Characterization of the PeV astrophysical neutrino energy spectrum with IceCube using down-going tracks

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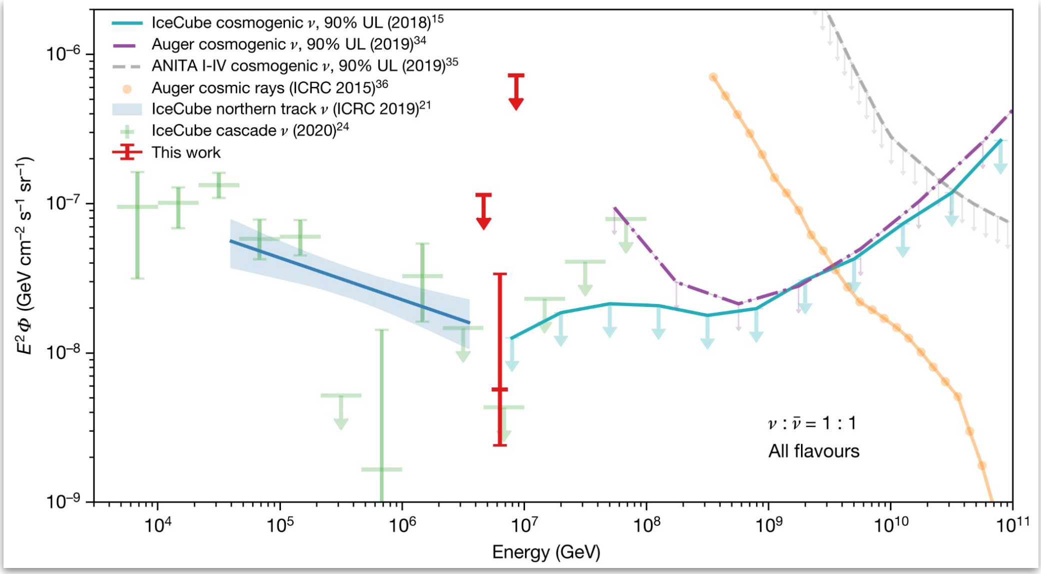
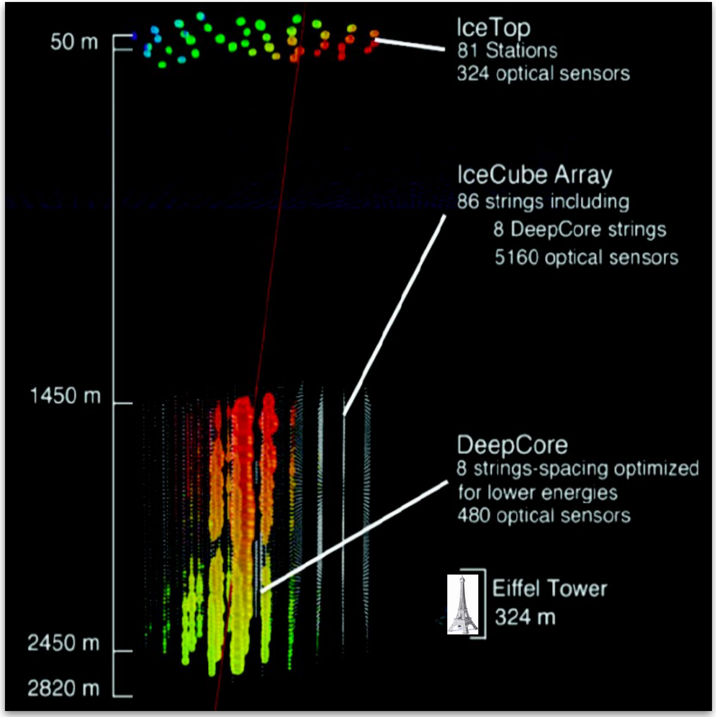
Introduction



The IceCube Collaboration. Detection of a particle shower at the Glashow resonance with IceCube. *Nature* 591, 220–224 (2021). https://doi.org/10.1038/s41586-021-03256-1

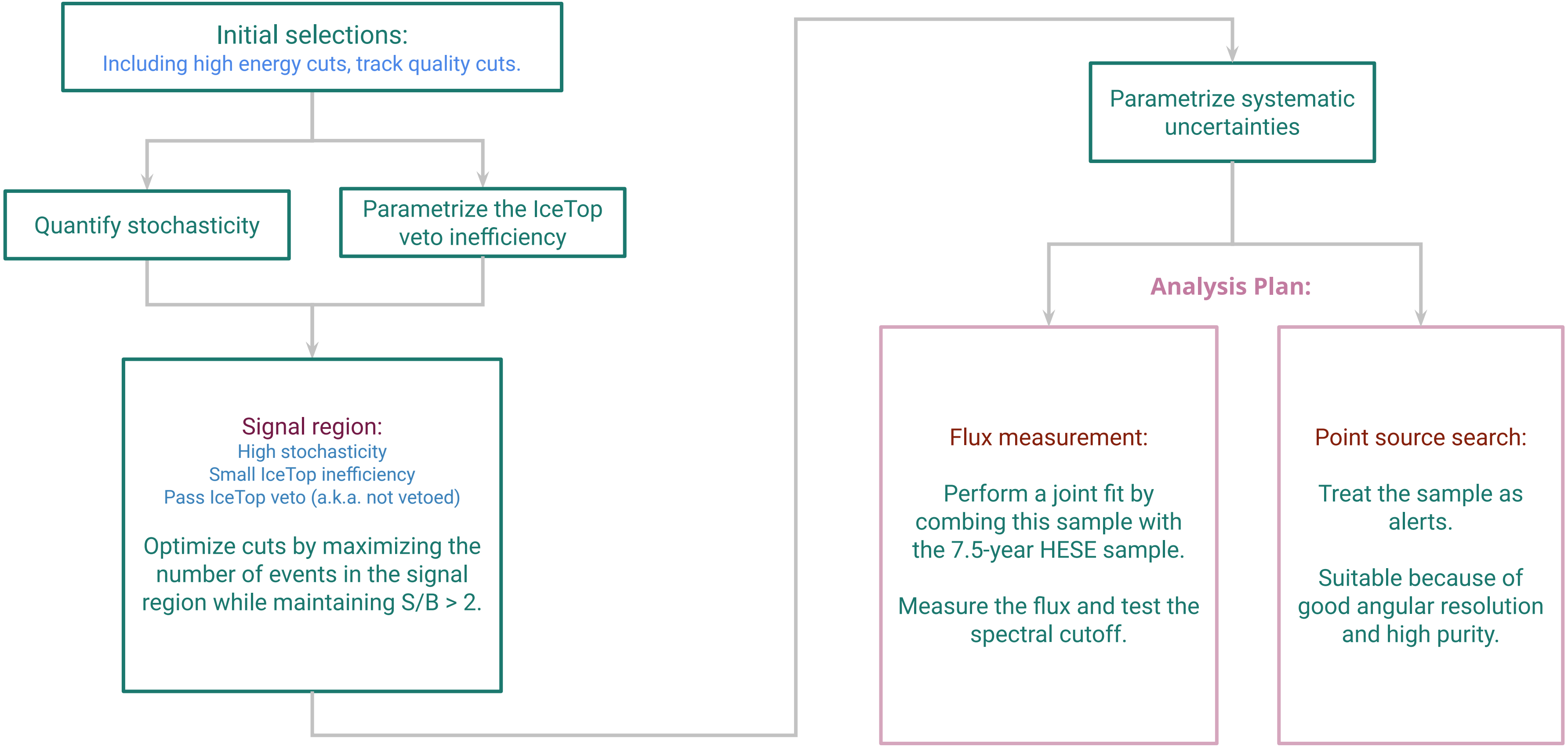
- Measuring the astrophysical neutrino flux could give us insights into the origin of cosmic rays.
- IceCube has observed a diffuse astrophysical neutrino flux since 2013.
- The deficiency of events above 2 PeV might indicate a spectral cutoff.
- Recent IceCube analyses have limited sensitivity to PeV neutrinos.
- To fill the gap between 1 PeV and 10 PeV, we have developed a new event selection that looks for down-going through-going high-energy tracks.

Techniques

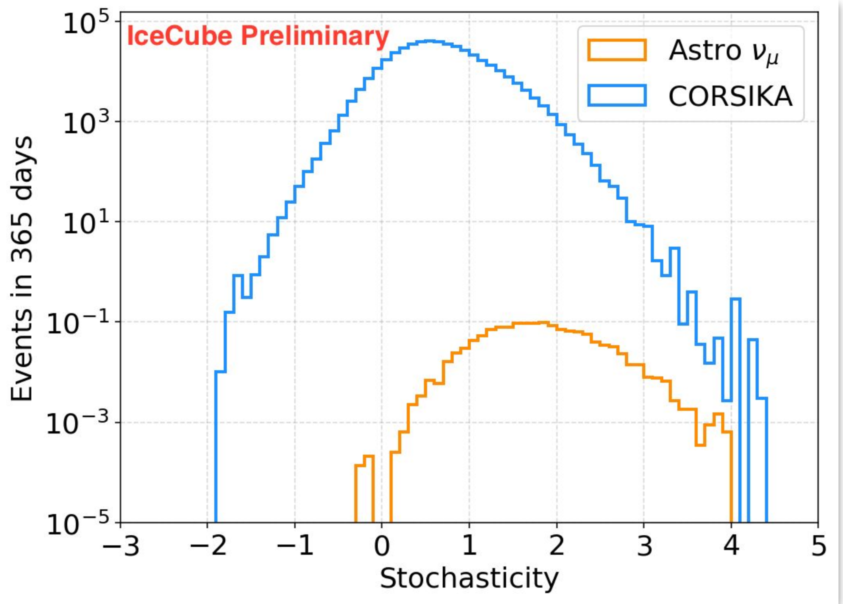


- Two techniques to reduce the 3kHz atmospheric muon background:
  a. Stochasticity cut
  b. IceTop veto
- The veto efficiency is parametrized in the high-background region and the veto is applied only in the veto-effective region.
- Remaining muon background in the signal region is estimated with a template fitting method.

Analysis Flowchart

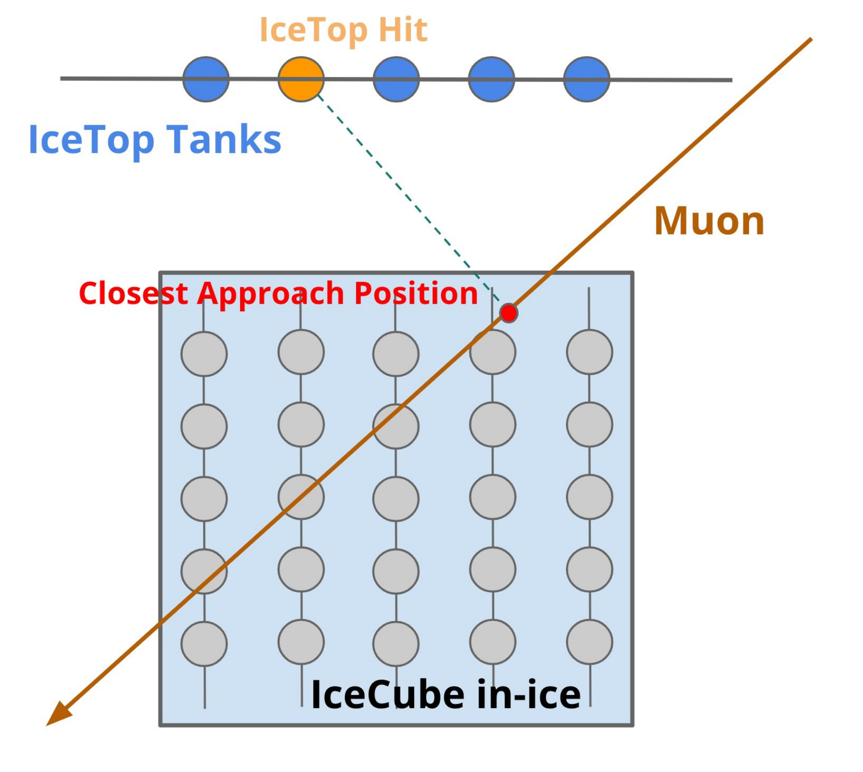


Stochasticity



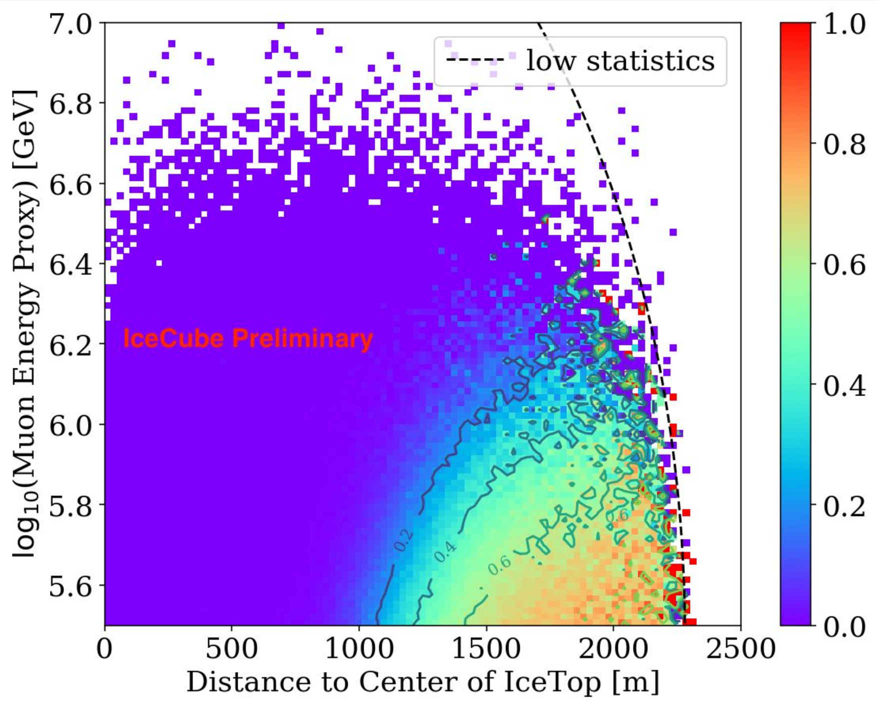
- Stochasticity is measured by fitting a line to the muon energy losses E_i and calculate the log of mean squared loss (MSE).
- Each squared loss is weighted by $\sqrt{E_i}$, a choice that maximizes the separation between signals and backgrounds.
- Left: stochasticity distribution of signals (nugen numu) vs. backgrounds (CORSIKA).
- There is an indistinguishable background from proton primaries that may create events where a single muon dominates.

IceTop veto



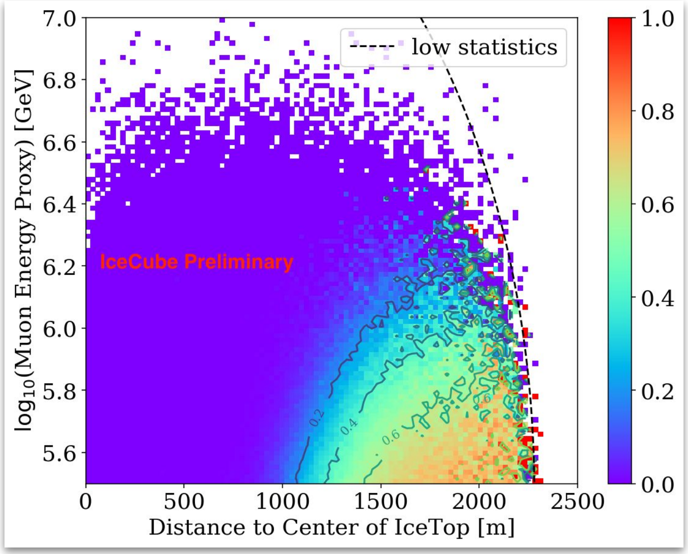
- For each IceTop hit, we calculate the time when the muon arrives at the closest approach position.
- If the IceTop hit time and the muon arrival time are within a time window, we consider this hit to be correlated with the event.
- For a given event, if there are >= 2 correlated IceTop hits, then the event is vetoed.

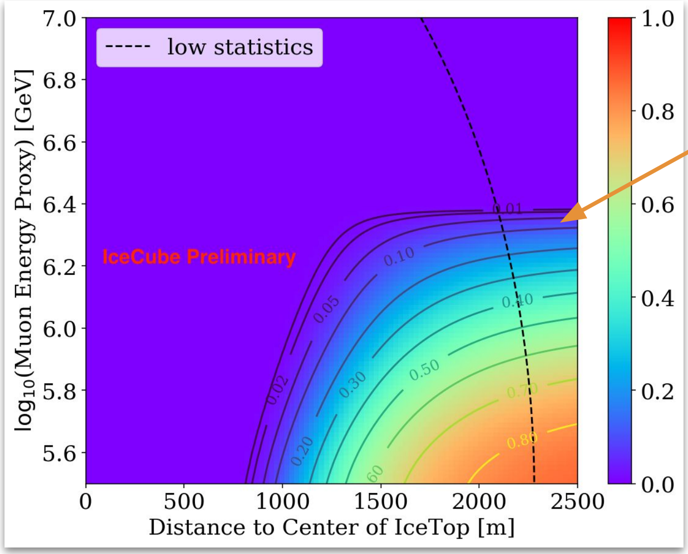
IceTop inefficiency



- The veto efficiency is parametrized as the IceTop inefficiency.
- Inefficiency is a function of muon energy and distance from the track to the center of IceTop array.
- Left: IceTop inefficiency from data (8 years from 2012 to 2019) in the background region (stochasticity < 0.8). In each bin, inefficiency is the fraction of events passing the IceTop veto.
- Therefore, inefficiency is between 0 and 1; a small value indicates good veto power.

IceTop inefficiency model

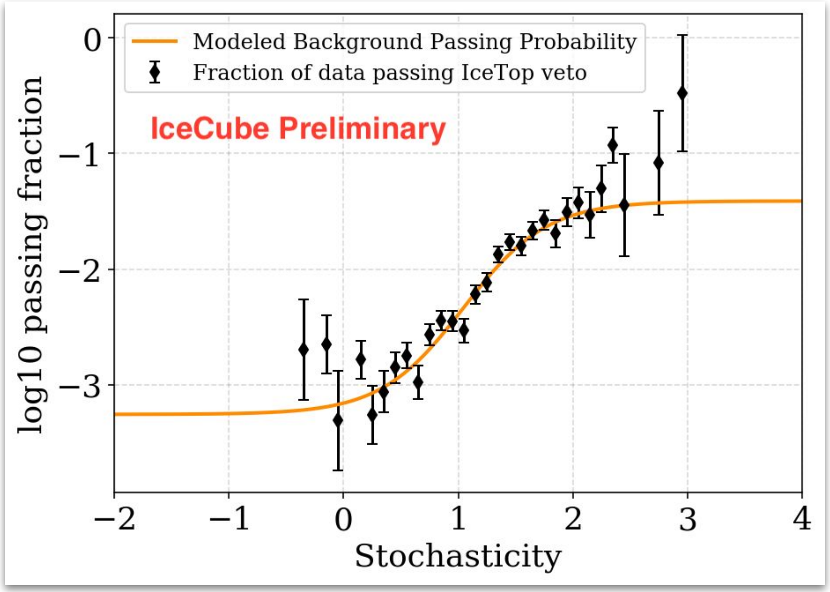




Low-statistics region

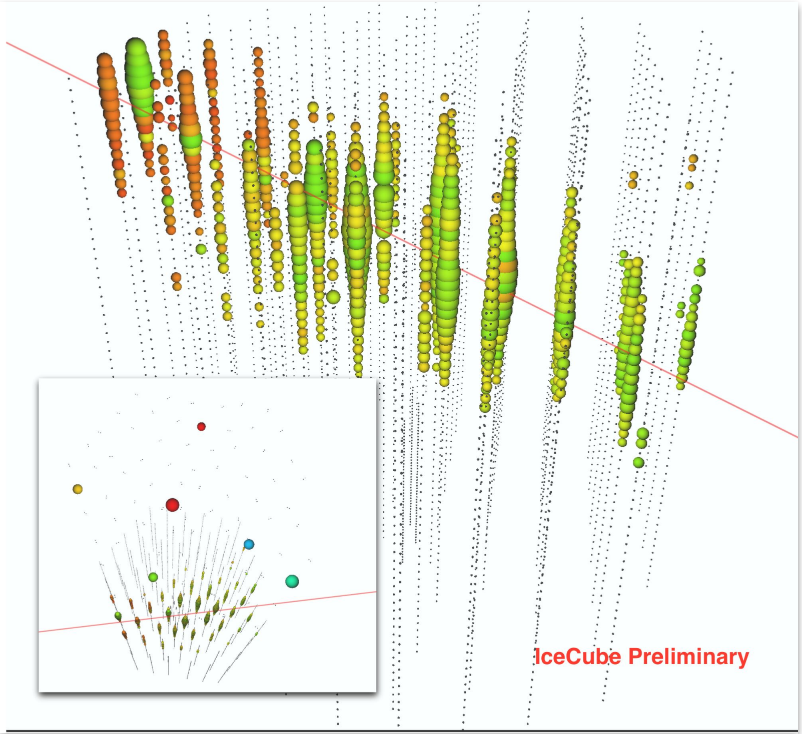
- Inefficiency from data is smoothened by fitting a 2-variable function. The result is the IceTop inefficiency model.
- In practice, inefficiency to the right of the low statistics boundary is manually set to a high value.
- Eventually, we only apply IceTop veto to events in the region where inefficiency is small enough.

Optimizing cuts & background estimation



- The signal region is defined by a series of cuts:
  a. Initial selections
  b. Stochasticity cut
  c. IceTop inefficiency cut
  d. Pass IceTop veto
- We optimize the cuts using the burn sample (10% of the full dataset) by maximizing the number of events in the signal region while maintaining S/B > 2.
- The backgrounds in the signal region are estimated on an event-by-event basis with a stochasticity template fitting method using CORSIKA.
- Left: black points show the fraction of data passing the veto for each stochasticity bin. The orange curve shows the result of the template fitting.
- The discrepancy at high stochasticity indicates signal.

Event visualization



- Optimization result:
  - Stochasticity > 2.5
  - IceTop inefficiency < 0.011
- For the burn sample, 2 events are found in the signal region with an estimated S/B ~ 2.2. Expect ~20 events after unblinding.
- Left: visualization of one event.

20% systematic uncertainties (not finalized) → event-wise background

	muon energy [PeV]	closest dist to IceTop center [m]	zenith [deg]	stochasticity	IceTop inefficiency	event-wise background
Event 1 (left)	$3.2^{+2.1}_{-1.2}$	1606	69	2.73	1e-5	0.11
Event 2	$1.2^{+0.7}_{-0.5}$	1034	40	2.97	0.00037	0.58

Systematics

- Three types of systematics:
  a. Background estimation uncertainties
     - Snow effect
     - Hyperparameters in stochasticity templates
  b. Detector systematics
     - DOM efficiency
     - Ice absorption/scattering
     - Hole-ice effects
  c. Flux uncertainties
     - Conventional and prompt normalizations
- Parametrized as nuisance parameters in the likelihood function:

$$\ln L(\boldsymbol{\theta}, \boldsymbol{\xi}) = \sum_i \ln\left(\frac{e^{-\mu_i}\mu_i^{k_i}}{k_i!}\right) + \sum_j \left(\frac{\xi_j - \xi_j^*}{\sigma[\xi_j]}\right)^2$$

Physics parameters

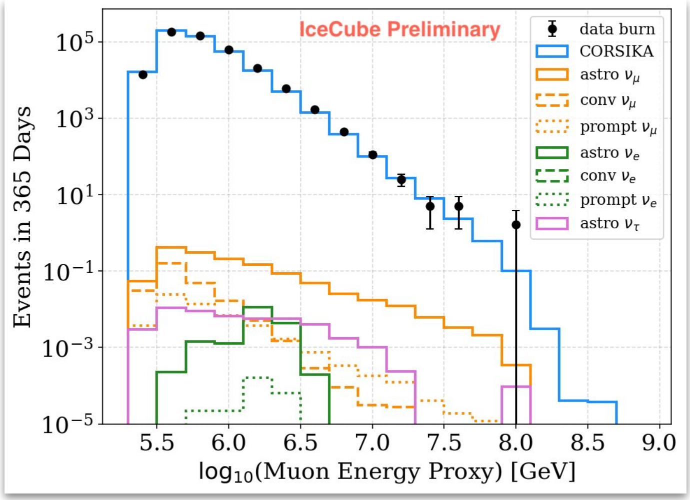
Nuisance parameters

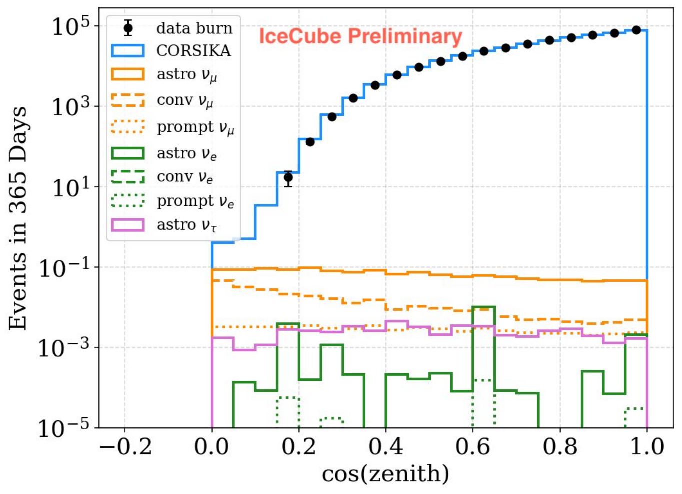
Conclusions

- We have developed a new event selection for PeV neutrinos using down-going tracks.
- We use stochasticity cuts and IceTop veto to reduce atmospheric muon backgrounds.
- The sample we obtain is at high energy and is relatively pure.
- As a next step, this sample will be combined with the HESE sample to do a combined fit; the existence of the spectral cutoff will be tested.
- This sample will be released as real time alerts.

Backup

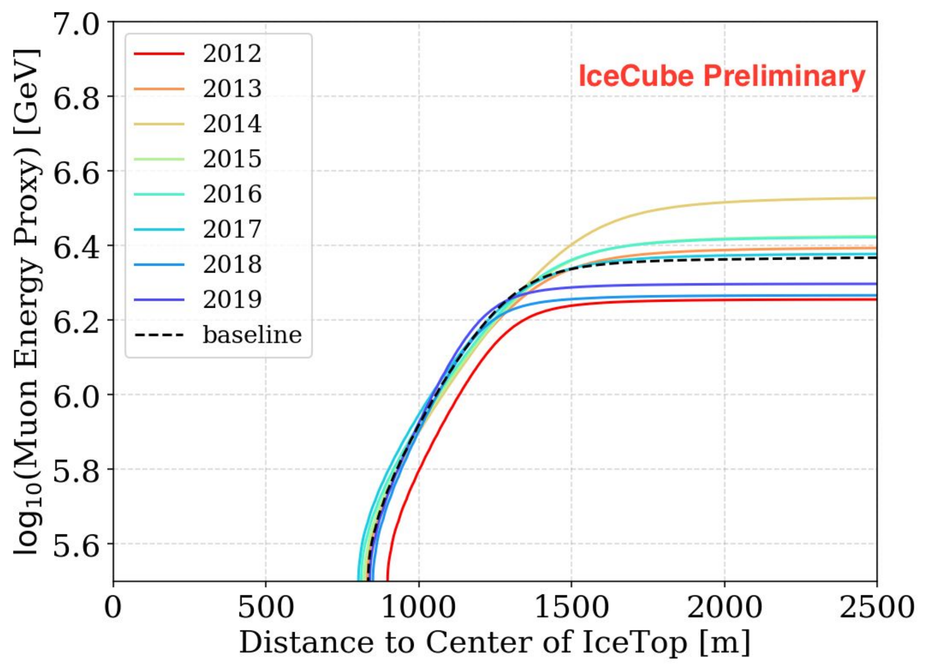
After initial selections



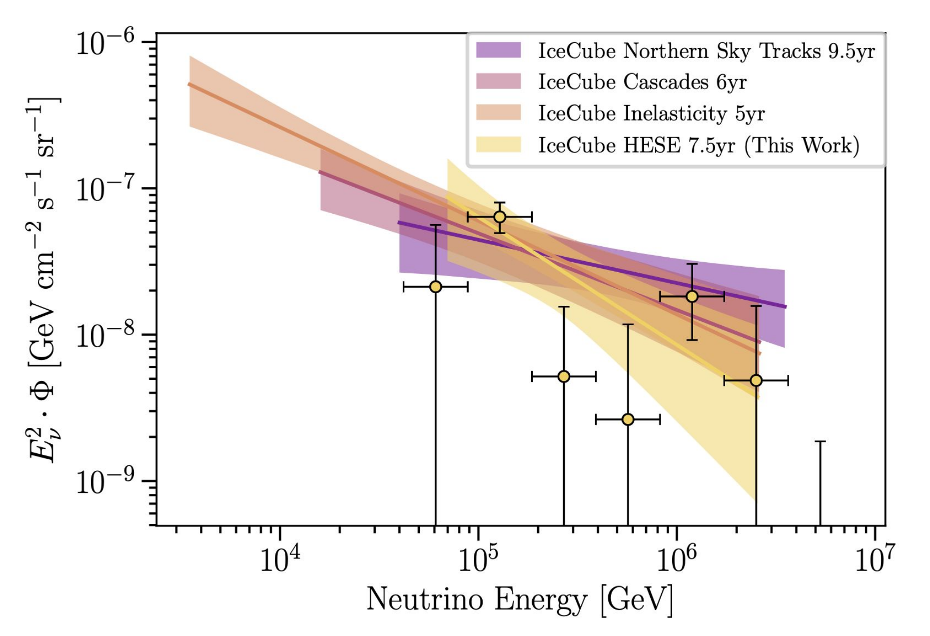


- Initial selection: muon energy > 300 TeV, zenith < 90^o, track length > 600 m, etc.

Snow effect


IceCube Preliminary
2012
2013
2014
2015
2016
2017
2018
2019
baseline
log10(Muon Energy Proxy) [GeV]
7.0
6.8
6.6
6.4
6.2
6.0
5.8
5.6
0
500
1000
1500
2000
2500
Distance to Center of IceTop [m]

Flux



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