCube per year (E> 0.1PeV).

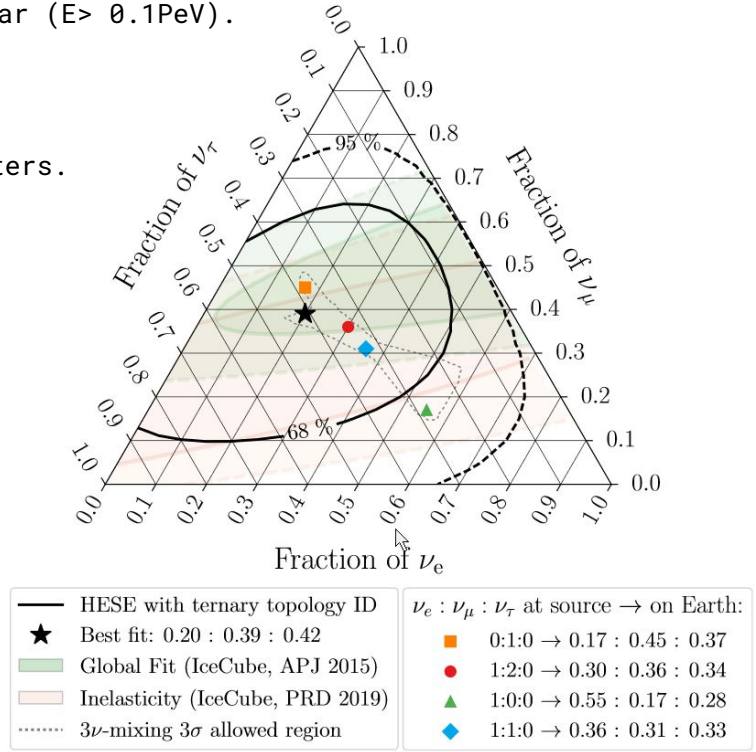
Double Cascade search:

- Topological classification with cuts based on best fit parameters.
  - Found 2 events in ~7.5 years of data.
  - "No ν_τ neutrinos" hypothesis disfavored at 2.8 sigma.

Double Pulse searches:

- Derivative based search for "double peaked" waveforms.
  - Found 3 events in ~8 years of data.
- Random Forest classifier using waveforms features.
  - Found 2 events in ~7.5 years of data.

Our goal is to increase analysis acceptance over the previous analyses by using more of the available event data.

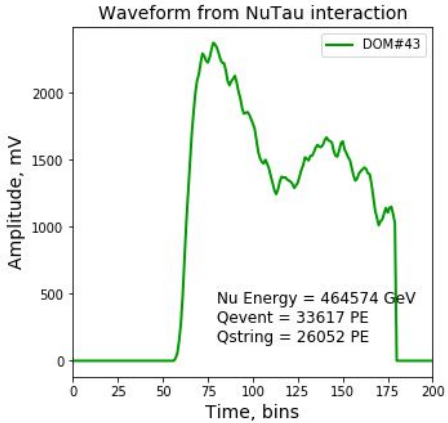


*All searches found one shared event.
*IceCube Collaboration, Measurement of Astrophysical Tau Neutrinos in IceCube's High-Energy Starting Events, Nov 6 2020.

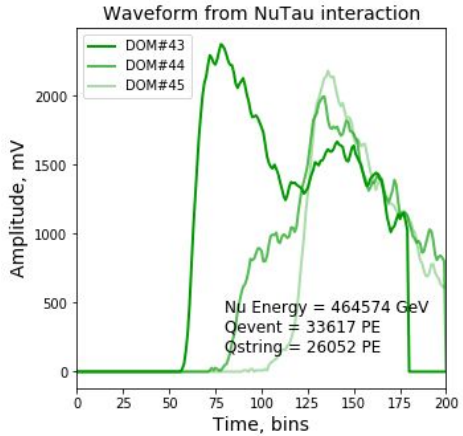
Our method

- Unlike previous analyses we are looking at up to 180 waveforms at the same time.
  - All waveforms from a single string in the event are combined to make an “image” (up to 60).
  - 3 strings/images for each event.
    (The highest charge string and its two highest charge neighbours.)

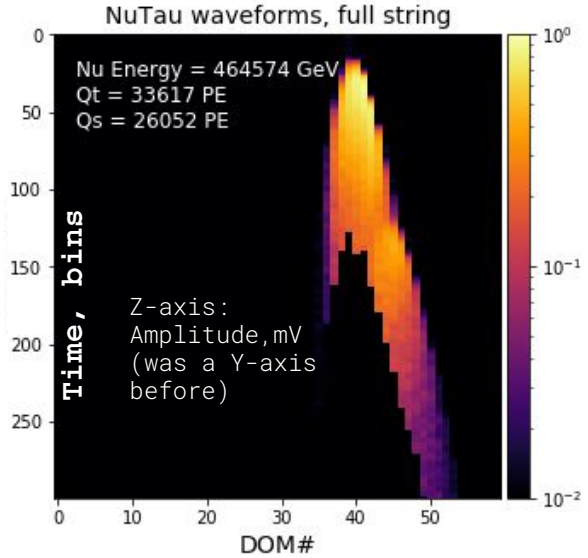
- We use machine learning to find ν_τ signatures using raw data, not features.
  The image format allows us to use Convolutional Neural Networks (CNN):
  - CNN can find features in raw data on its own (no need to select them by hand).
  - Widely recognized as well-suited for image classification.



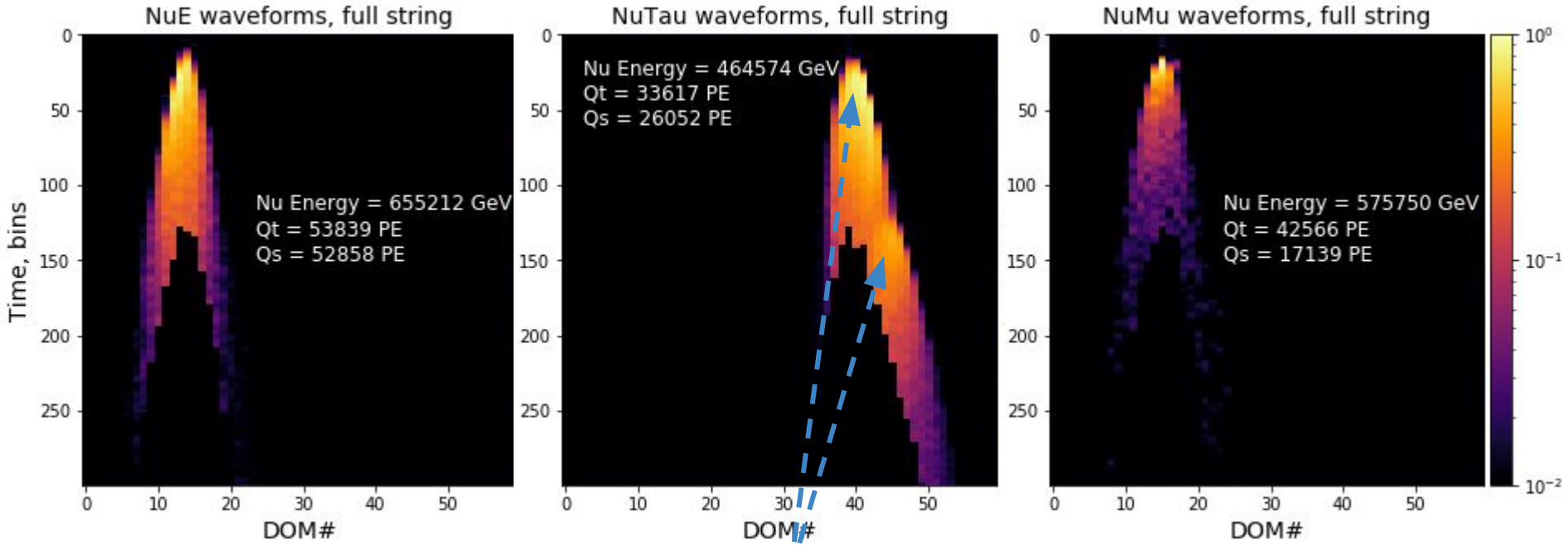
Single waveform
Bin: ~ 3 ns



Waveforms from three neighbouring
DOMs on the same string



Double pulse signature



Qt = Total charge
Qs = String charge
Time bin: ~ 3ns

Double pulse structure visible as two (partial) hyperbolas

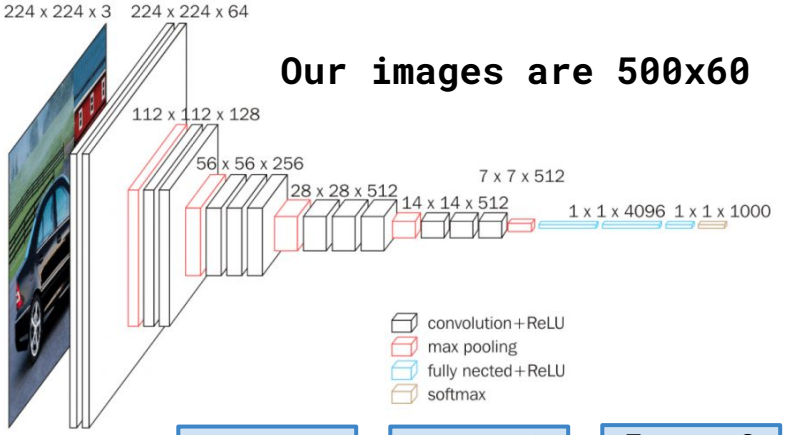
Our CNN

- We trained two separate networks:
  - Reject single pulses (NET1, 400k events per class)
  - Reject tracks. (NET3, 600k events per class)

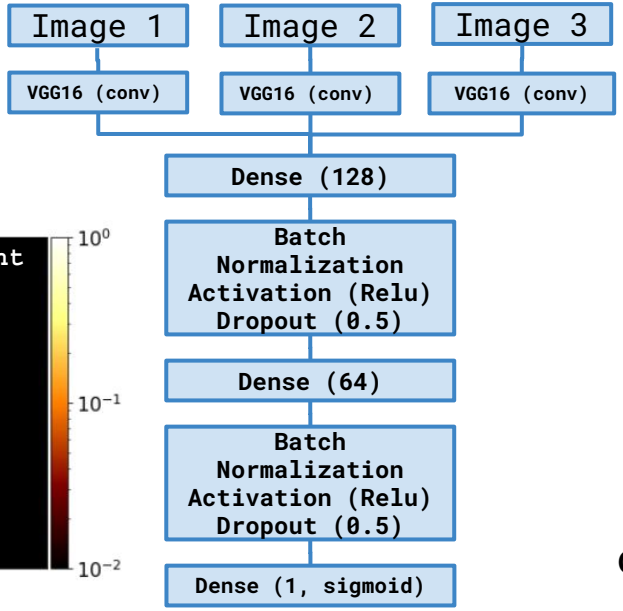
- The network is based on the VGG16 architecture.
  - The convolutional part of VGG16 is applied to three images in parallel.
  - Outputs are joined and put through several dense layers (plus dropout and batch normalization).

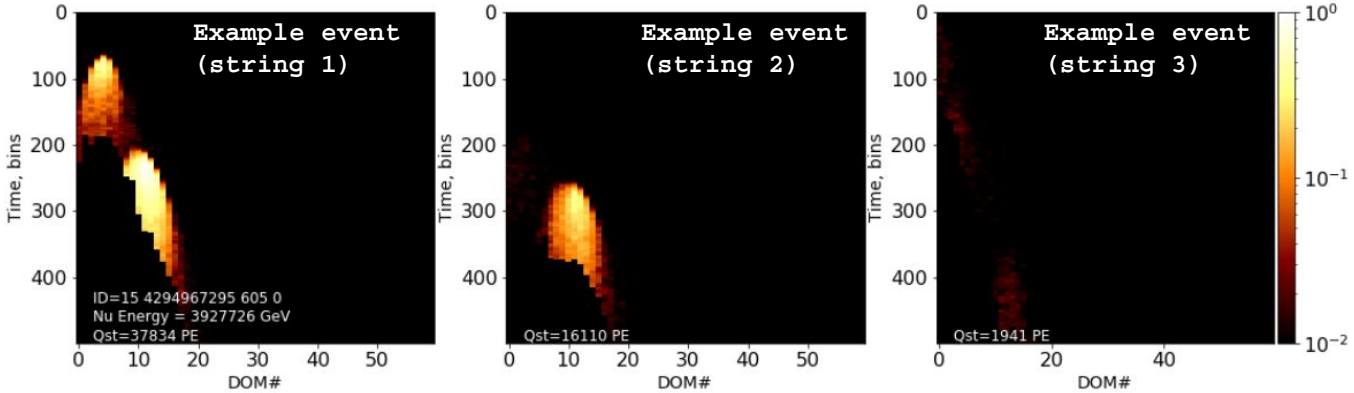
- The final output is a “probability” of event being a ν_τ.

- For training we used only higher charge events (> 2000PE on maximum charge string).



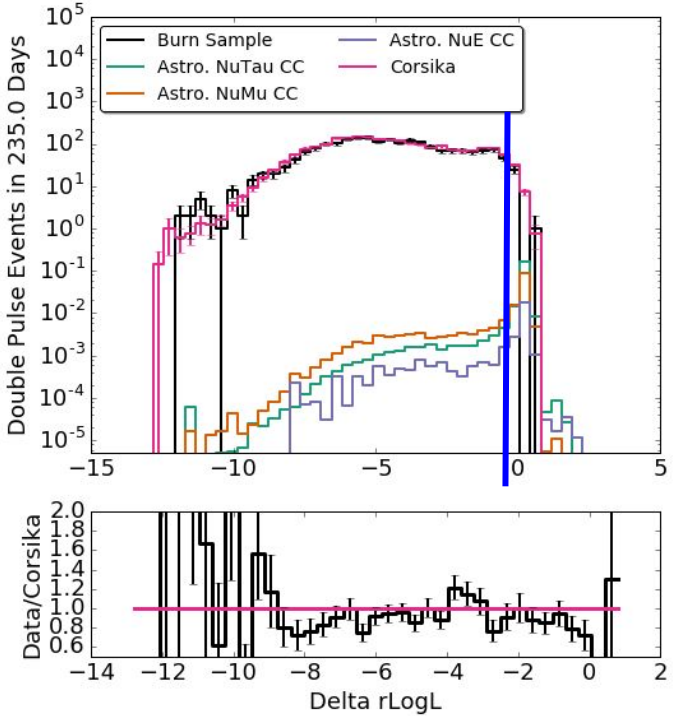
Our images are 500x60

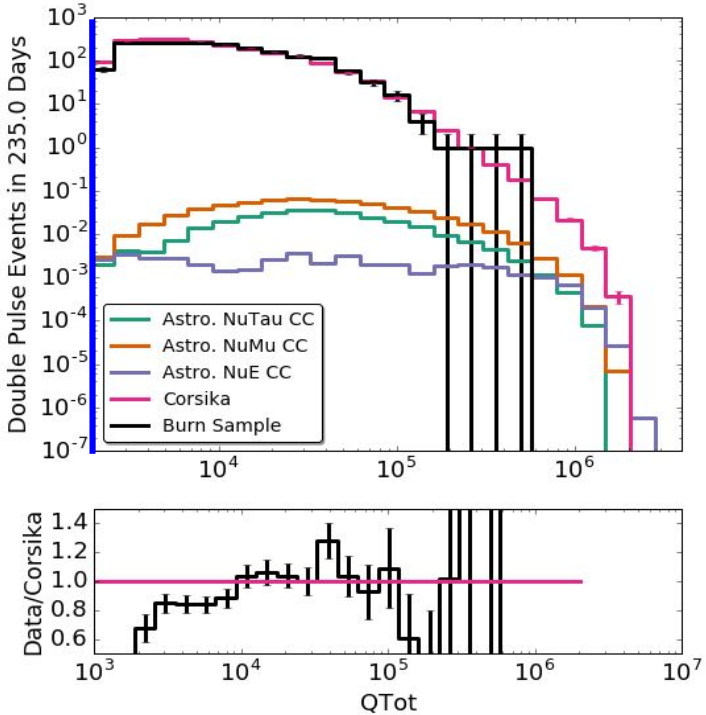




Initial Cuts

- Cuts we apply before the NET1 and NET3:
  - Likelihood difference between Cascade and Track reconstruction hypothesis.
  - Total charge > 1000 PE (Not shown: Highest string charge > 400PE, Other two strings > 0PE)

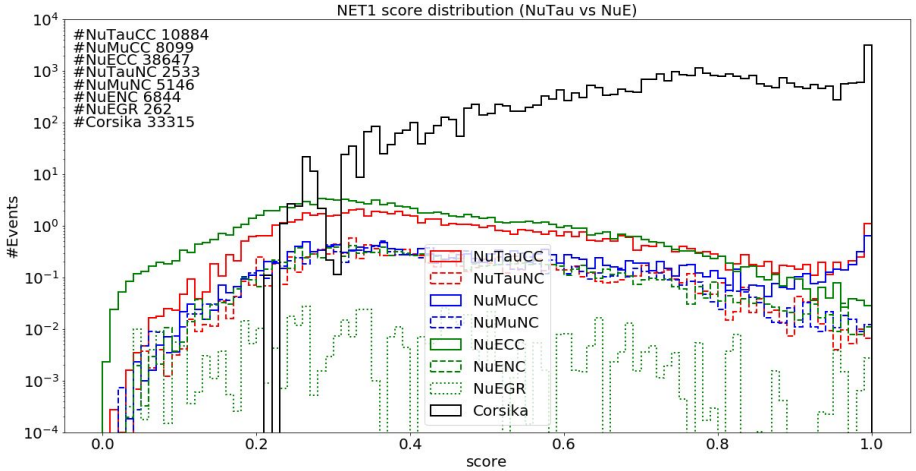


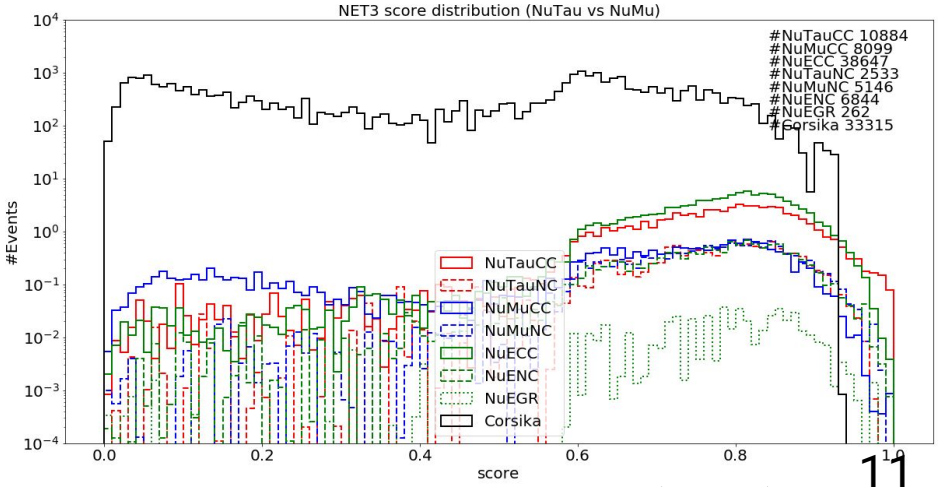


*Corsika - Atmospheric Muon Simulation, Burn sample - IceCube data sample.
*L.J.Wille, Ph.D. Thesis: [The Search for High Energy Tau Neutrinos using the IceCube Neutrino Observatory].

Network scores

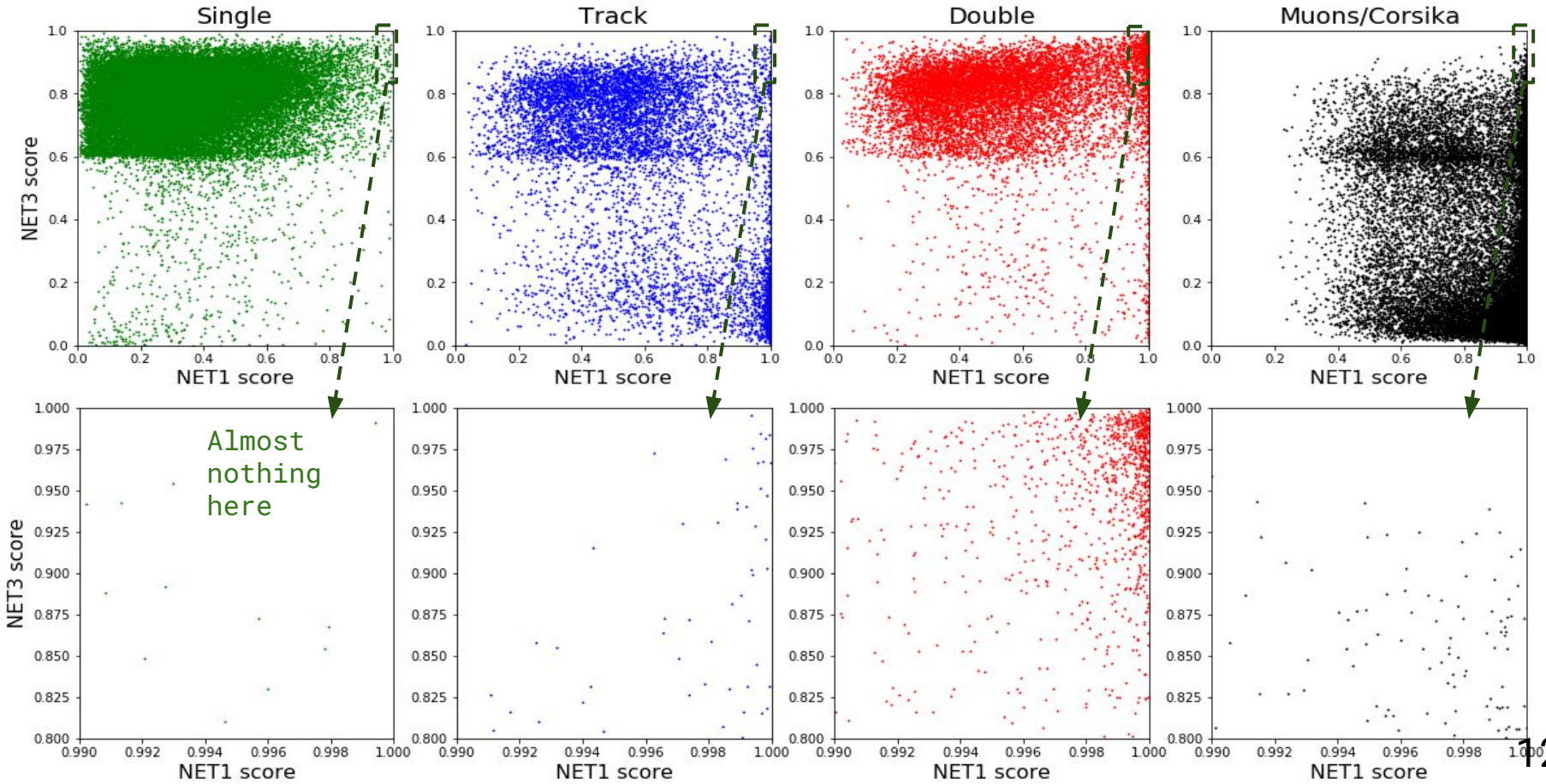
Particle\Cut	After initial cuts (events per year)	NET1>0.99 (events per year)	NET3>0.8 (events per year)	Both networks (events per year)
CC ν_τ	66.6 ± 1.1	1.11 ± 0.06	29.7 ± 0.7	0.87 ± 0.05
CC ν_μ	18.7 ± 0.4	0.64 ± 0.05	4.7 ± 0.2	0.028 ± 0.011
CC ν_e + NC	141.6 ± 1.0	0.062 ± 0.009	63.9 ± 0.6	0.041 ± 0.02
Muons (Corsika)	30900 ± 820	3209 ± 218	1481 ± 179	49 ± 22





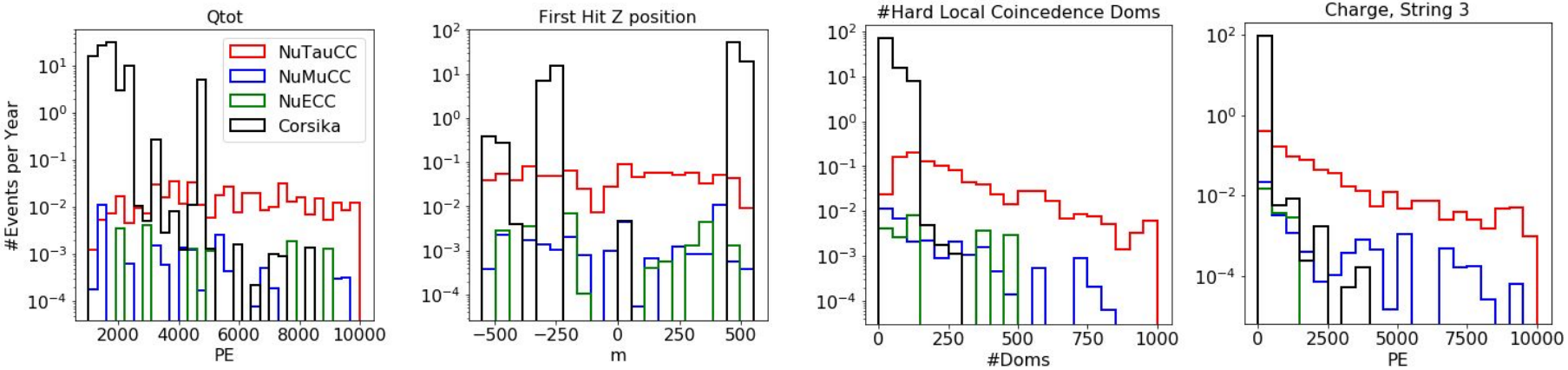
*Assumed Flux: The IceCube high-energy starting event sample: Description and flux characterization with 7.5 years of data. (γ=2.88)

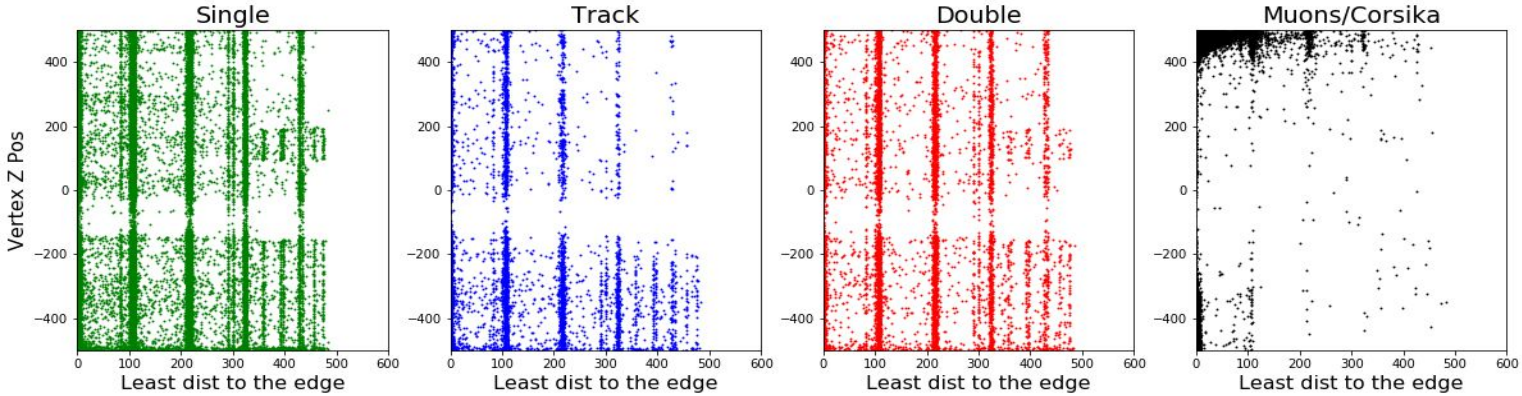
Network scores



Potential muon cuts

We clearly need to apply more/harsher cuts to reduce muon background. We are waiting to process more muon simulation before we make decisions. But we have many options.





Result so far and next steps

- Processing more muon simulation and burn sample
- Deciding on the final cuts
- Doing statistical analysis:
  - Systematic studies:
    - DOM efficiency
    - Ice properties
    - Atmospheric background uncertainty
    - Astrophysical neutrino flux uncertainty
  - Sensitivity calculations
- Unblinding.

	Annual rate	
Particle type	Previous analysis (similar cuts)	This work (preliminary)
NuTau	0.234 ± 0.002	0.84 ± 0.05
NuMu	0.16 ± 0.01	0.028 ± 0.011
NuE	0.046 ± 0.002	0.022 ± 0.008
Muons	16 ± 4	30 ± 19

The closest possible comparison to a previous analysis.

Summary

This talk describes a way of looking for ν_τ events in IceCube.

- Raw digitizer waveforms from all DOMs on one string are combined into a 2D image. Images from certain ν_τ events have a distinctive double pulse feature.
- We have trained two convolutional neural networks to find ν_τ signatures in two types of background: single cascades and tracks.
- We are investigating possibility of removing more background events using straight cuts.
- If we are as successful in removing background events as previous analyses we maybe able to see ~5 ν_τ events in IceCube data.
- Eventually we plan to implement a filter for real time ν_τ alerts based on this work.

Thank you!

Back up slides

Cuts applied	Previous analysis (Logan, Level 5)	This work (preliminary)
Total charge	2000 PE	1000 PE
Dom Charge	432 PE	
String charge		400 PE
LLH cut	>-0.5	>-0.1
FirsthitZ	<475	<475

Network scores

Test data had charge cuts applied to it
Qtot>1000PE and Qst>400PE:

Total = 316 ± 4
Single = 153 ± 2
Double = 76.7 ± 1.2
Track = 85.9 ± 0.8

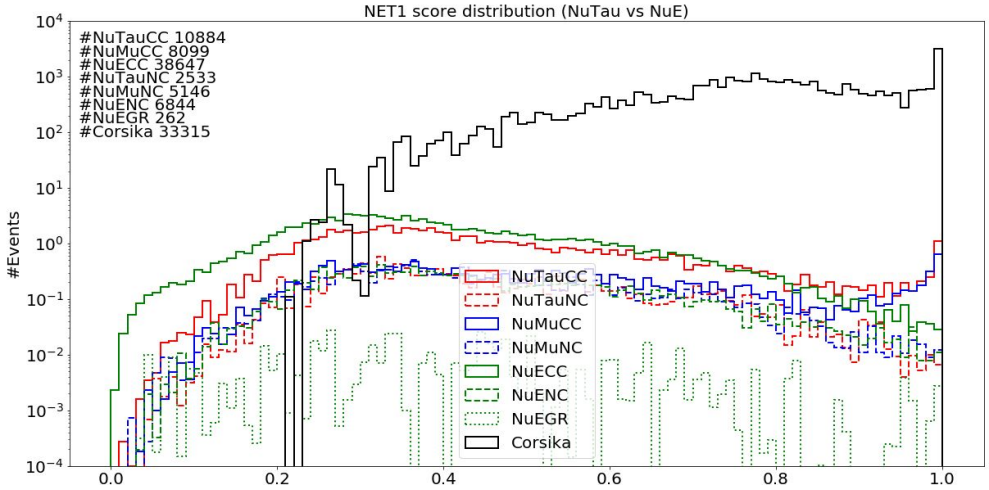
NuTauCC = 76.7 ± 1.2
NuTauNC = 13.6 ± 0.5
NuMuCC = 85.9 ± 0.8
NuMuNC = 14.1 ± 0.4
NuECC = 112 ± 1.0
NuENC = 13.4 ± 0.3
NuEGR = 0.64 ± 0.07
Corsika = 0.001 ± 0.0

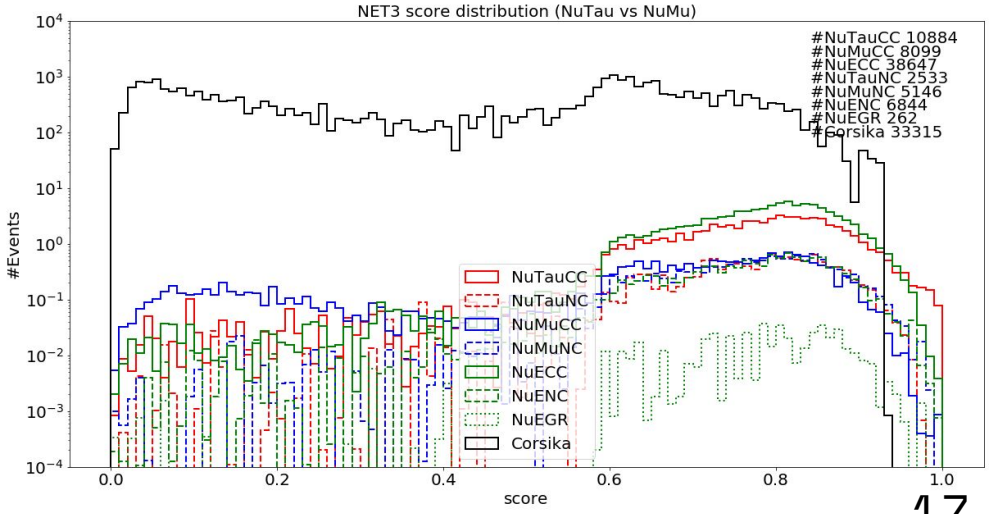
Track rates look similar, but different track-like events pass each network's cut

Rates (per year) after networks:

NuTau vs NuE (NET1),Cut=0.99
Single = 0.10 ± 0.03
Double = 1.57 ± 0.09
Track = 10.9 ± 0.2
NuTauCC = 1.570 ± 0.09
NuTauNC = 0.007 ± 0.005
NuMuCC = 10.9 ± 0.2
NuMuNC = 0.012 ± 0.006
NuECC = 0.040 ± 0.011
NuENC = 0.011 ± 0.005
NuEGR = 0.032 ± 0.007
Corsika = 0.057 ± 0.001

NuTau vs NuMu (NET3), Cut=0.8
Single = 68.4 ± 1.3
Double = 32.6 ± 0.7
Track = 10.1 ± 0.3
NuTauCC = 32.6 ± 0.7
NuTauNC = 5.4 ± 0.3
NuMuCC = 10.1 ± 0.3
NuMuNC = 5.7 ± 0.2
NuECC = 51.3 ± 0.6
NuENC = 5.73 ± 0.19
NuEGR = 0.28 ± 0.05
Corsika = 0.001 ± 0.000



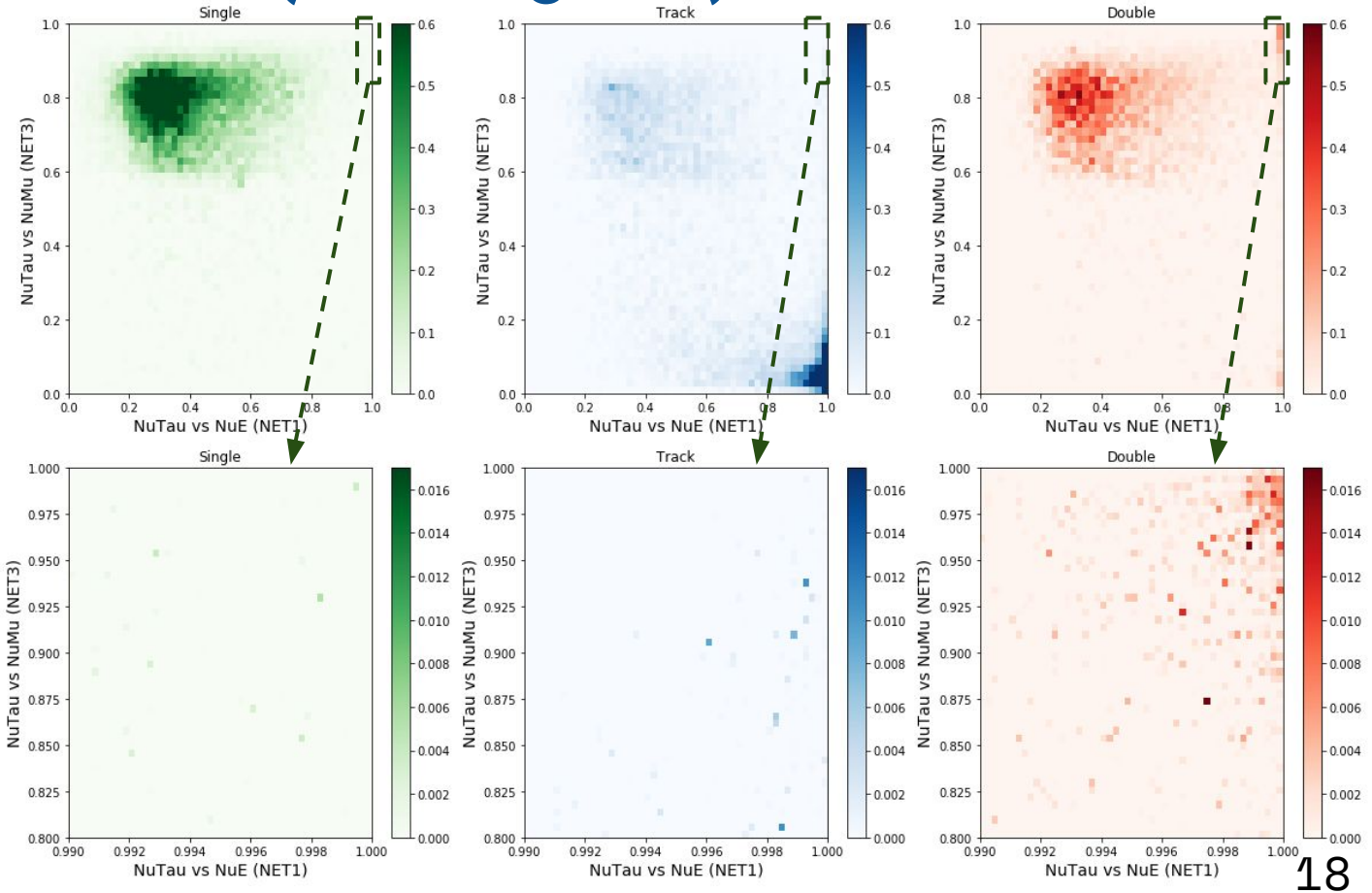


Network scores (histogram)

Annual Rates after both cuts

Single = 0.04 ± 0.02
Double = 0.91 ± 0.05
Track = 0.11 ± 0.02
NuTauCC = 0.91 ± 0.05
NuTauNC = 0.006 ± 0.005
NuMuCC = 0.11 ± 0.02
NuMuNC = 0.003 ± 0.002
NuECC = 0.023 ± 0.008
NuENC = 0.008 ± 0.004
NuEGR = 0.002 ± 0.001
Corsika = 0.000 ± 0.000

Zoom to cut region:
Score NET1>0.99
Score NET3>0.8

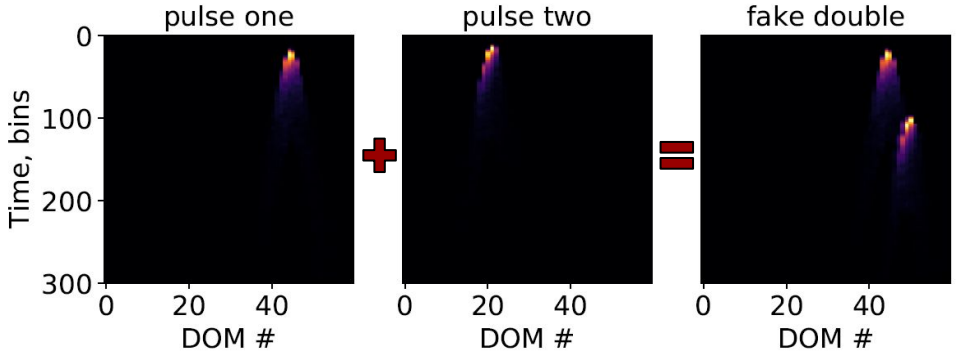


Those are the same events as in scatter plots on slide 8, but binned and weighted.

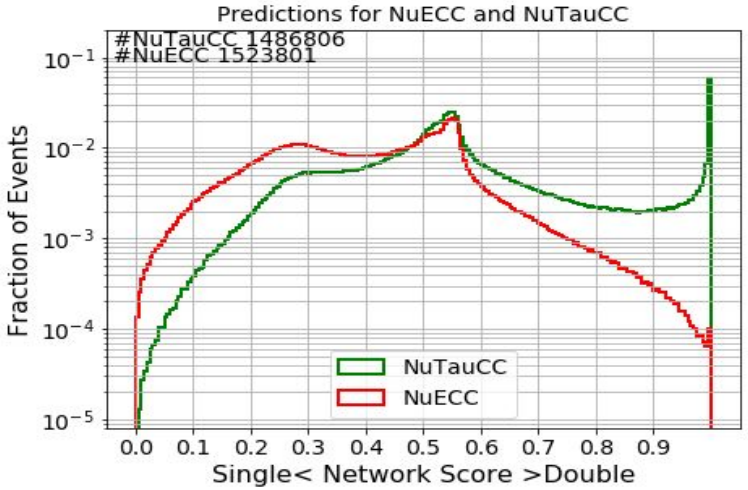
Validation

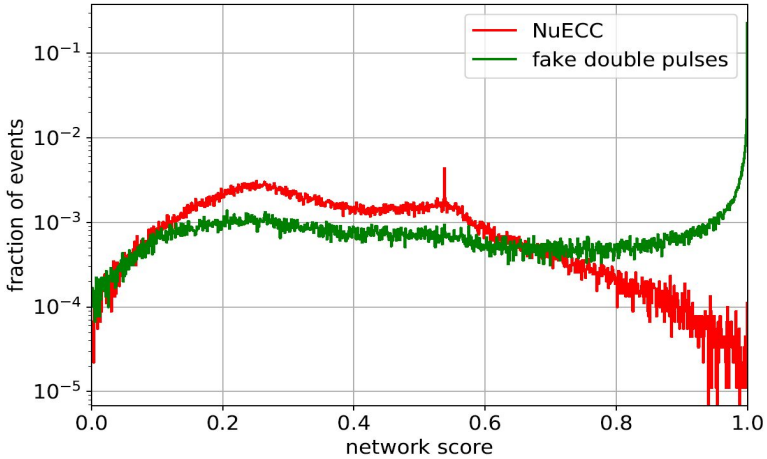
- \+ General CNN methods — Hard to interpret
  - Visualizing feature maps
  - Class activation maps
- ✓ Other evidence
  - NC events -> single pulses (Trained on NuECC only)
  - Improvement from adding strings
- ✓ Fake Double Pulses:

Superposed single pulse images.



1. Pulse one, with Charge=Q_1, Time=T_1, DomZ=Z_1
2. Find pulse with Q_2, T_2, Z_2 such as $0.05*Q_1<Q_2<20*Q_1$
3. Translate T_2 randomly so $T_1 + 1 < T_2 < T_1 + 100$ samples
4. Translate Z_2 randomly $0<Z_2<20*((T_2-T_1)/100)$





Same network, "real" and fake double pulses (not the same NuE)

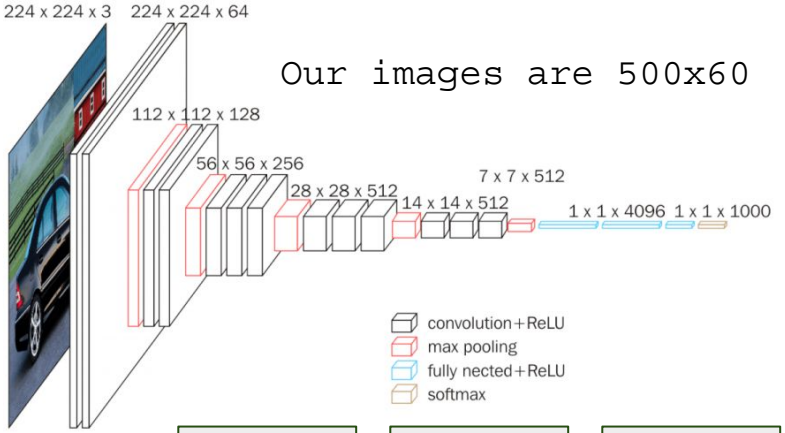
Our CNN

- Our network is based on the VGG16.
  - The convolutional part of VGG16 is applied to **three images in parallel**.
  - Outputs are joined and put through several dense layers (plus dropout and batch normalization).

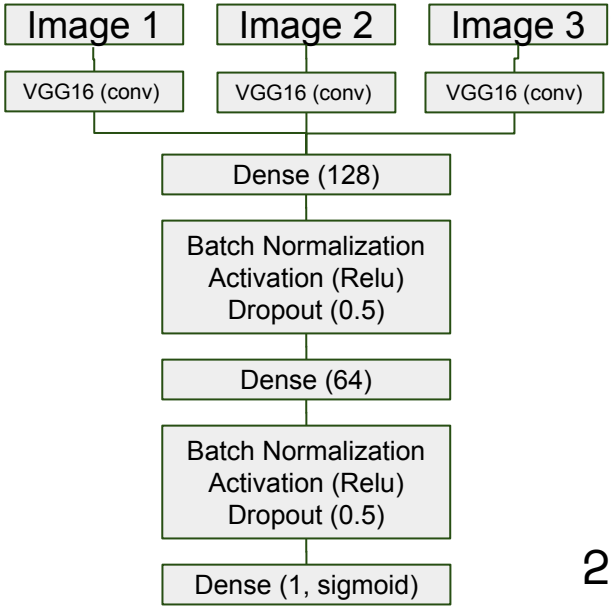
- For training we used events that have at least **2000PE** of charge on maximum charge string.

- The output is a "probability" of event being a double pulse. We trained **two separate networks**: one to reject single pulses and one to reject tracks. The first one (**NET1**) was trained on 200k events per class, the latter (**NET3**) on 300K events per class.

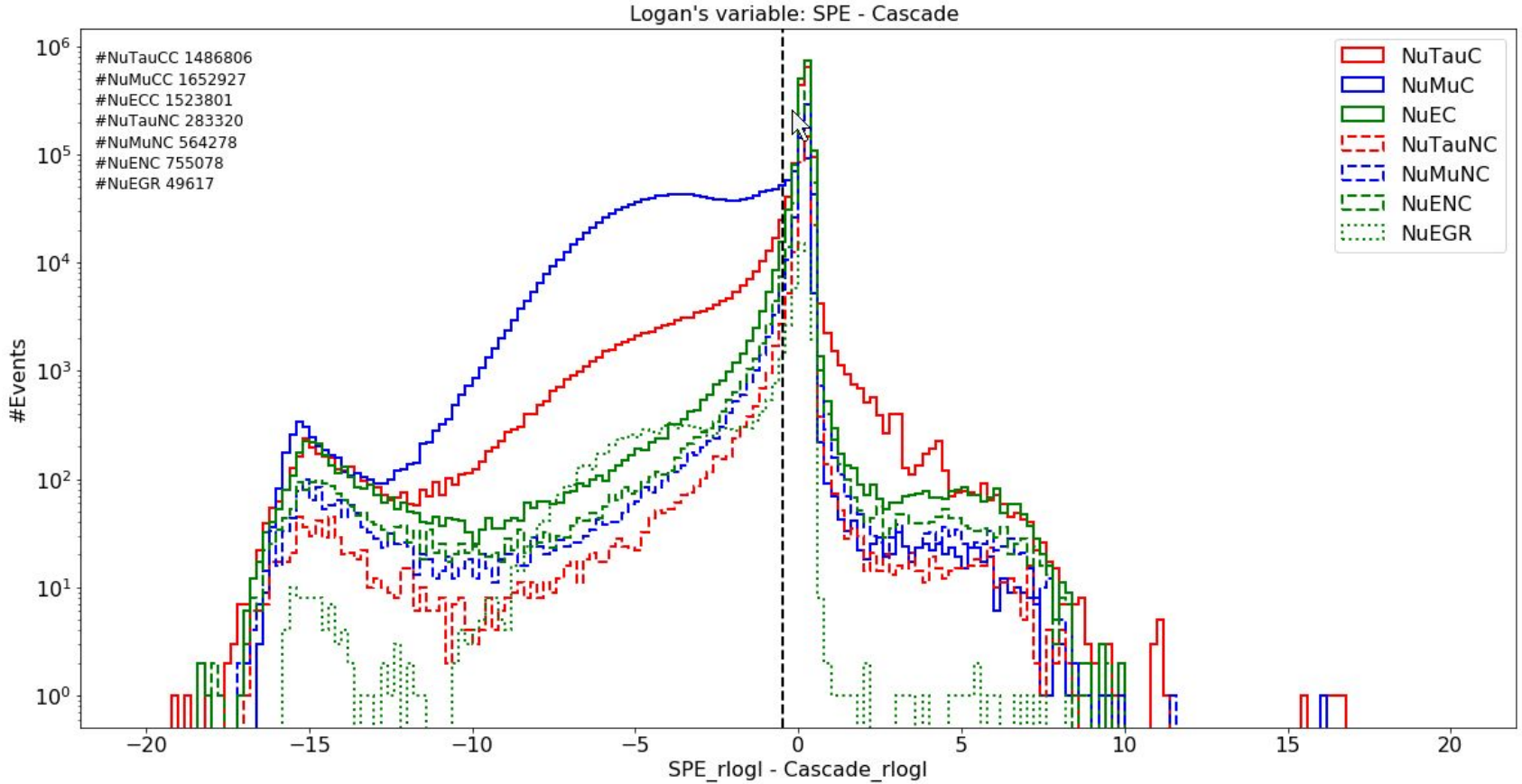
- *Additionally we've tried:*
  - *Support Vector Machine*
  - *Various normalizations and kernel sizes*
  - *Simpler network with three conv layer*
  - *One image network*
  - *Xception network*
  - *VGG16 with fixed weights*
  - ***Three class VGG16 network (single, double, track)***
  - ***VGG16 (double vs everything)***



Our images are 500x60



Track removal cuts 1



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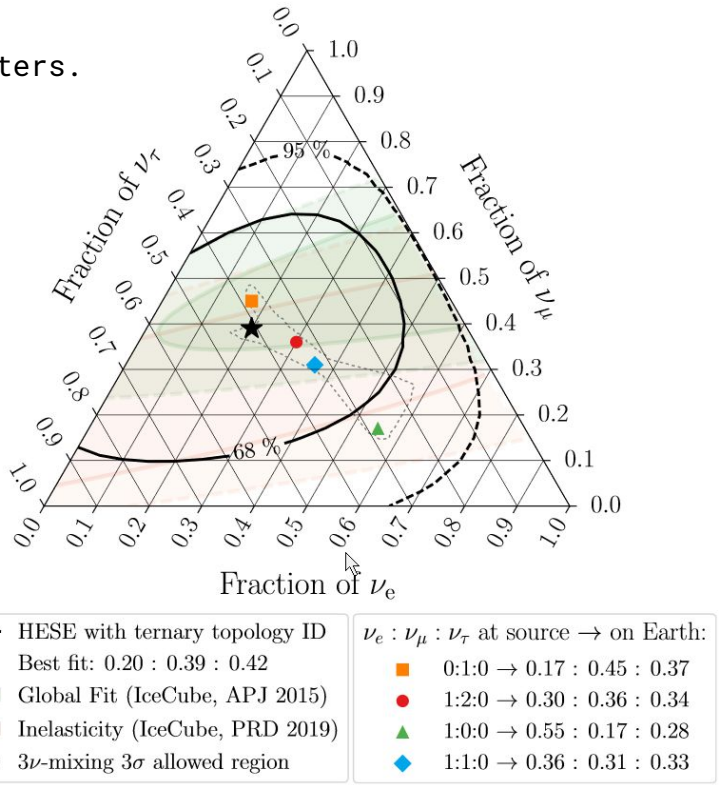
From the measured flux we expect ~ 5 ν_τ events in IceCube per year (E> 0.1PeV).

- Topological classification with cuts based on best fit parameters.
  - Expected: **2.3** events, **1.5** of them ν_τ in 7.5 years of data.
- Derivative based search for “double peaked” waveforms.
  - Expected: **3.13** events, **1.72** of them ν_τ in 8 years.
- Random Forest classifier using waveforms features.
  - Expected: **3.08** events, **2.10** of them ν_τ in 8 years.

All analyses found the same two events.
The probability of them being ν_τ was calculated ~76% and ~98%.

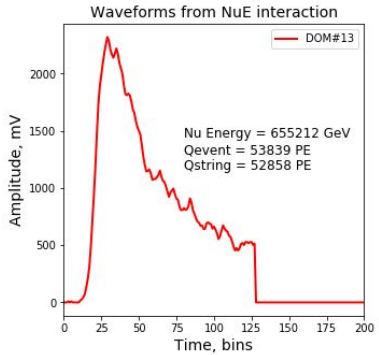
“No ν_τ neutrinos” hypothesis disfavored at 2.8 sigma.

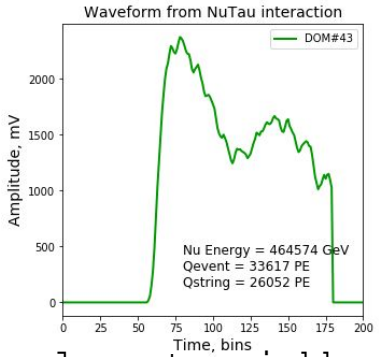


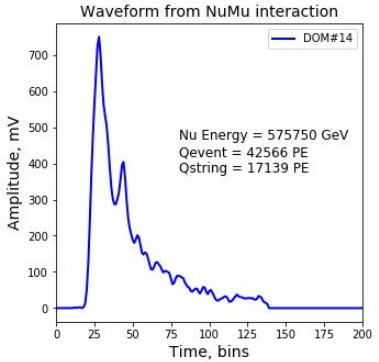
*All analyses assume different neutrino fluxes for estimation.
*IceCube Collaboration, Measurement of Astrophysical Tau Neutrinos in IceCube's High-Energy Starting Events, Nov 6, 2020

ATWD Waveforms

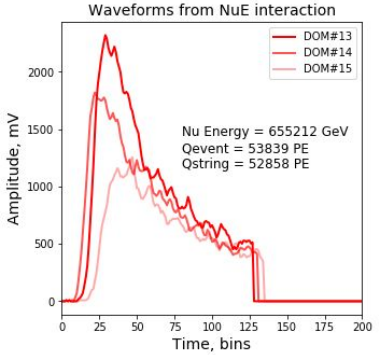
Single waveforms

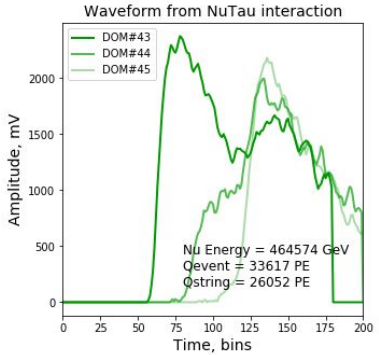


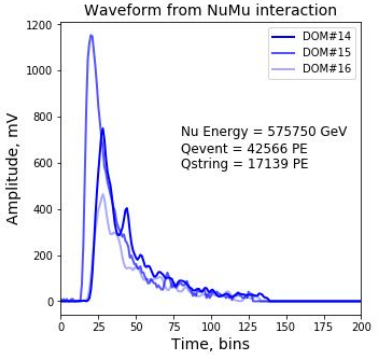




With closest neighbours

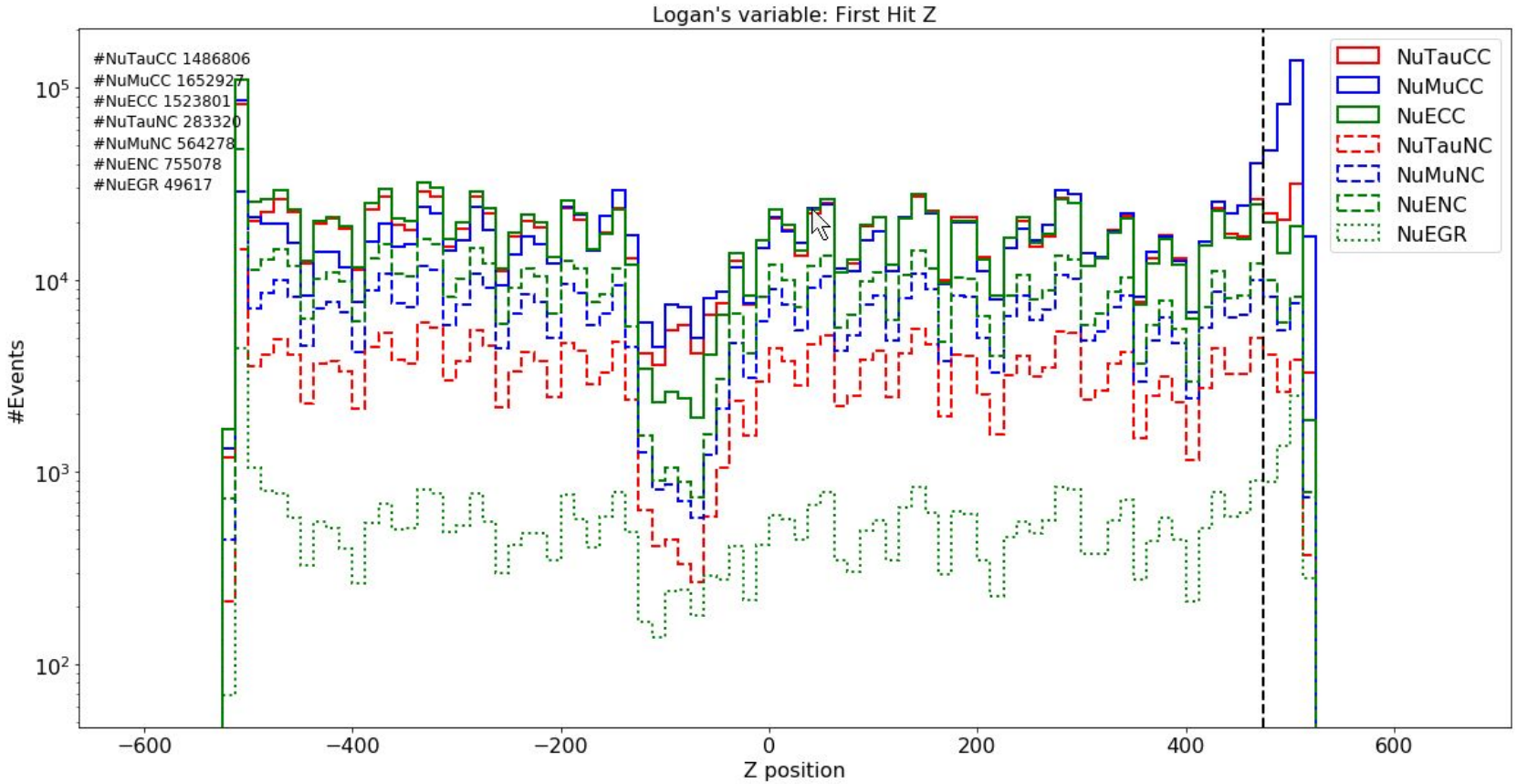




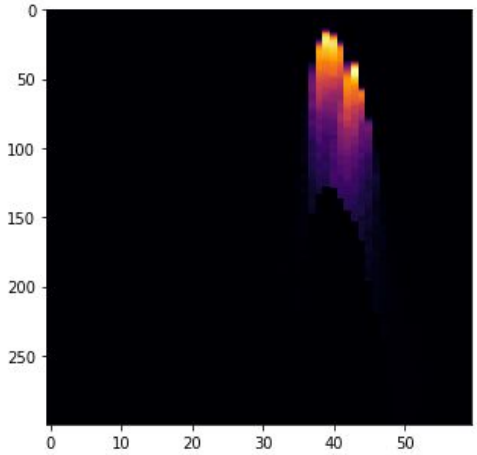


1 bin ≈ 3 ns

Track removal cuts 2

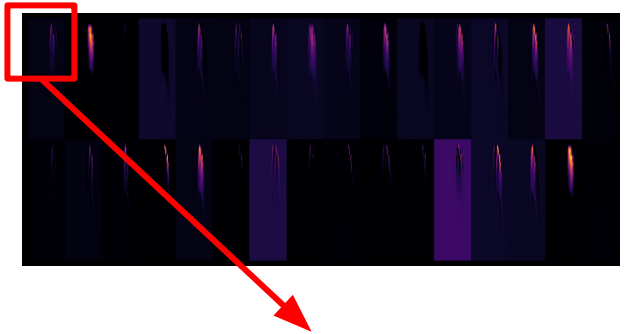


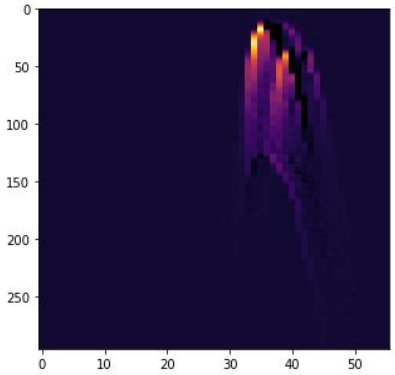
Visualising intermediate feature maps



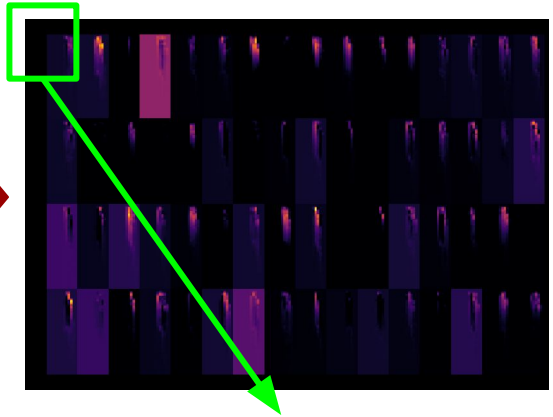
Original image

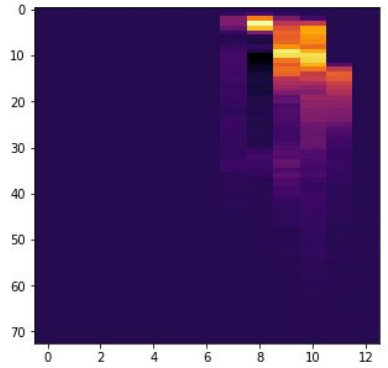
Convolution 1:
32 feature maps





Max Pooling 2:
64 feature maps

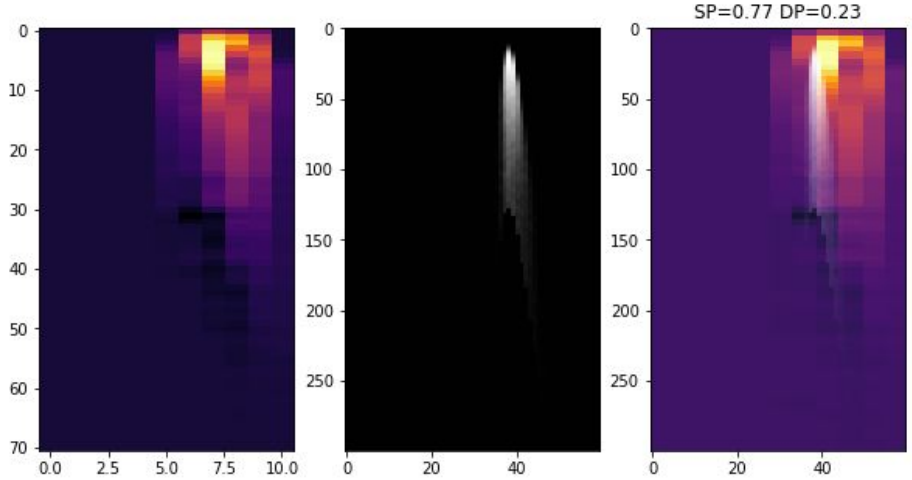




Class Activation Map (CAM)

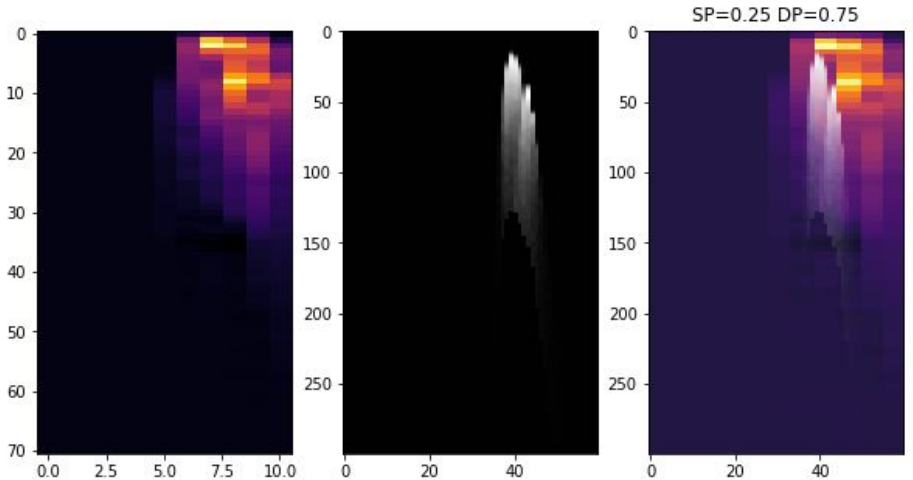
Shows what part of the image activate a particular class, or, in other words, what the CNN is looking at while classifying the image.

NuTau event 1



CAM | **Original image** | **Overlay**

NuTau event 2

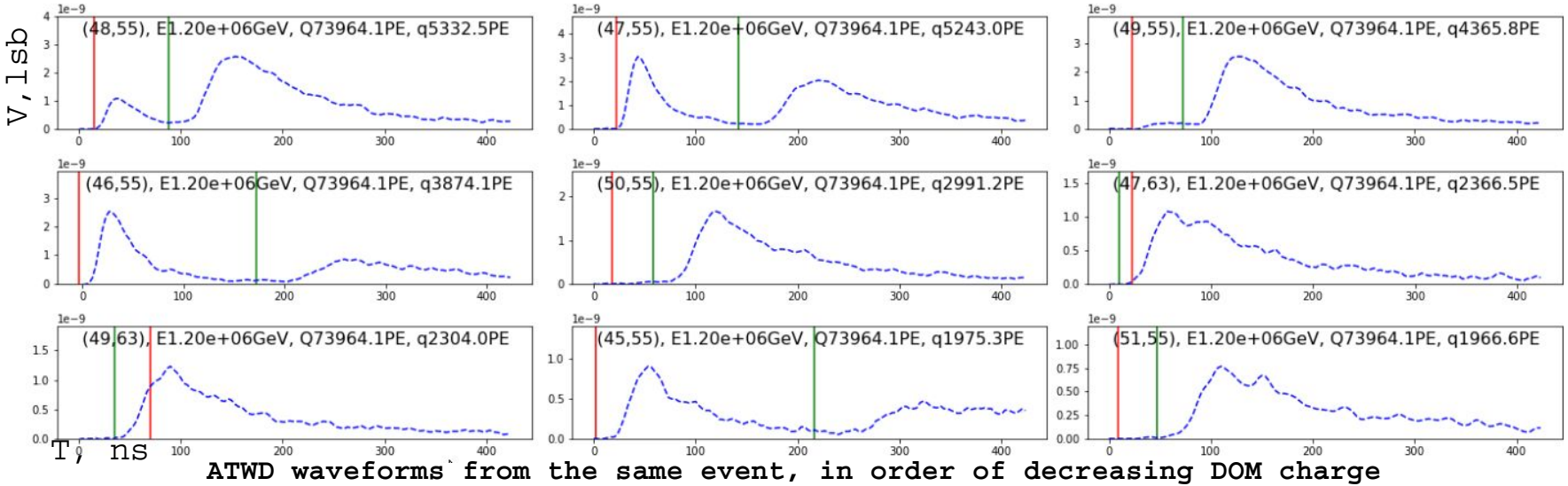


CAM | **Original image** | **Overlay**

In both cases CAM is stretched to image dimensions.
These images are produced with different model (not the one on slide 13)

Nearby DOM waveforms

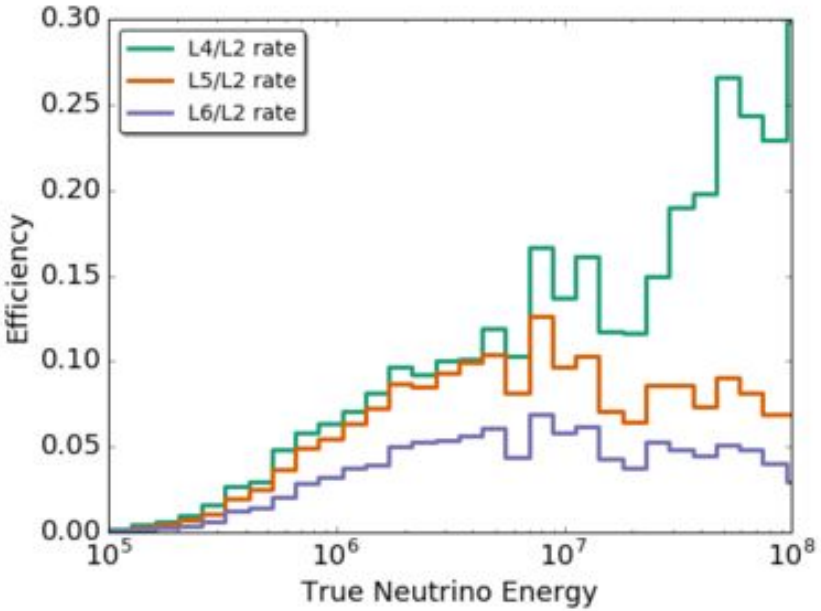
At the top: (DOM, string), Tau energy, Total Charge, DOM charge.
Lines indicate direct light arrival time from interaction and decay.

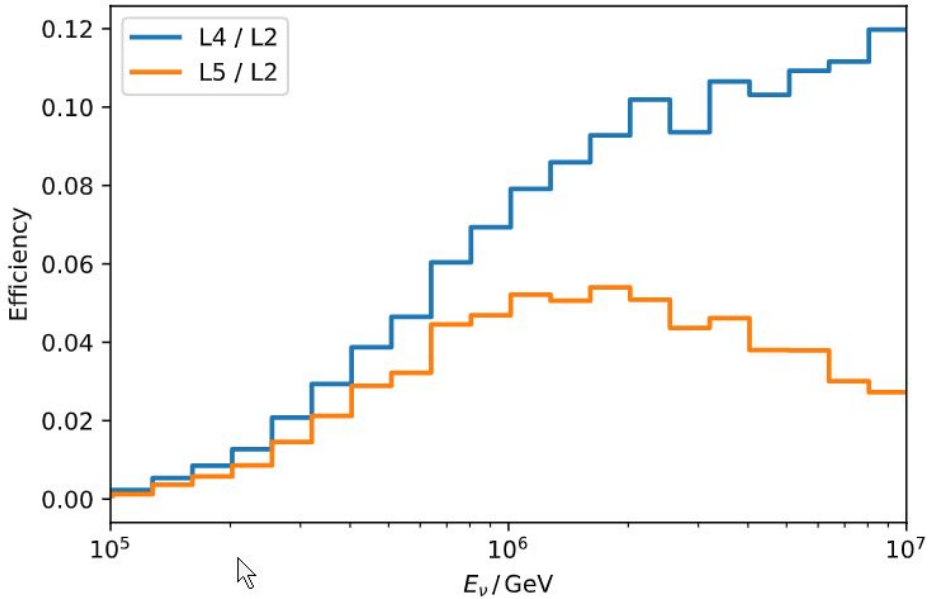


ATWD waveforms from the same event, in order of decreasing DOM charge

It's common for all double pulse waveforms in the event to be on the same string. Usually the string with the most charge.

Double Pulse search efficiency





L. Willie's analysis cuts efficiency.
L4 - DPA cut
L5 - Removing tracks
L6 - Additional background removal

M.Meier analysis cuts efficiency
L4 - DP identification
L5 - Cascade selection