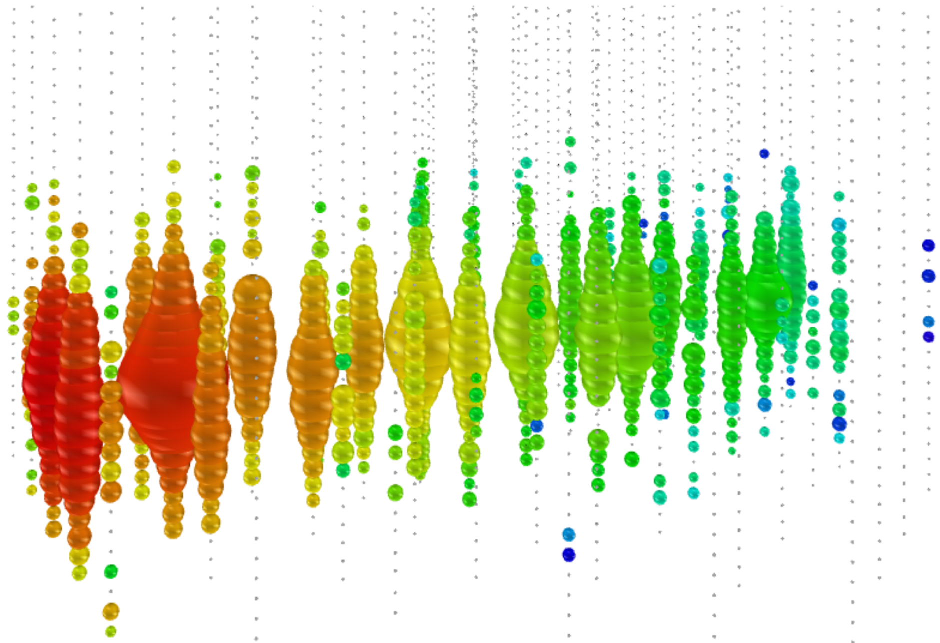
technische universität dortmund

SFB 876 Providing Information by Resource-Constrained Data Analysis

lehrstuhl physik e5



Measurement of Energy Spectra via Deconvolution with IceCube

Tim Ruhe for the IceCube Collaboration

Workshop on Reconstruction and Machine Learning in Neutrino Experiments

tim.ruhe@tu-dortmund.de


THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
SNOLAB
University of Alberta–Edmonton
DENMARK
University of Copenhagen
GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster
JAPAN
Chiba University
NEW ZEALAND
University of Canterbury
REPUBLIC OF KOREA
Sungkyunkwan University
SWEDEN
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Georgia Institute of Technology
Lawrence Berkeley National Lab
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Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
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University of Maryland
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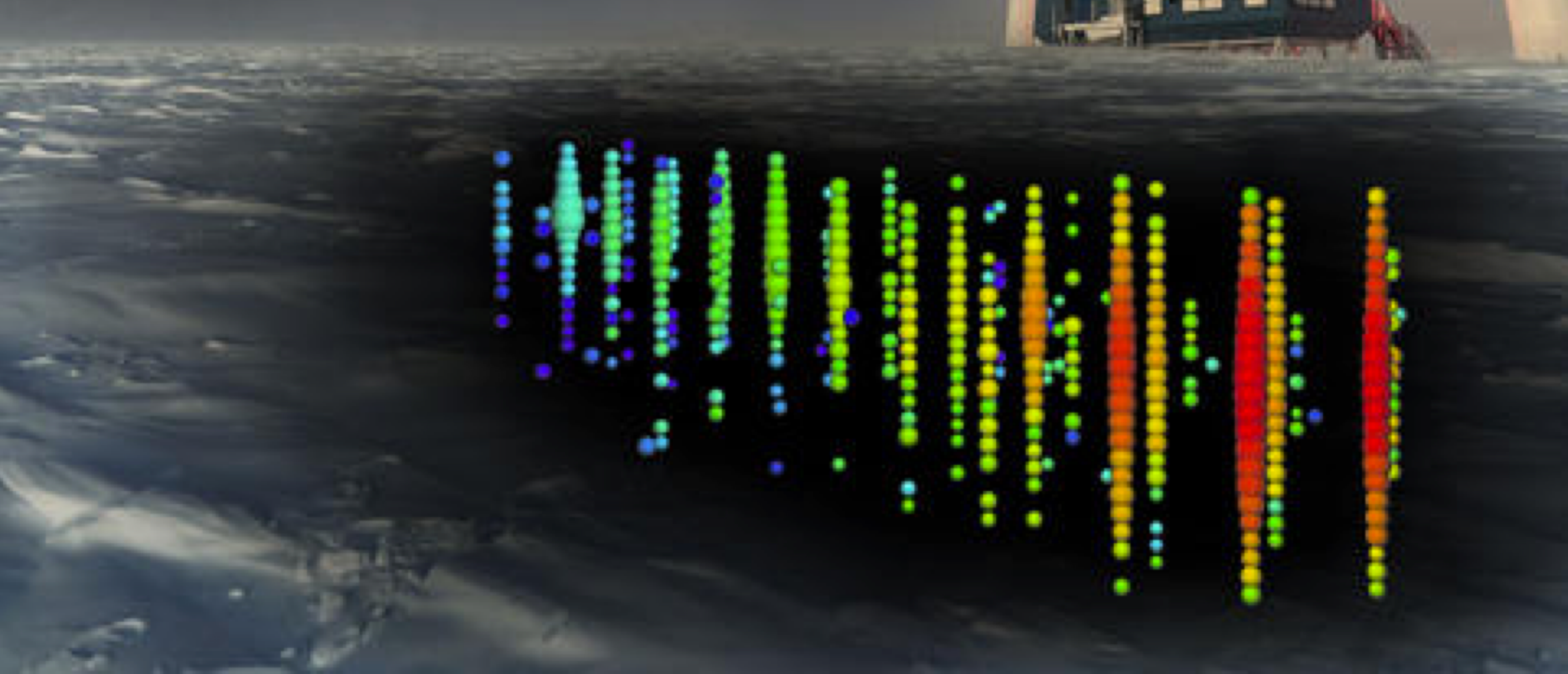
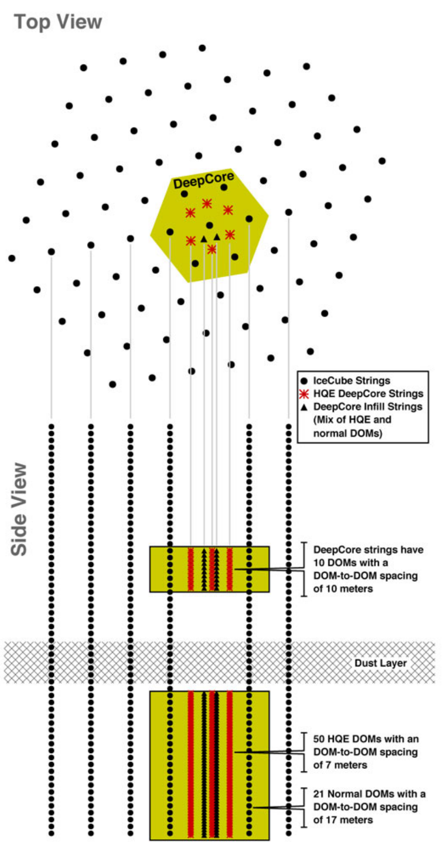
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

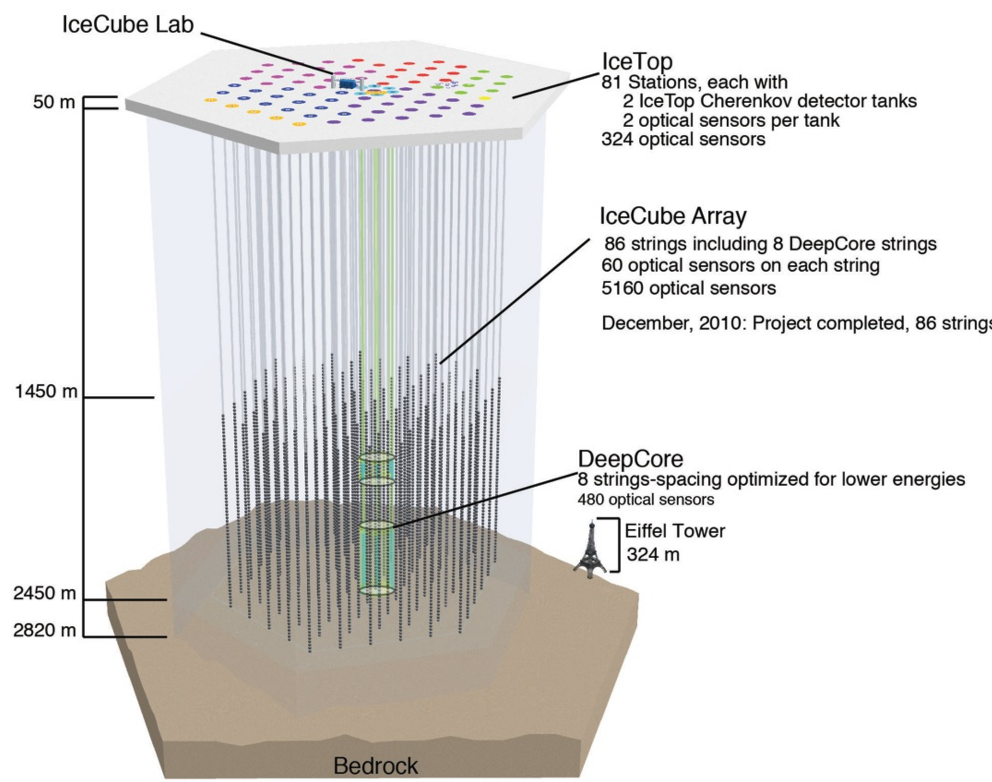
What to expect from this talk

- Introduction to the IceCube detector
- Very Short Introduction to Unfolding
- Atmospheric Neutrino Spectra
- High Energy Starting Events (HESE)
- Tau Neutrino Detection with Machine Learning
- Neural Networks for Reconstruction

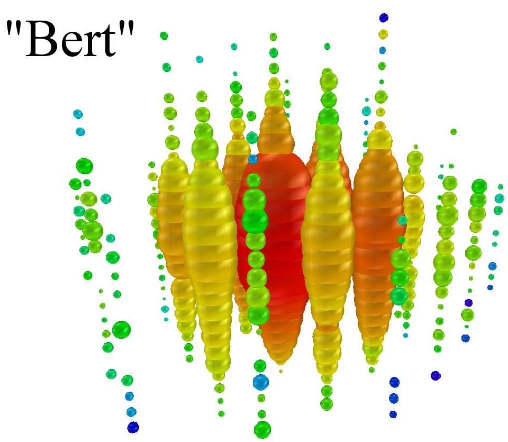


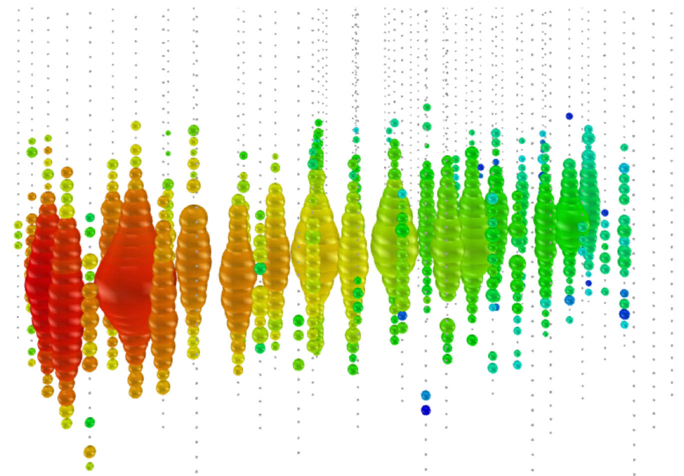
IceCube and DeepCore





Event Signatures in IceCube





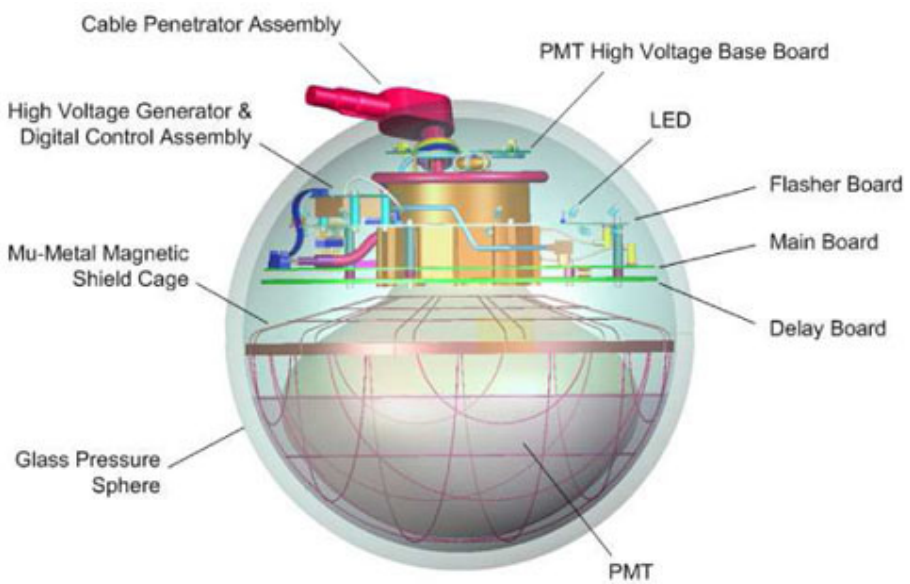
Cascade like events:

- ν_e - CC and all flavour NC interactions
- Interaction inside instrumented volume
- Poor angular resolution $\approx 15°$
- Good energy resolution

Track like events:

- ν_μ - CC interactions
- Interaction may happen outside instrumented volume
- Good angular resolution $\approx 1°$
- Poor energy resolution

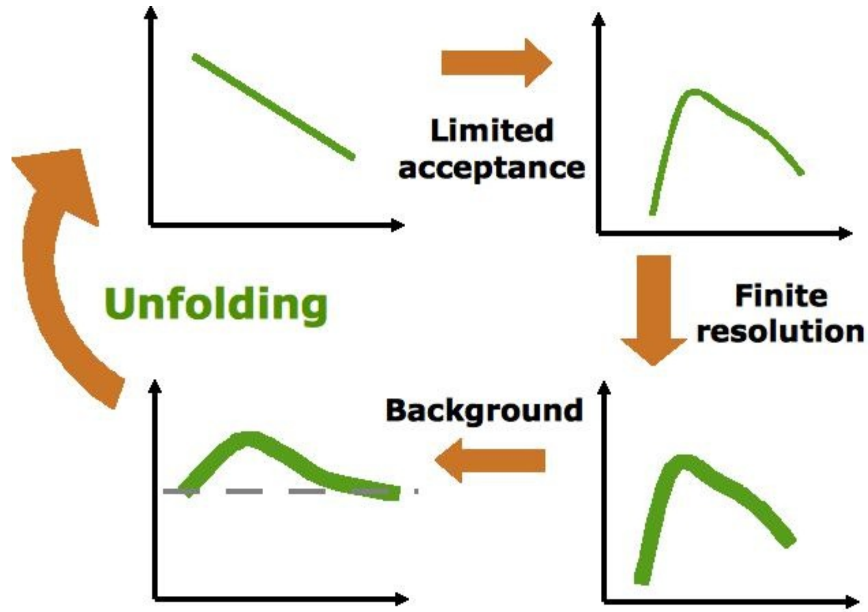
The Fundamental Unit of IceCube: The DOM



- Downward facing 10“ PMT (Hammamatsu R7081-02), 25% Peak QE
- High Voltage Supply
- Electronics
- Flasher LEDs
- Higher QE (34%) for DeepCore DOMs (Hammamatsu R7081MOD)
- Very few DOM failures (mostly during deployment)
- Slightly larger fraction of DOMs with *issues* (mostly non-standard Local Coincidence)

Deconvolution in a Nutshell

$$\underbrace{\frac{dN_\mu}{dE_\mu}}_{\text{Muon energy spectrum}} = \int_{E_\mu}^{\infty} \underbrace{\left(\frac{dN_\nu}{dE_\nu}\right)}_{\text{Neutrino energy spectrum}} \underbrace{\left(\frac{dP(E_\nu)}{dE_\mu}\right)}_{\text{Physics of neutrino interaction}} dE_\nu$$



- Production of charged lepton in neutrino interaction is governed by stochastical processes
- Additional smearing, due to several detector effects

Mathematically: Fredholm integral equation of the first kind:

$$g(y) = \int_{E_{min}}^{E_{max}} A(E,y) f(E) dE$$

Deconvolution in a Nutshell

$$\underbrace{\frac{dN_\mu}{dE_\mu}}_{\text{Muon energy spectrum}} = \int_{E_\mu}^{\infty} \underbrace{\left(\frac{dN_\nu}{dE_\nu}\right)}_{\text{Neutrino energy spectrum}} \underbrace{\left(\frac{dP(E_\nu)}{dE_\mu}\right)}_{\text{Physics of neutrino interaction}} dE_\nu$$

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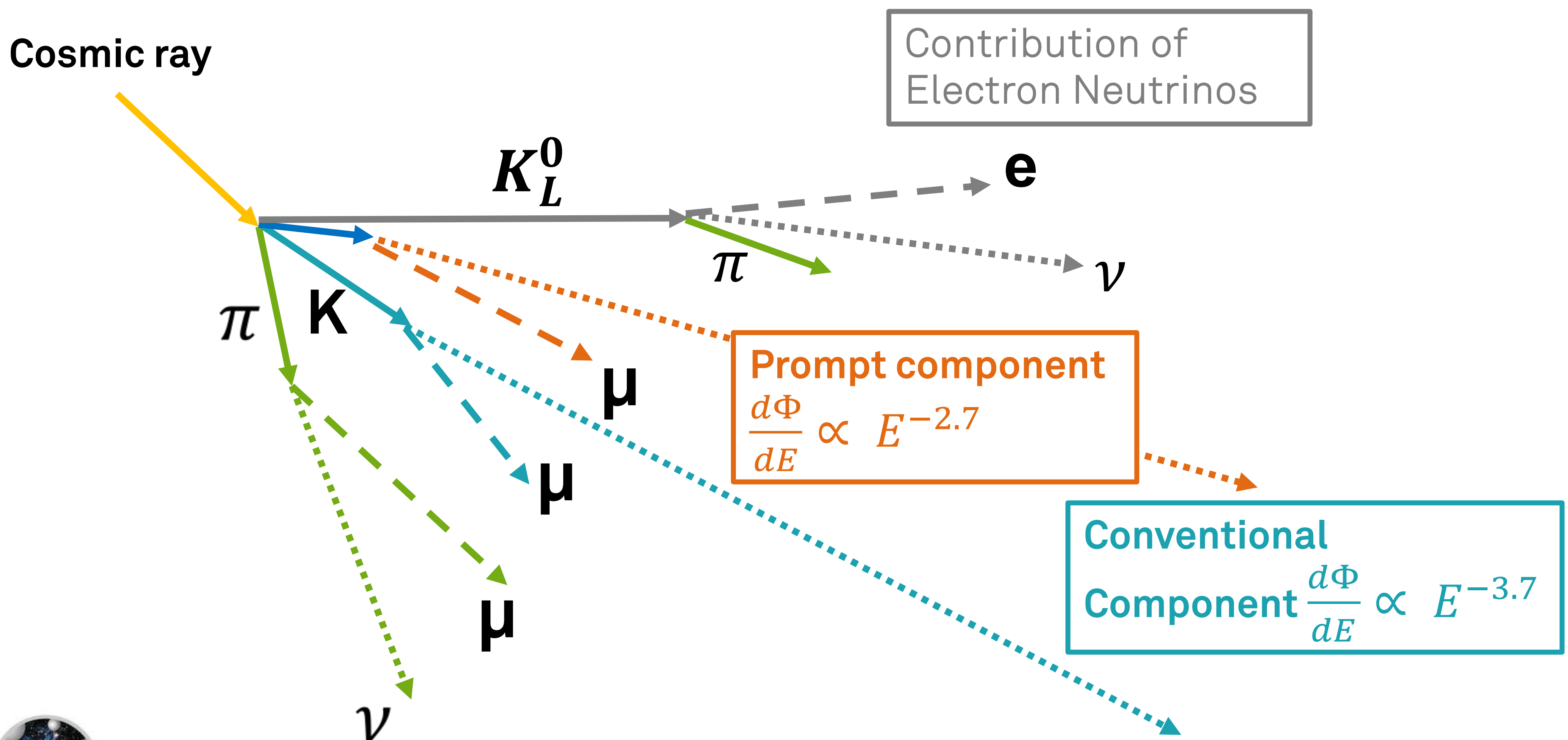
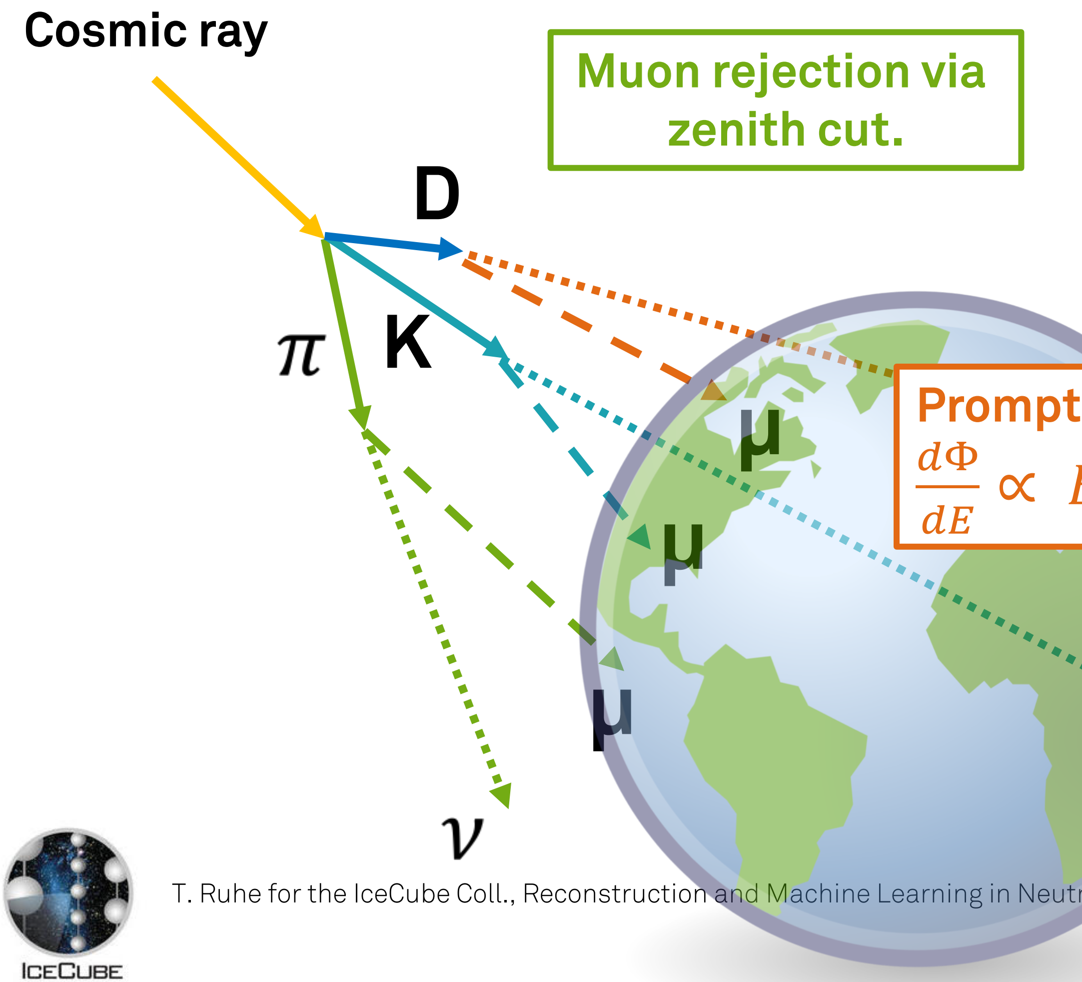
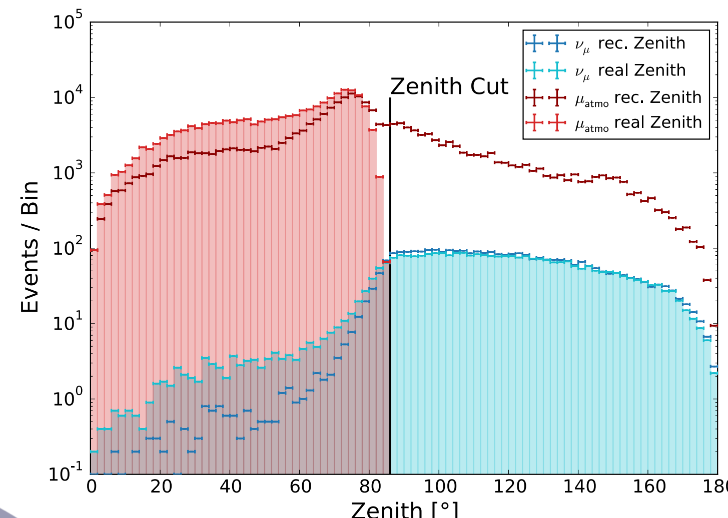
Atmospheric Neutrinos



Atmospheric Neutrinos





General Background Rejection Strategy

Variable Selection → Classifier Training → Cut on Classifier Output

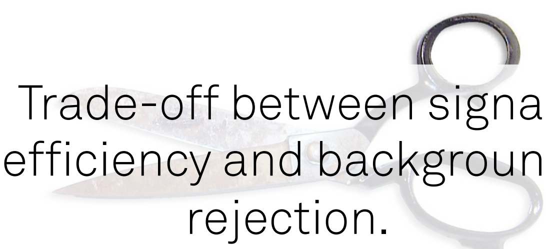
Picture: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=14260

General Background Rejection Strategy

Variable Selection → Classifier Training → Cut on Classifier Output

~1200 Features

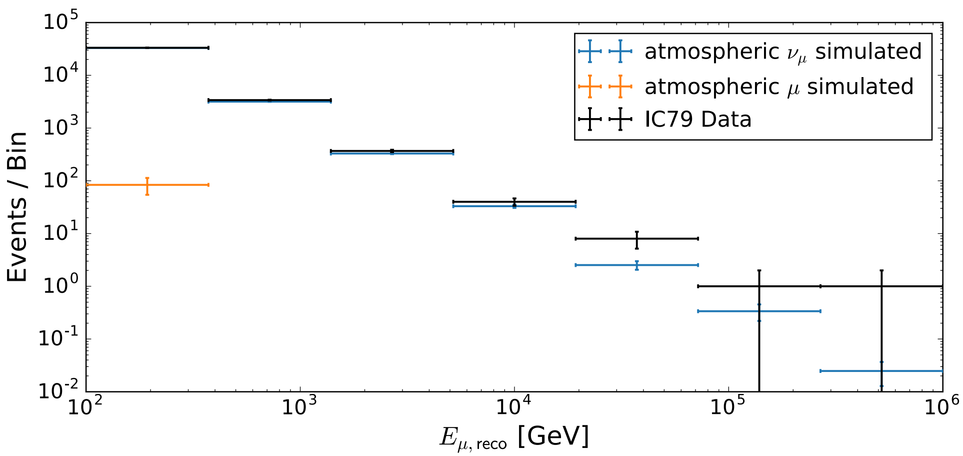
Signal to Background Ratio: 10^{-3}



Trade-off between signal efficiency and background rejection.

General Background Rejection Strategy

Variable Selection → Classifier Training → Cut on Classifier Output



Purity generally above 99%.

Even more important: Make sure there are no muons in bins with small statistics.

Feature Selection with mRMR

Initially
1219

blacklisted
1129

constant & useless
855

Correlation cut
323

Data/MC Clf
311

mRMR
60

M. Börner, PhD thesis (2018)

- Select features according to relevance and redundancy
- Feature set is built by iteratively adding features that fulfill the following criterion

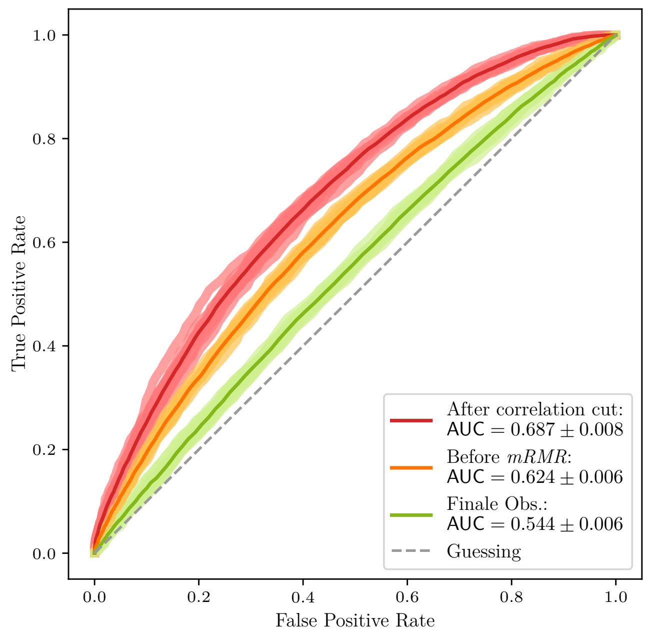
$$\max_{x_j \in X - S_{m-1}} \left[I(x_j, c) - \frac{1}{m-1} \sum_{x_i \in S_{m-1}} I(x_i, x_j) \right]$$

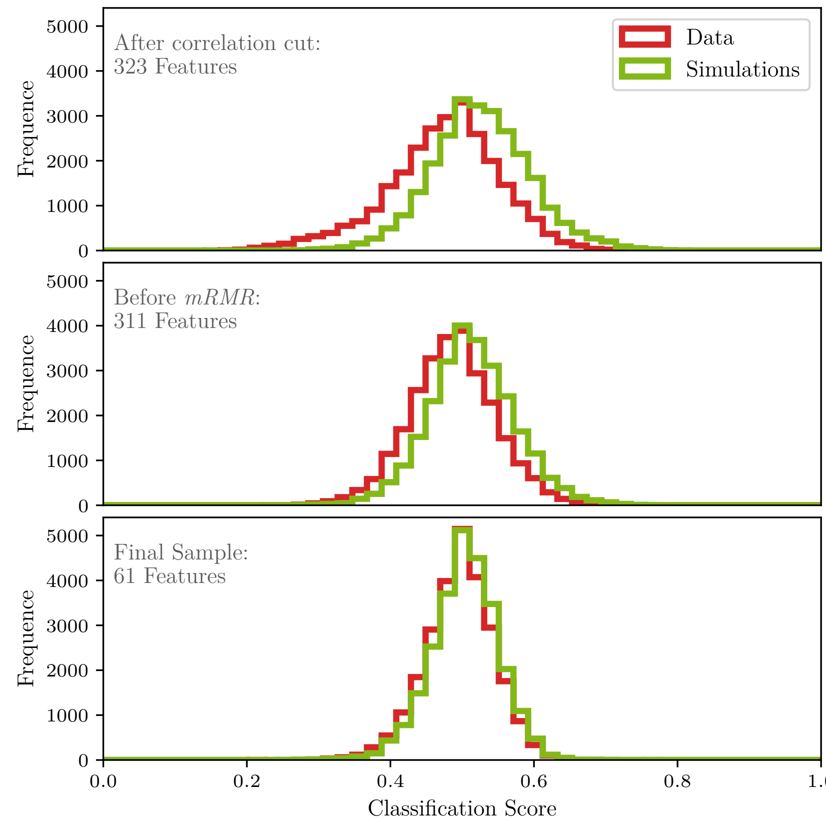
Peng, H.C., Long, F., and Ding, C., IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. 27, No. 8, pp. 1226–1238, 2005.

Ding, C., & Peng, H., *Journal of bioinformatics and computational biology*, *3*(02), 185-205. (2005)

Handling Data/MC Mismatches

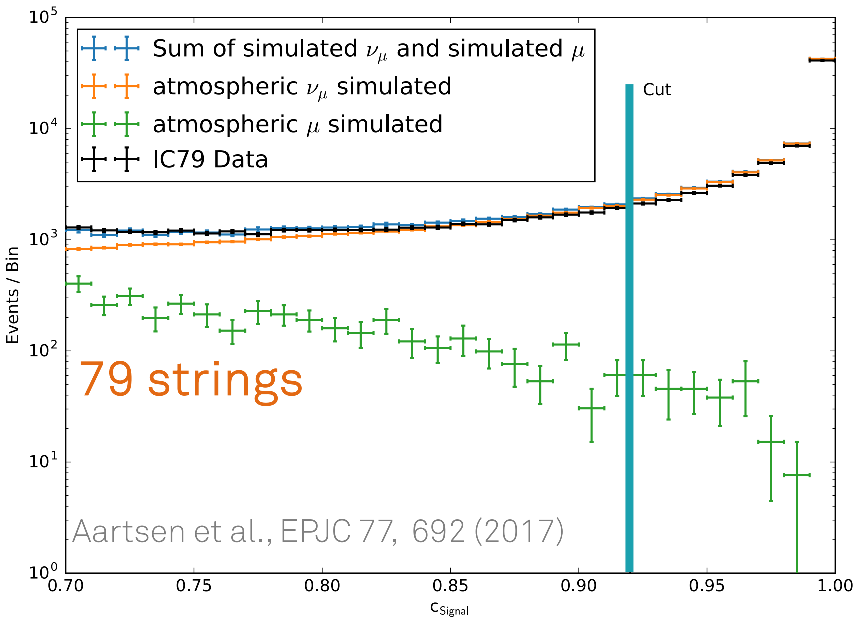
Train classifier to distinguish data and simulation.



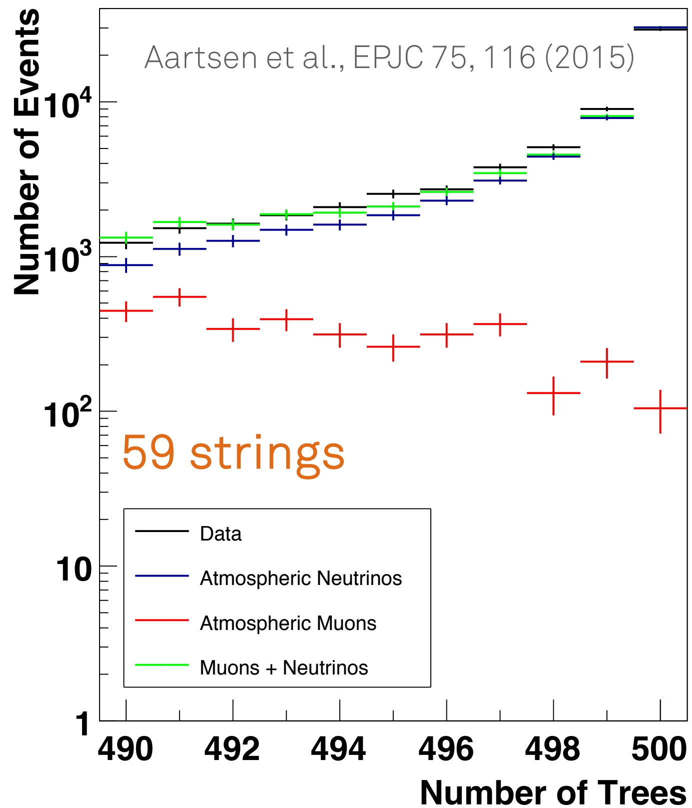


M. Börner, PhD thesis (2018)

Classifier Training an Output

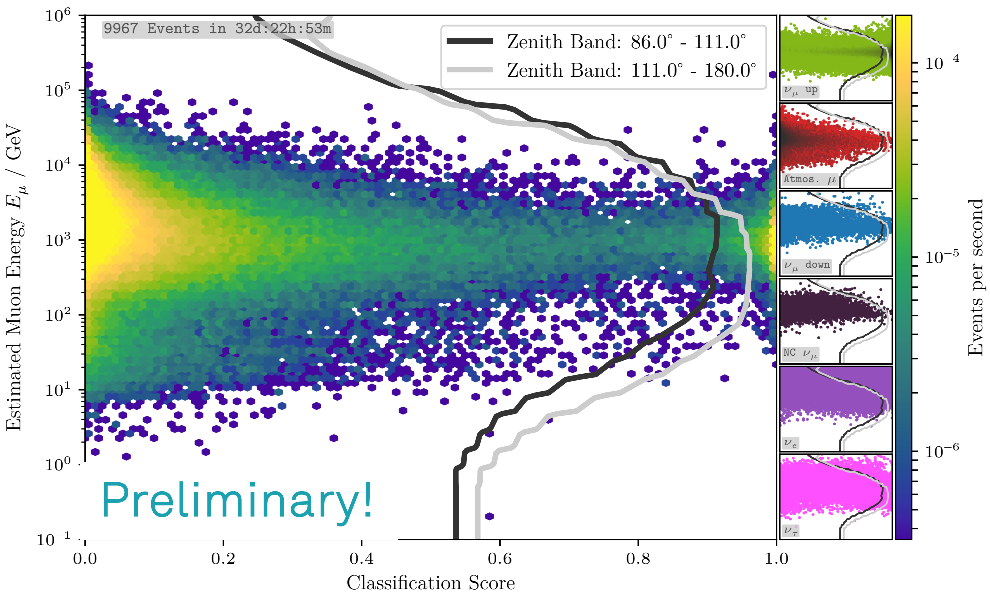


~ 200 neutrino candidates per day

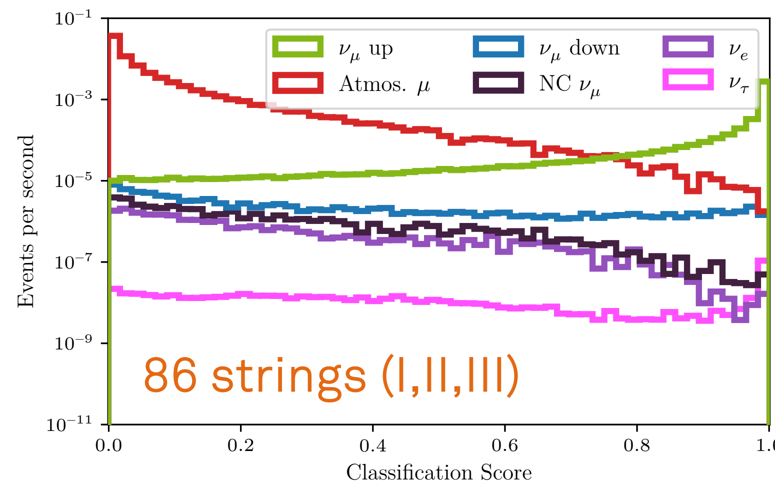


~ 80 neutrino candidates per day

Classifier Training and Output



~ 300 neutrino candidates per day



Classifier output is energy and zenith dependent.

Score cut as a function of energy and zenith.

M. Börner, PhD thesis (2018)

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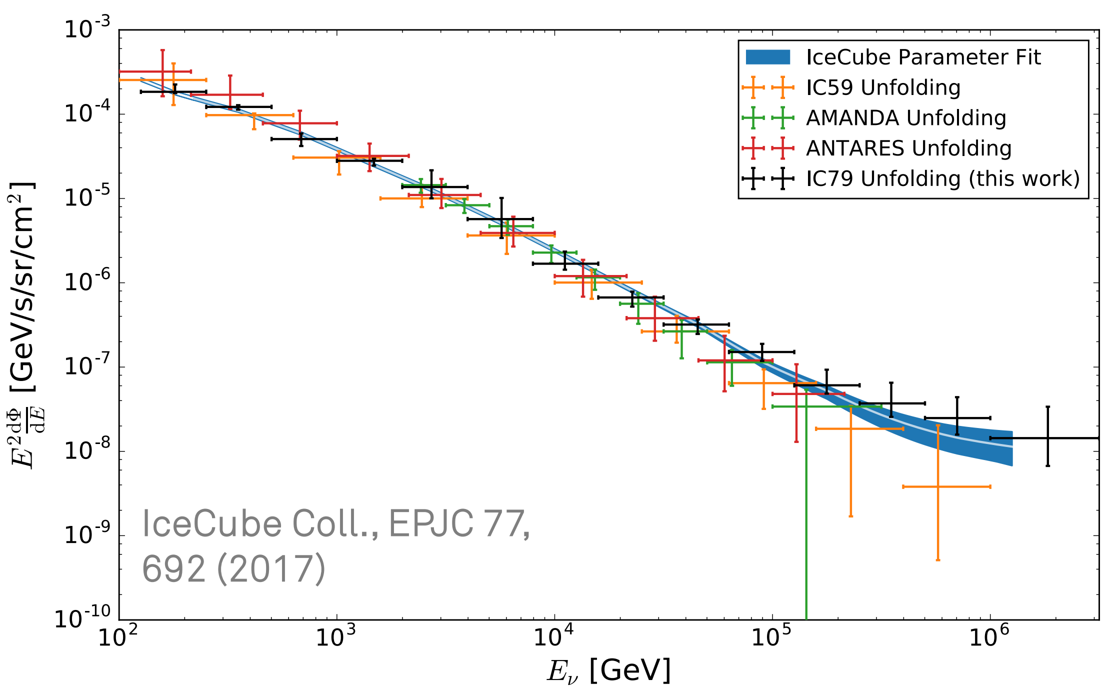
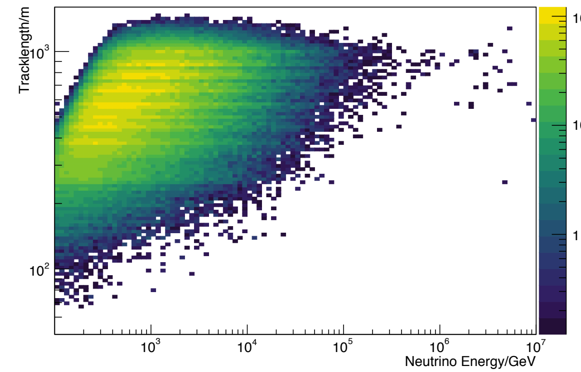
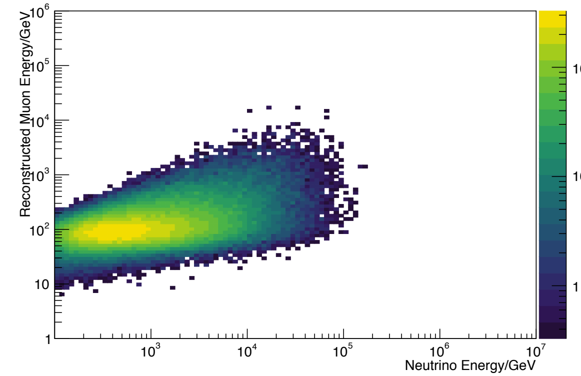
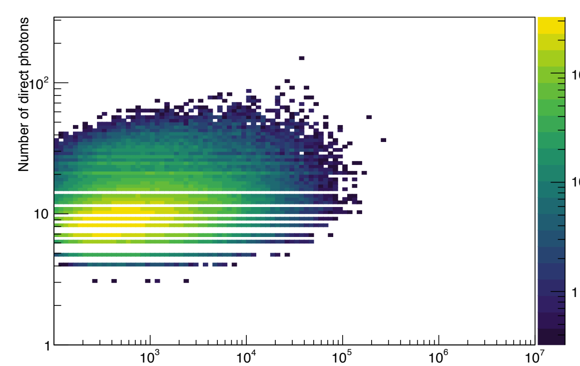
Results on Atmospheric ν_μ Spectra









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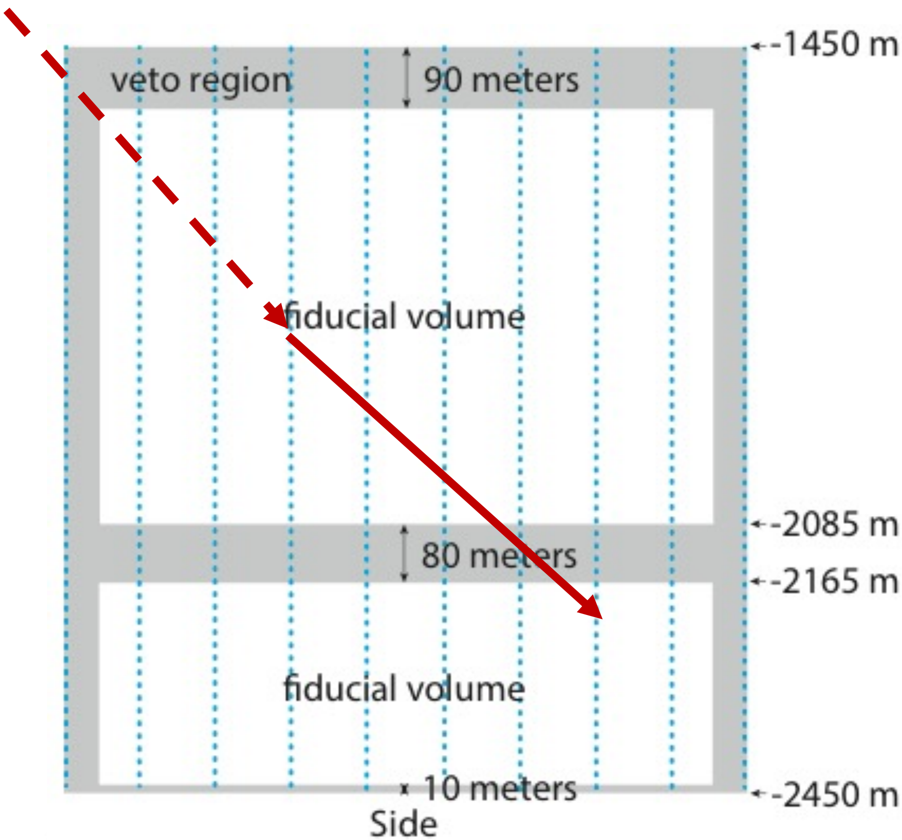
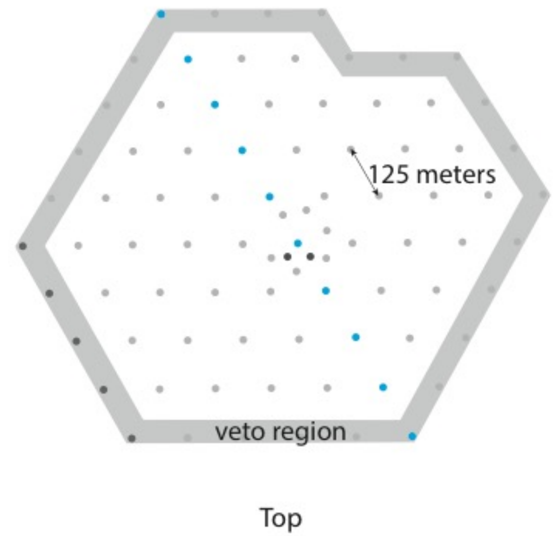
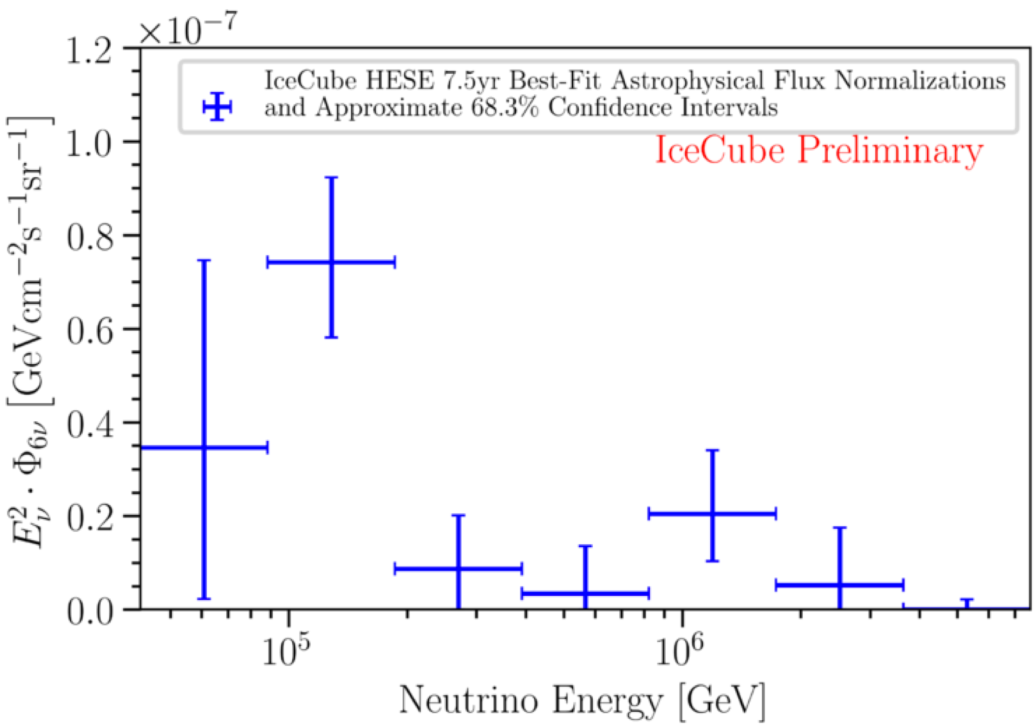
High Energy Starting Events





- Select events starting inside the detector
- Charge threshold of 6000 pe
- Less than 3 of first 250 pe in veto layer
- ~ 30 TeV deposited inside the detector

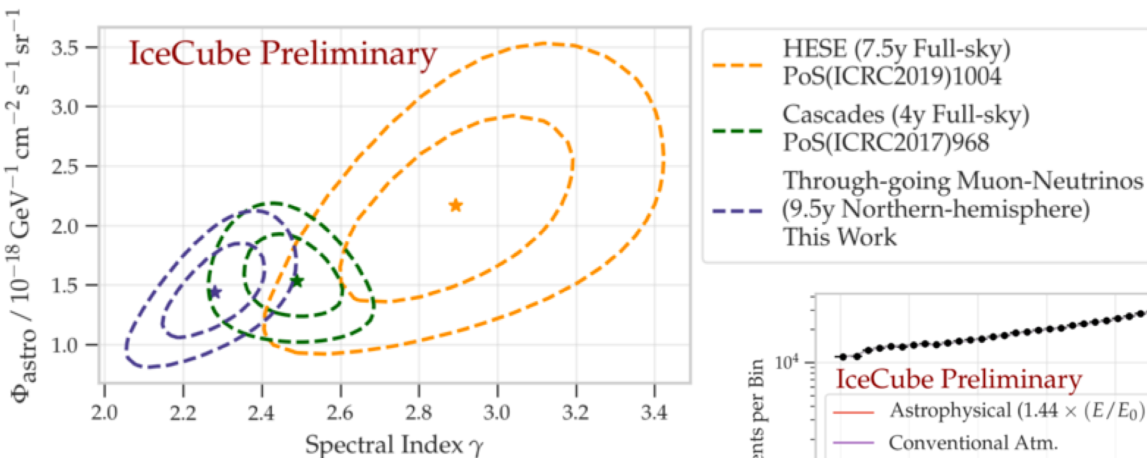
HESE Energy Spectrum



- Segmented Fit
- Assume E^{-2} flux and fit normalization per bin

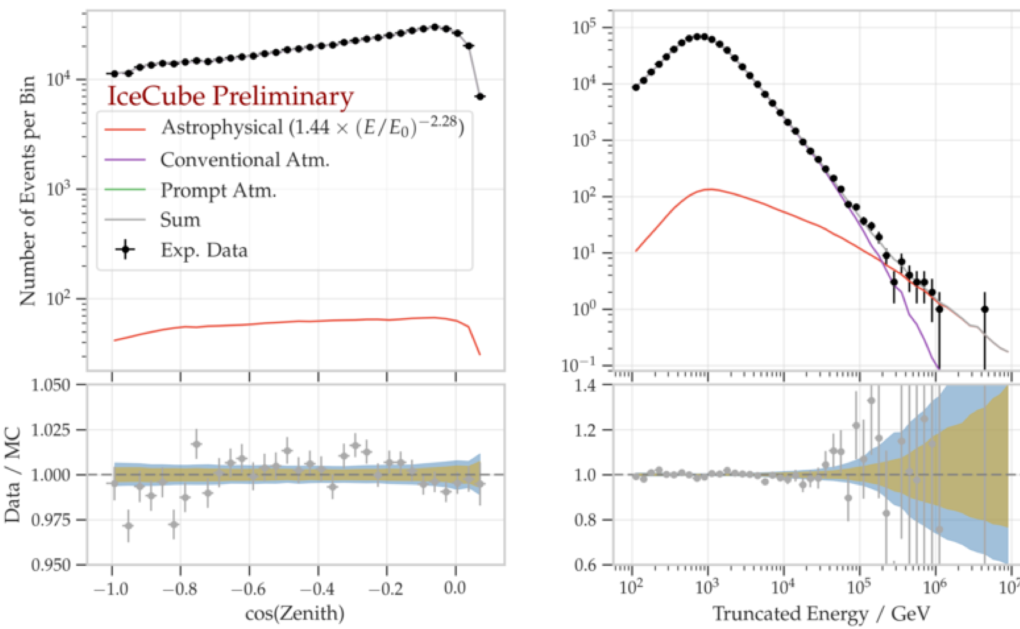
- Requires assumption on spectral shape
- Challenge: Small number of events

Neutrinos from the Northern Hemisphere



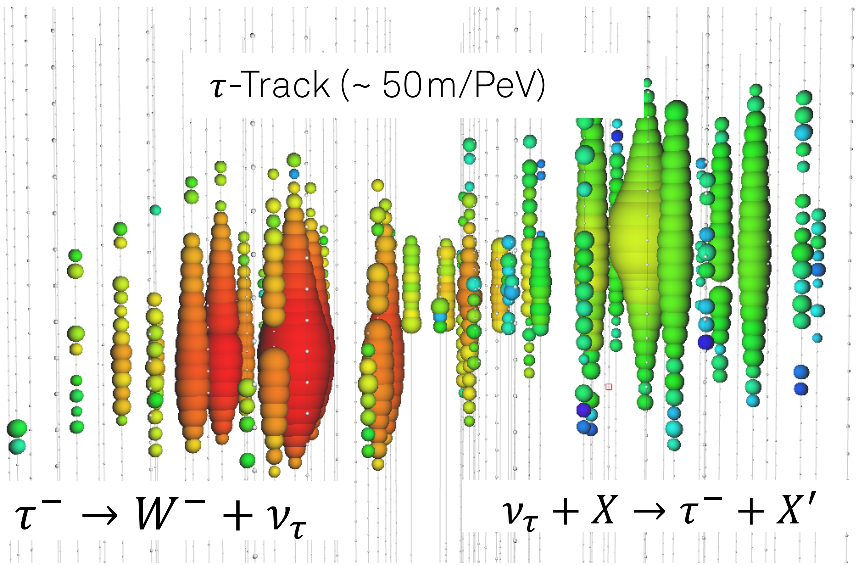
arxiv:1908.09918

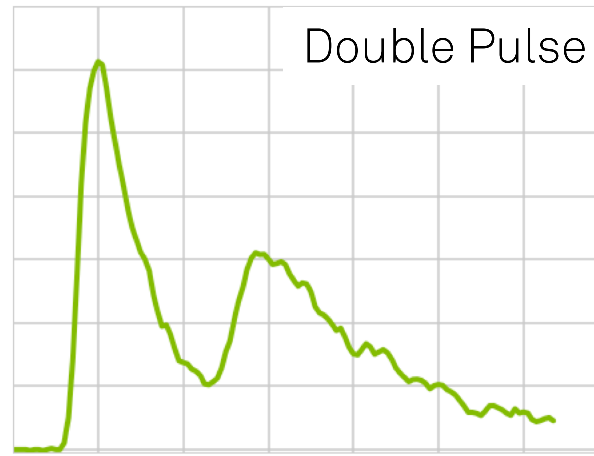
Llh-Fit to extract spectral index and normalization of the different flux components.

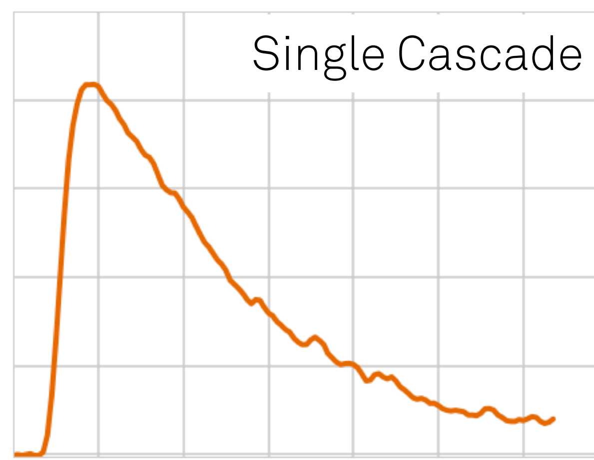


Requires more stringent assumptions on the spectral shape (power law).

Tau Neutrino Signatures

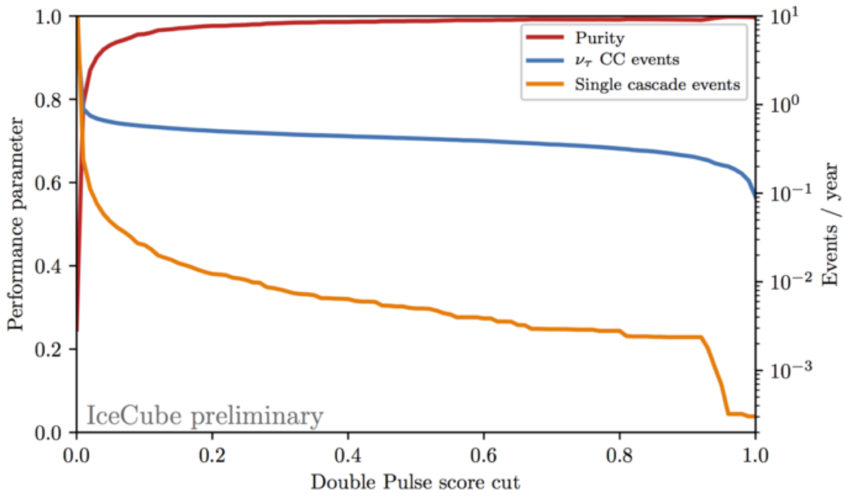




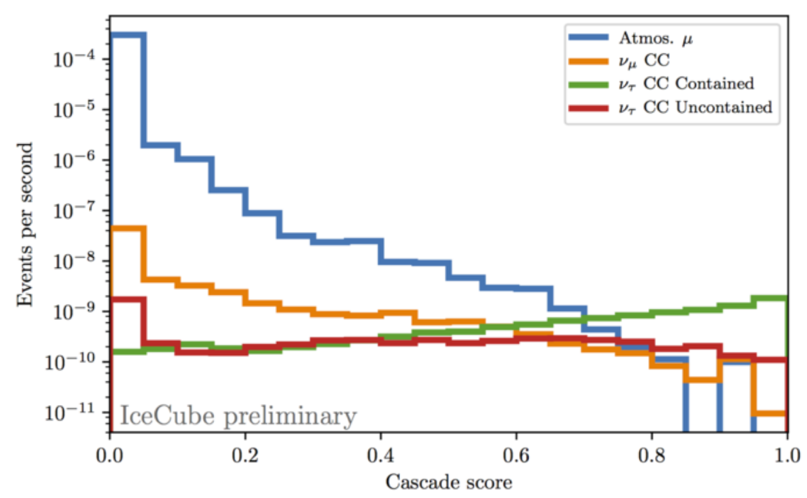


Double Pulse Identification with Machine Learning

Random Forest #1



Random Forest #2



Score Cut: 0.2

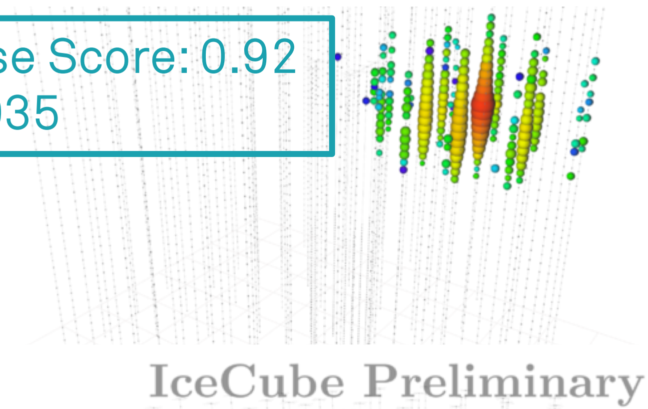
Purity increases to 97%

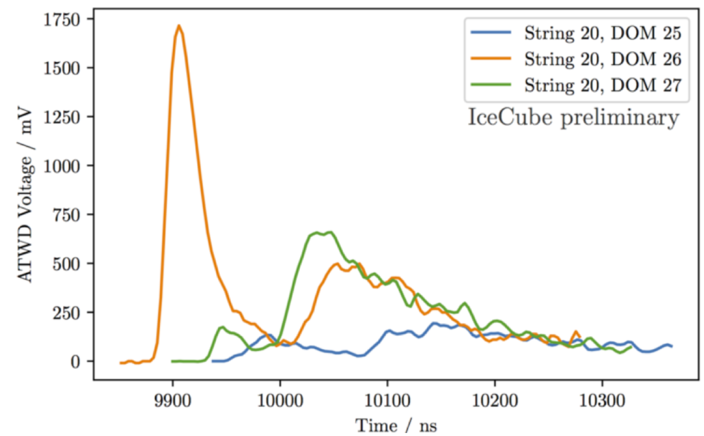
Score Cut: 0.62 (optimized via Model Rejection Factor)

2 Events survive both cuts

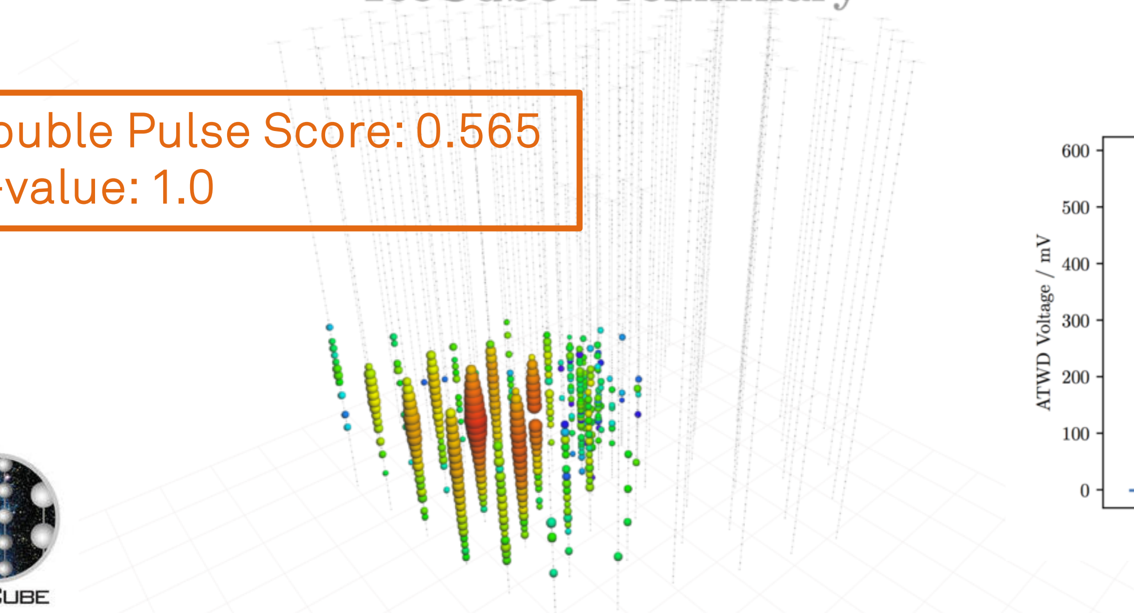
Double Pulse Identification with Machine Learning

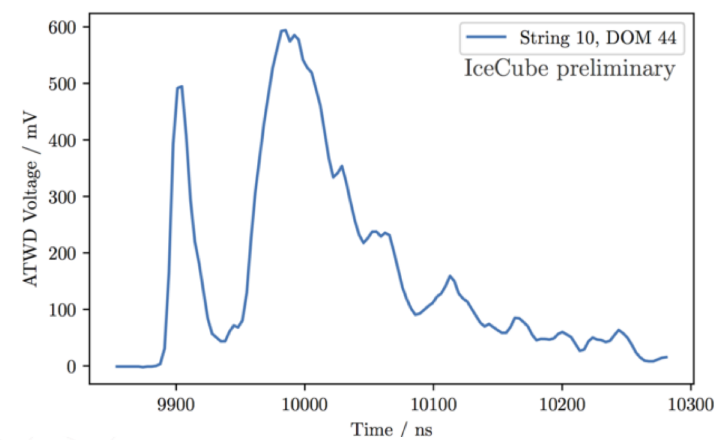
Double Pulse Score: 0.92
p-value: 0.035





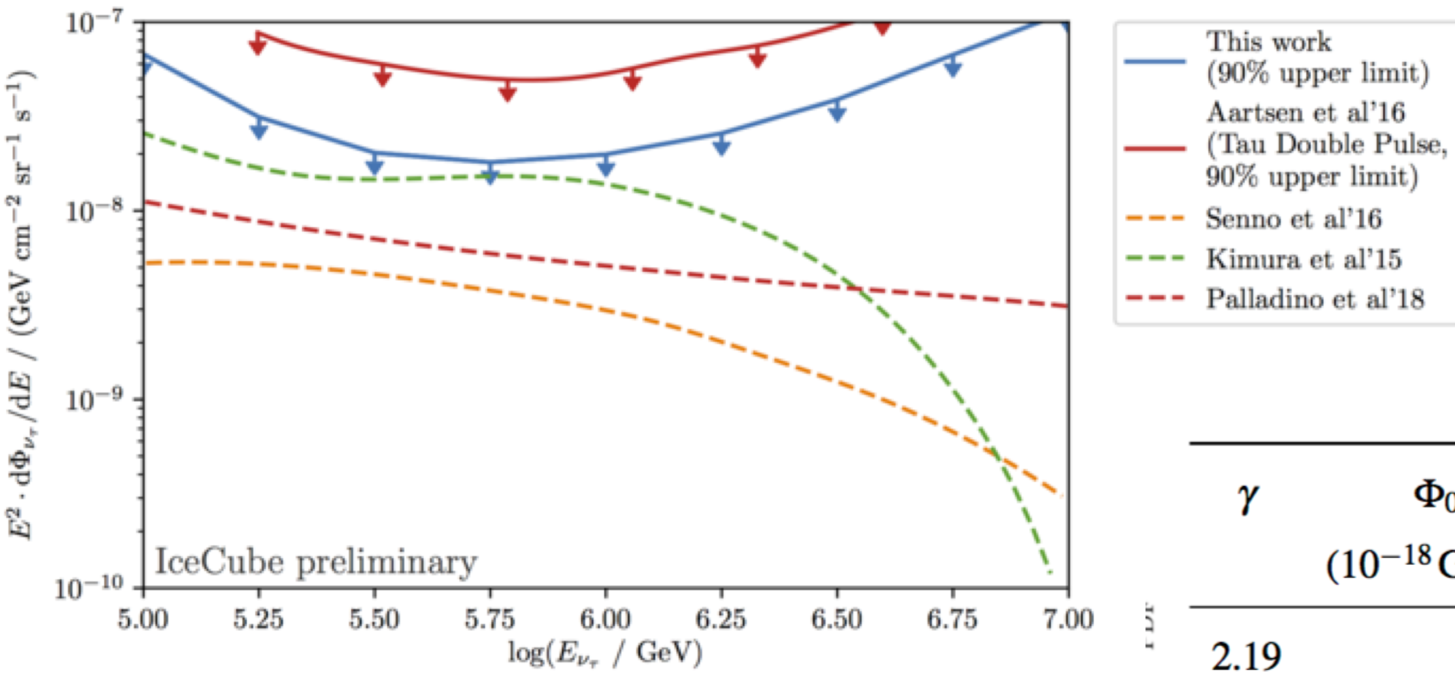
Double Pulse Score: 0.565
p-value: 1.0





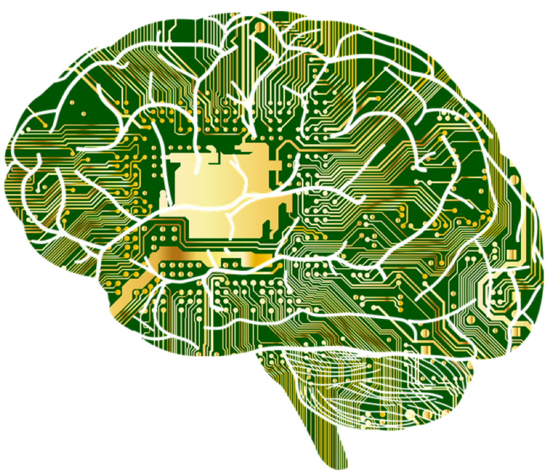
IceCube

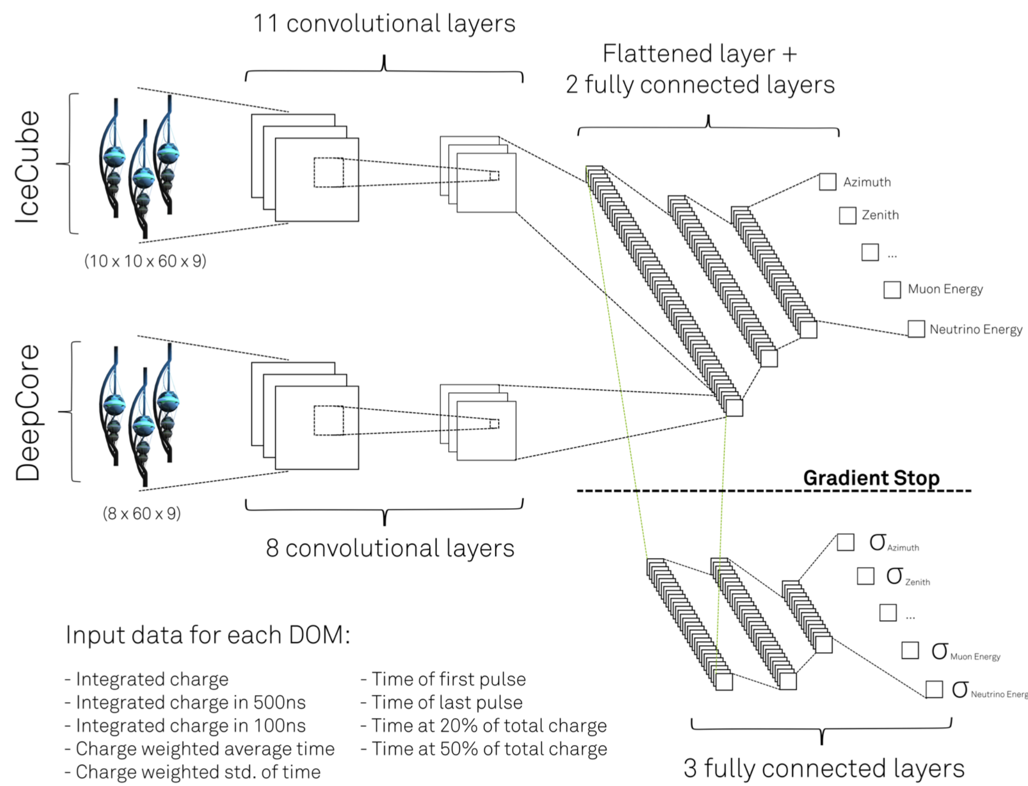
Double Pulse Identification with Machine Learning



γ	Φ_{0,ν_τ} at 100 TeV / ($10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$)
2.19	$0.45^{+0.79}_{-0.31}$
2.50	$0.83^{+1.46}_{-0.59}$
2.89	$1.62^{+2.78}_{-1.11}$

Reconstruction with Deep Neural Networks



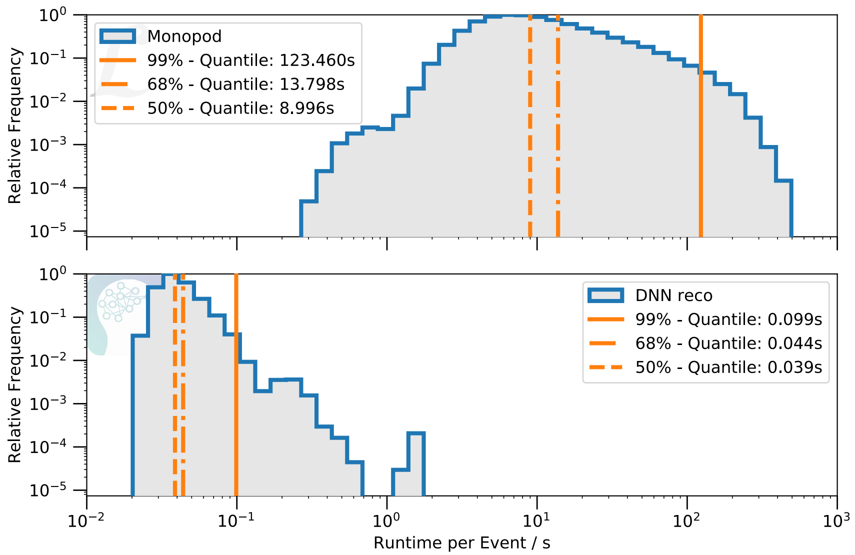


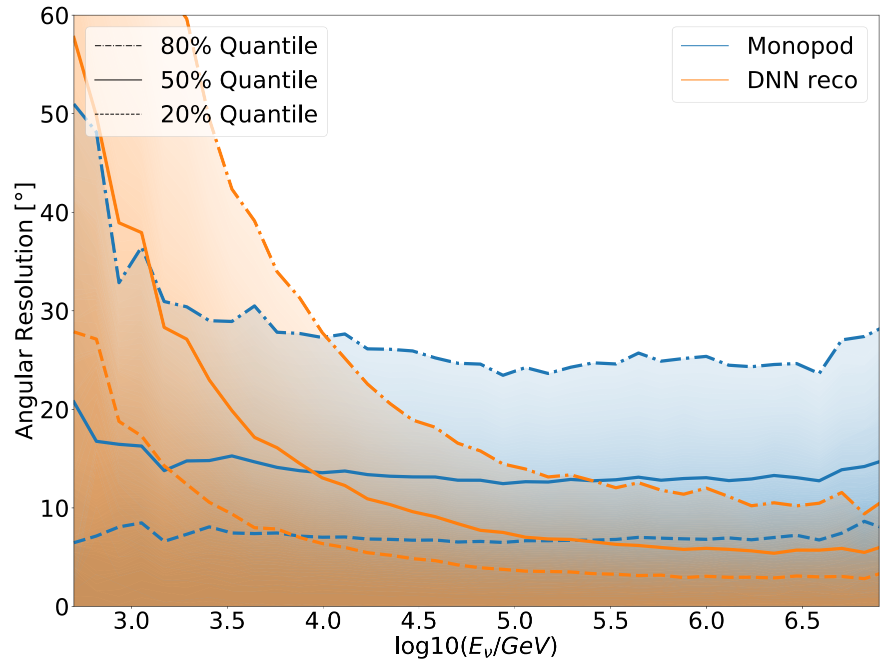
Input data for each DOM:

- Integrated charge
- Integrated charge in 500ns
- Integrated charge in 100ns
- Charge weighted average time
- Charge weighted std. of time
- Time of first pulse
- Time of last pulse
- Time at 20% of total charge
- Time at 50% of total charge

Reconstruction with Deep Neural Networks

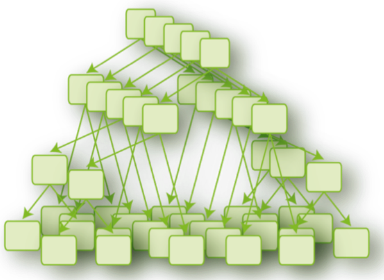
- Stable runtime
- Largely independent of event characteristics
- Great for running in online analyses

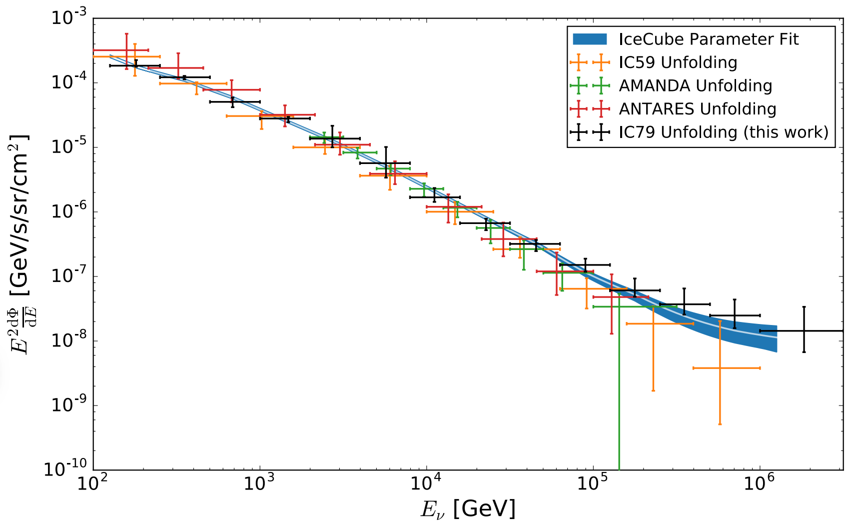


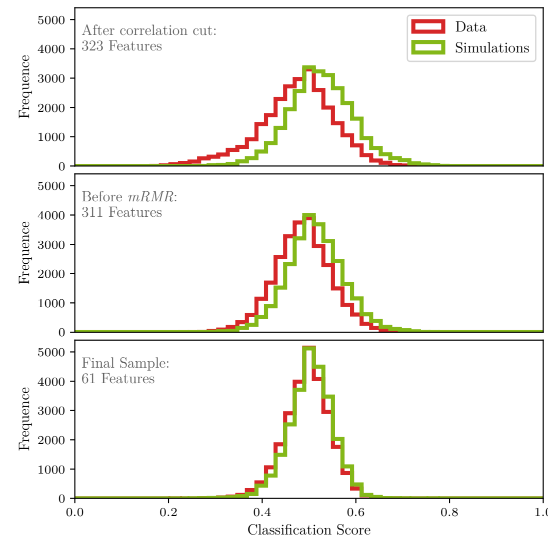


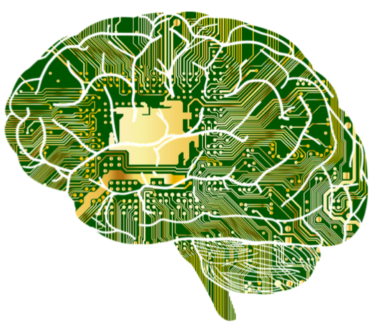
Energy resolution evaluated for specific event sample (cascades)

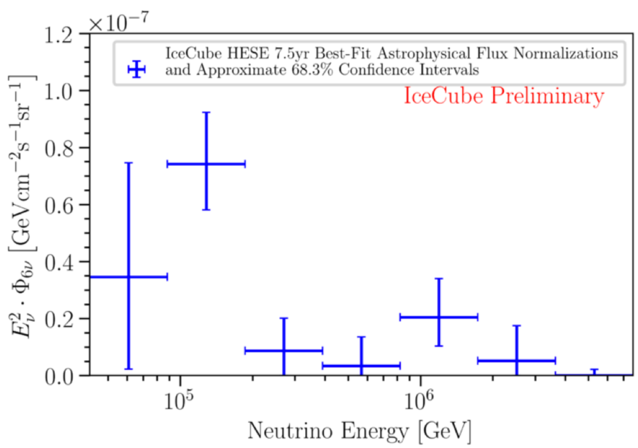
Summary

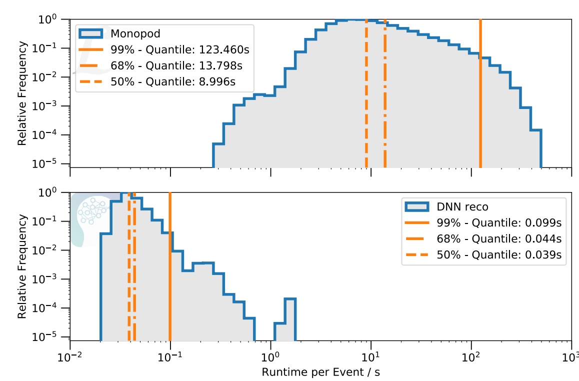



IceCube Parameter Fit
IC59 Unfolding
AMANDA Unfolding
ANTARES Unfolding
IC79 Unfolding (this work)
$E^2\frac{d\Phi}{dE}$ [GeV/s/sr/cm^2]
E_ν [GeV]


After correlation cut:
323 Features
Data
Simulations
Before mRMR:
311 Features
Final Sample:
61 Features
Frequence
Classification Score




IceCube HESE 7.5yr Best-Fit Astrophysical Flux Normalizations
and Approximate 68.3% Confidence Intervals
IceCube Preliminary
$E_\nu^2 \cdot \Phi_{6\nu}$ [GeV cm^{-2}s^{-1}sr^{-1}]
Neutrino Energy [GeV]


Monopod
99% - Quantile: 123.460s
68% - Quantile: 13.798s
50% - Quantile: 8.996s
DNN reco
99% - Quantile: 0.099s
68% - Quantile: 0.044s
50% - Quantile: 0.039s
Relative Frequency
Runtime per Event / s

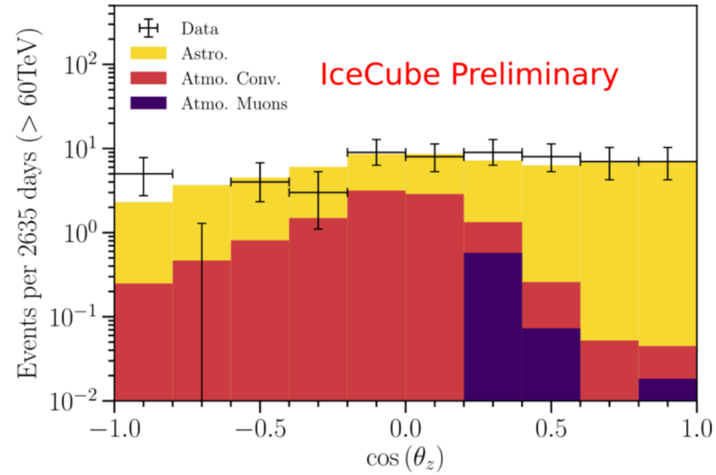
Backup Slides

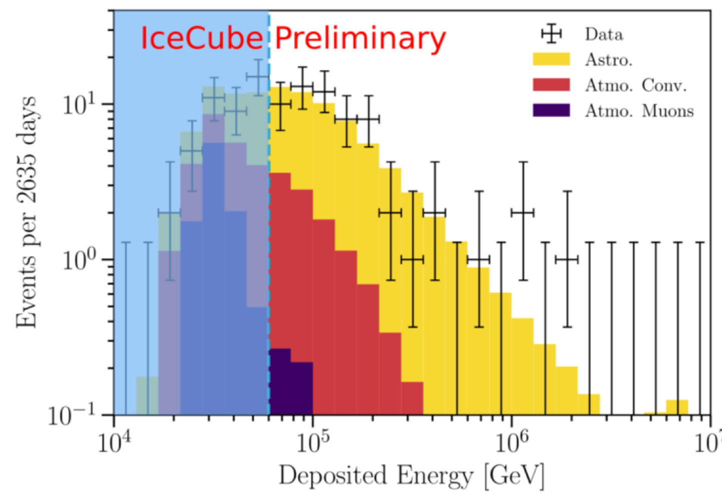
HESE Background Estimation

Main backgrounds are:

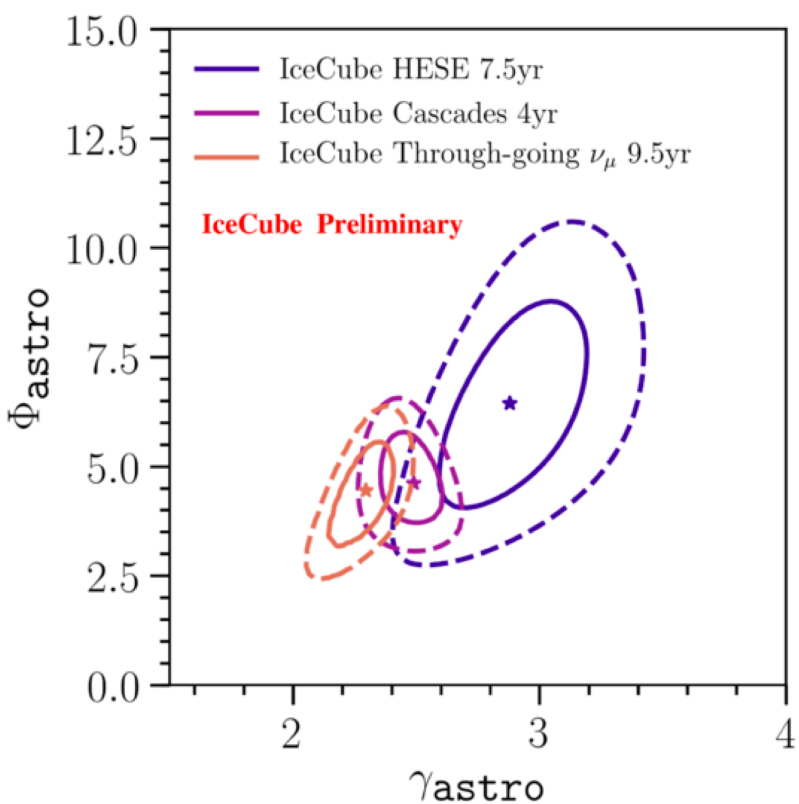
- Atmospheric muons
  - Estimated in data-driven method
  - 10.3 in 7.5 yrs. of data
- Atmospheric neutrinos
  - Strongly disfavored by energy and directional distribution
  - 23.2 events in 7.5 yrs. of data

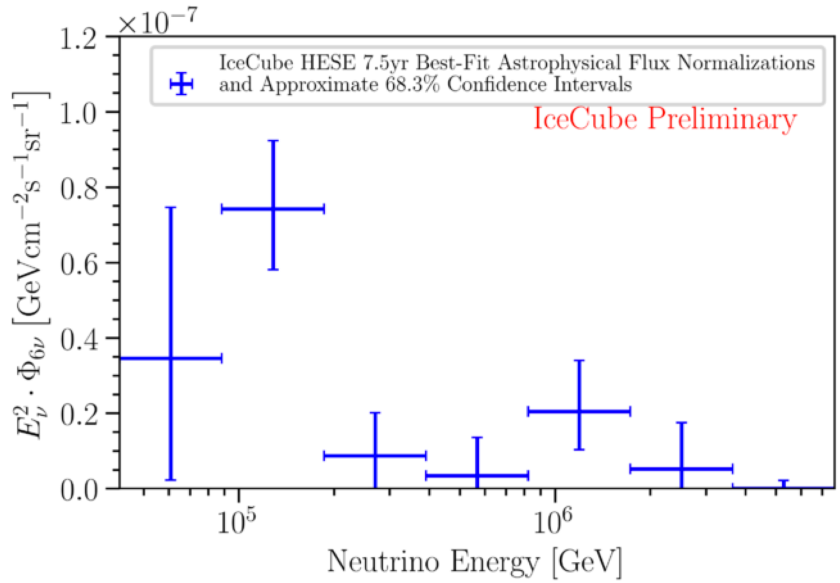
Significance is estimated using total event number and event properties.





7.5 Year Results



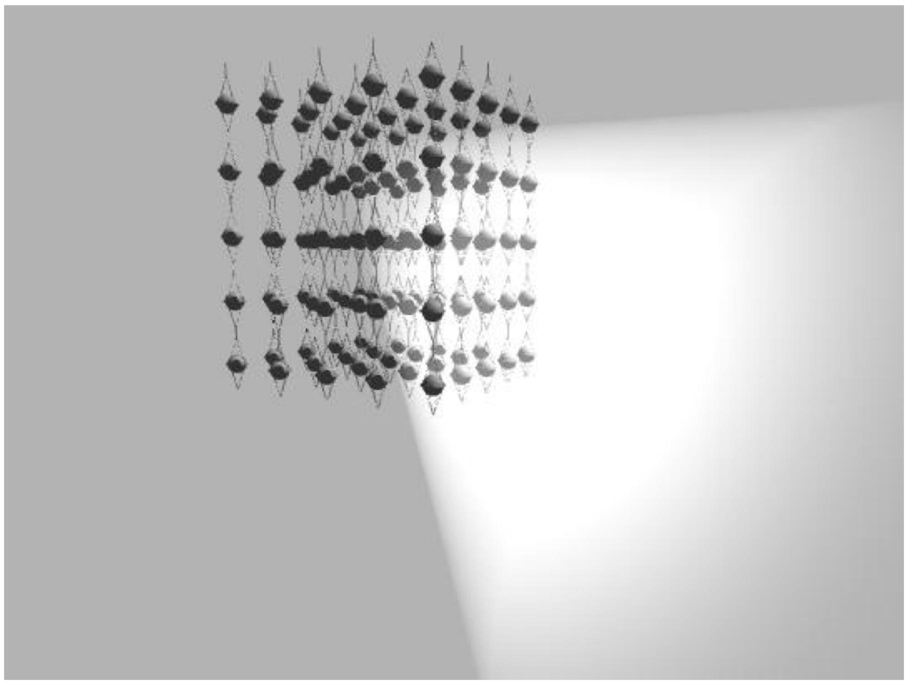


Single Power Law Fit:

$$\gamma = 2.89^{+0.19}_{-0.20}$$

$$\Phi_0 = 6.45^{+1.46}_{-0.46} \times 10^{-18}\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

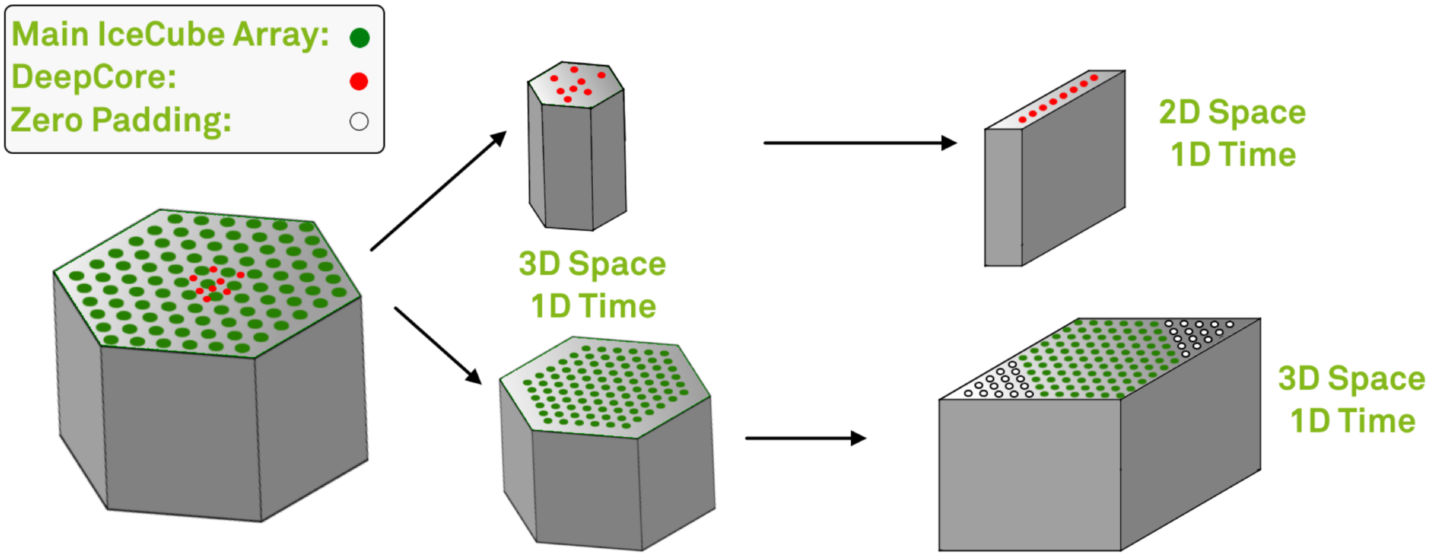
Detection Principle

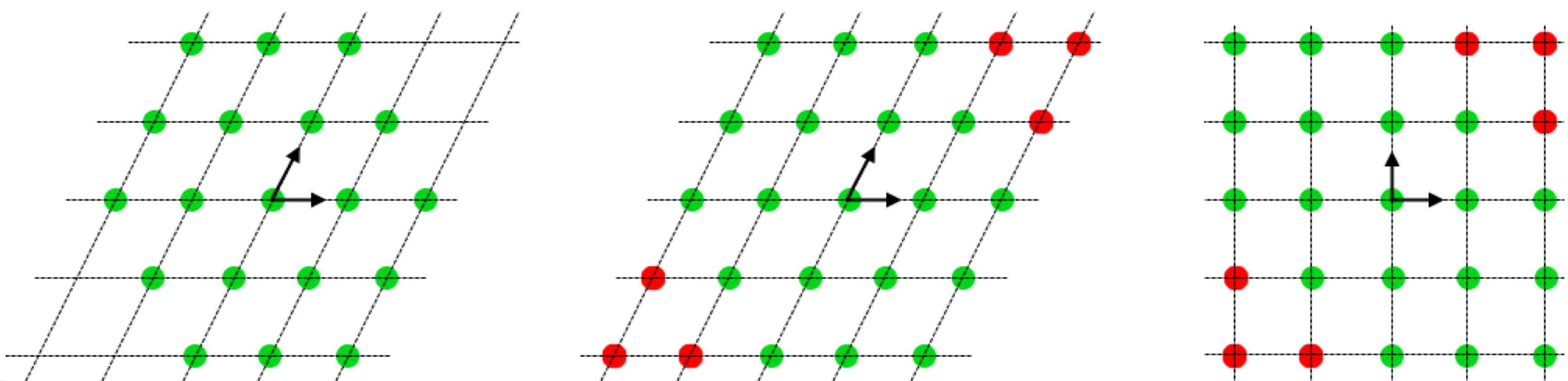


- Neutrino detection via charged leptons:

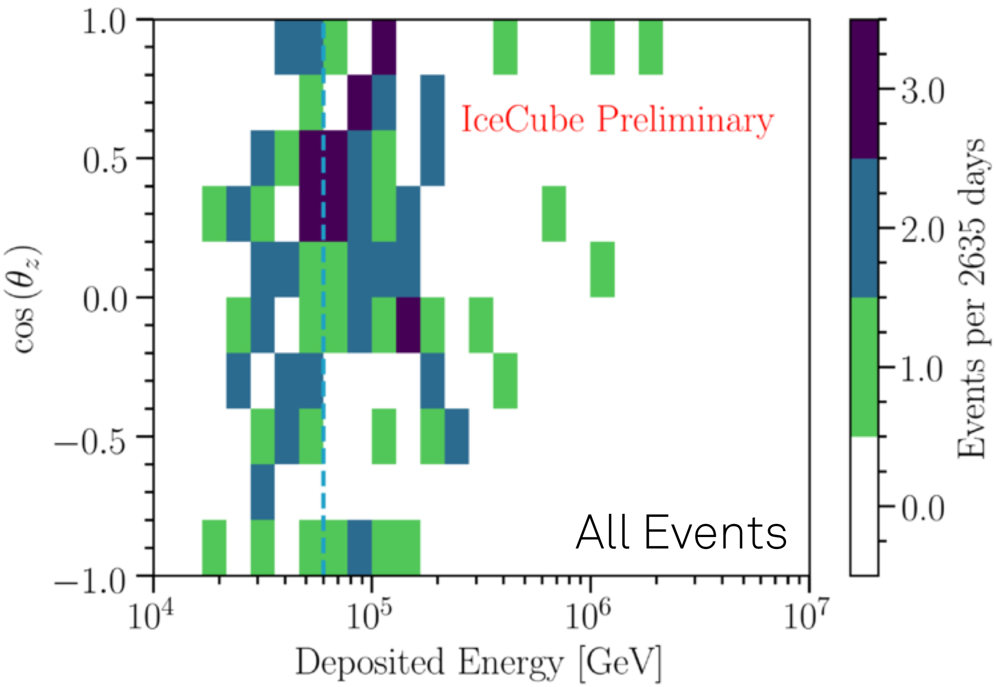
$$\nu_l + X \longrightarrow l + X'$$

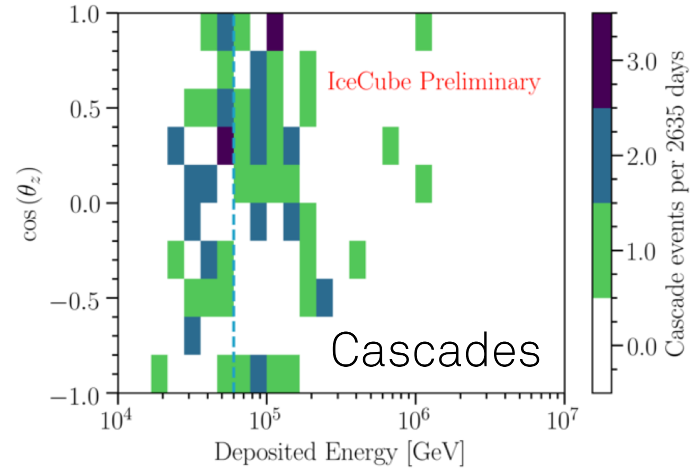
- Interaction in the ice or the bedrock
- Detection of Cherenkov light by Digital Optical Modules (DOMs)

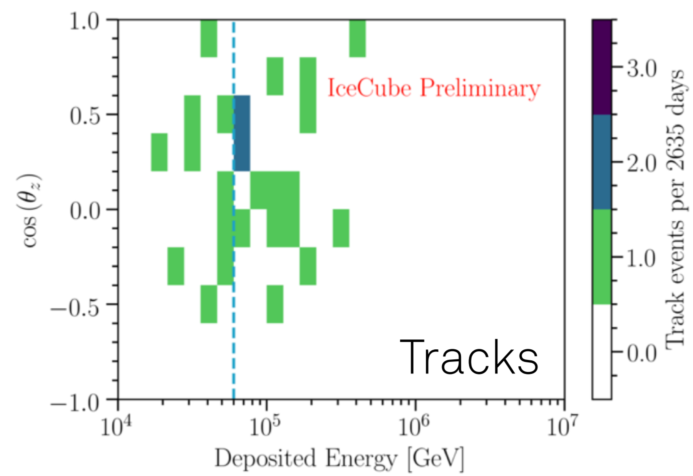

Main IceCube Array:
DeepCore:
Zero Padding:
3D Space
1D Time
2D Space
1D Time
3D Space
1D Time



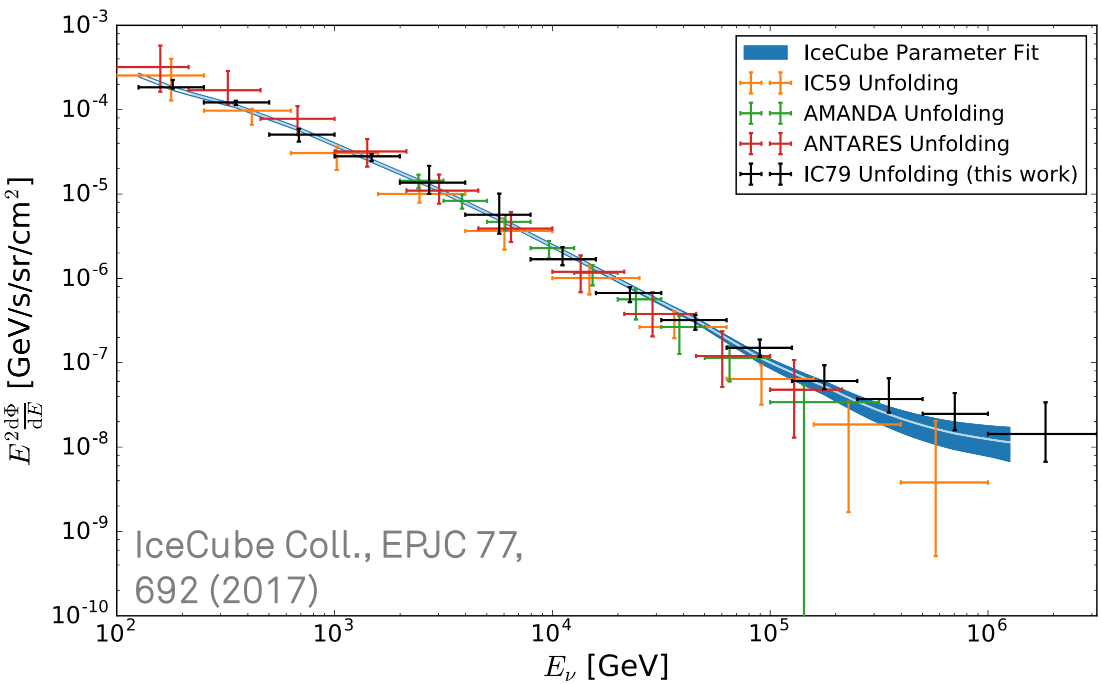
HESE Energy and Zenith Distribution

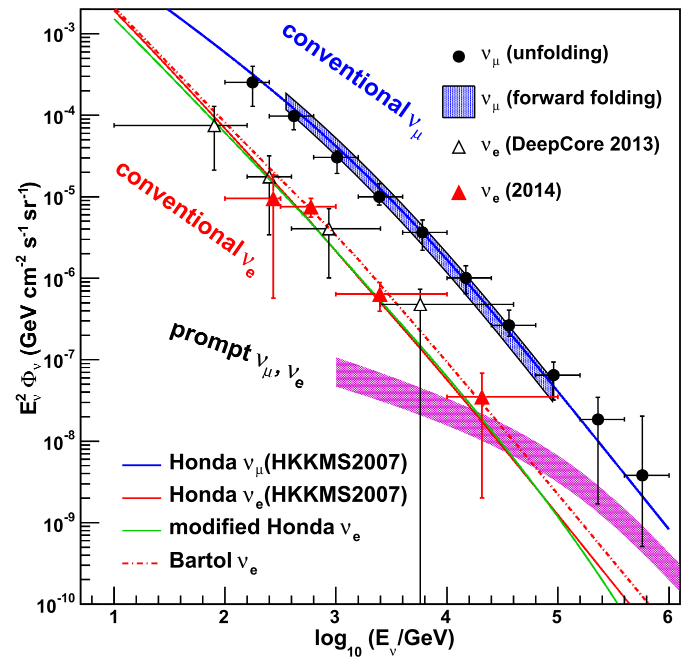






Results on Atmospheric Neutrino Spectra





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