A combined analysis of the diffuse astrophysical neutrino flux using IceCube's high-energy through-going muon tracks and cascades

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Contents

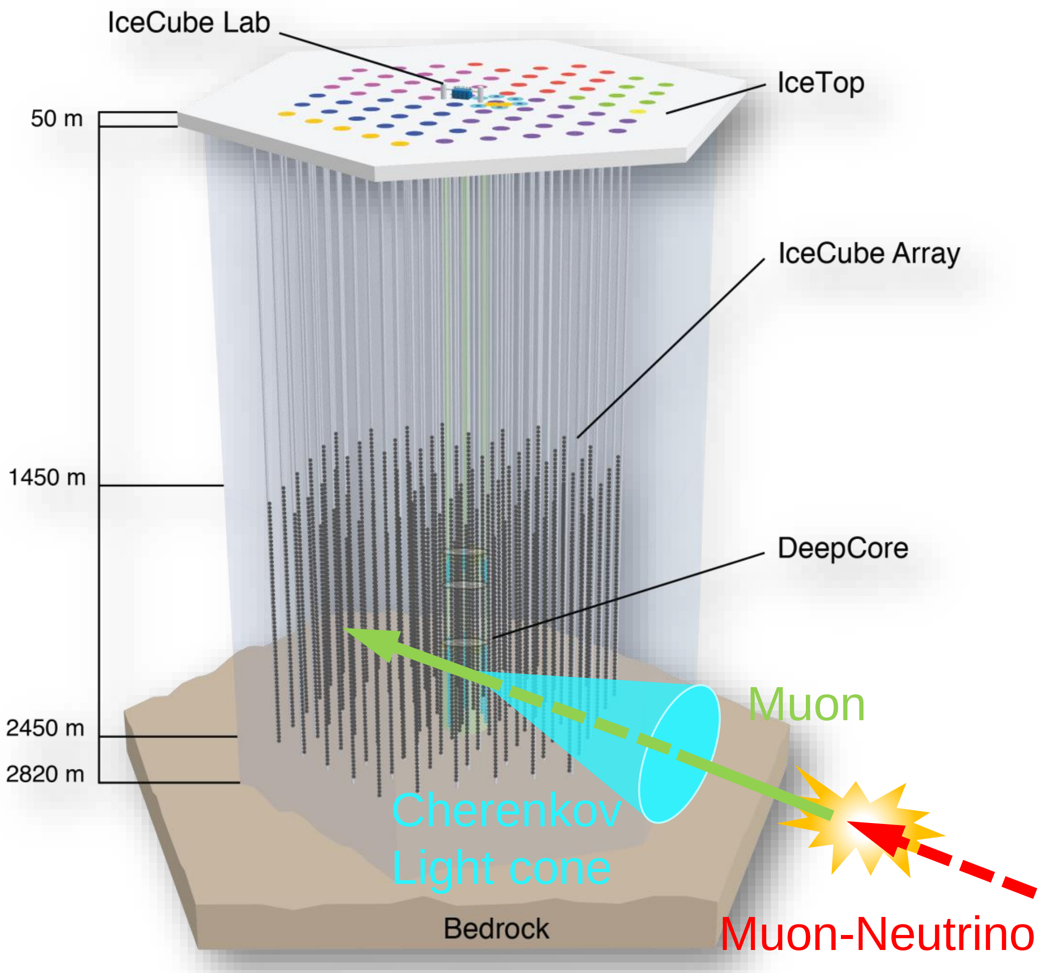
The IceCube Neutrino Observatory

- Neutrino detector at the geographic South Pole

- In-ice detector with 5160 Digital Optical Modules (PMT with onboard digitization) on 86 strings
- 1 km³ instrumented volume in a depth of 1450m to 2450m

- Detecting Cherenkov radiation of secondary particles of ν-interactions

➢ First observation of a flux of high-energy astrophysical neutrinos in 2013
DOI: 10.1126/science.1242856



DOI: 10.1088/1748-0221/12/03/p03012

The Astrophysical Neutrino Flux

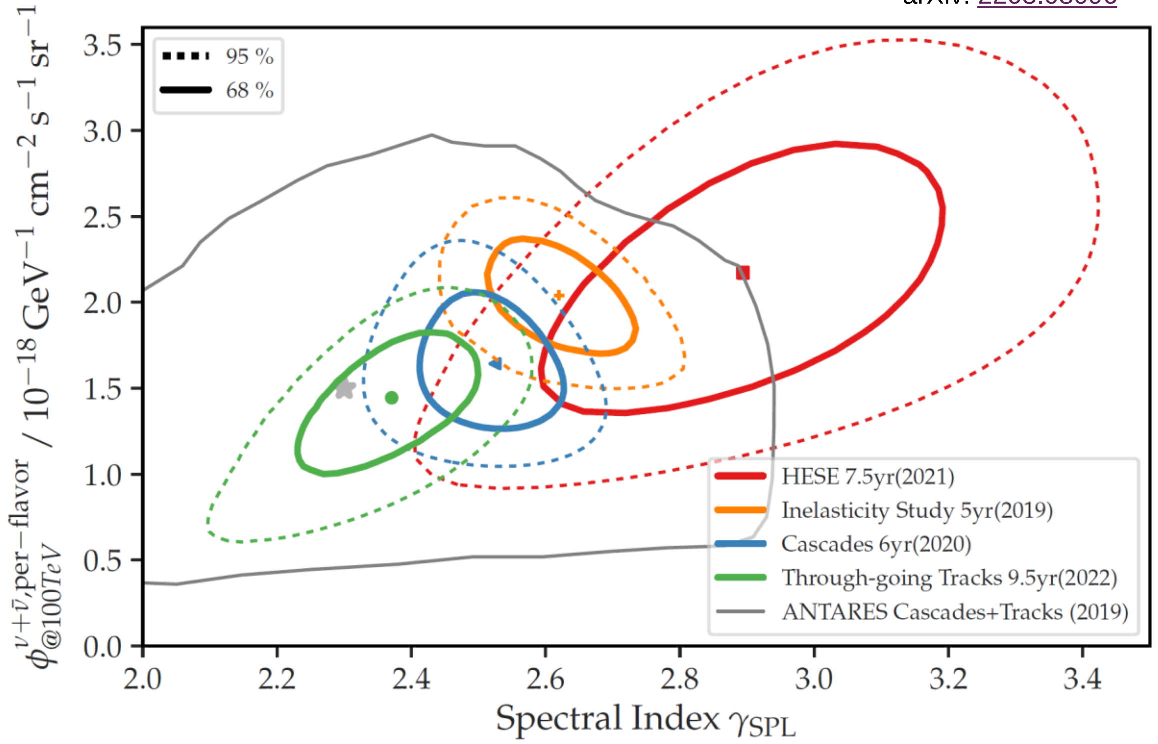
- Typically, the astrophysical neutrino flux is modelled by a (single) power-law with two free parameters, spectral index and flux normalization:

$$\Phi_{astro} = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\gamma}$$

- Confirmation of this flux in multiple different IceCube detection channels, however, the measured flux properties differ:
  - Through-going tracks: harder best-fit
  - Cascades: best-fit in between
  - HESE: rather soft best-fit

- How does the “global” picture of IceCube’s high energy astrophysical neutrino flux look like?
  - Combination of these complementary detection channels in a combined fit of IceCube’s neutrino data
  - First step: through-going muon tracks and cascades

arXiv: 2203.08096



Analysis Method: Binned Likelihood and Forward Folded Fit

Binned likelihood analyses: Comparing experimental data to the simulation-based expectation in a histogram, here, reconstructed energy and zenith angle.

Combined fit: fit for multiple analysis histograms (e.g. through-going tracks and cascades) at the same time:

- Per bin likelihoods add up if analysis histograms are fully de-correlate i.e., there is no overlap between them
- Common and shared basis of all fit (signal + nuisance) parameters

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- Common and shared basis of all fit (signal + nuisance) parameters for a consistent treatment

Key component for a combined fit is the consistent treatment of signal and background as well as systematic uncertainties:

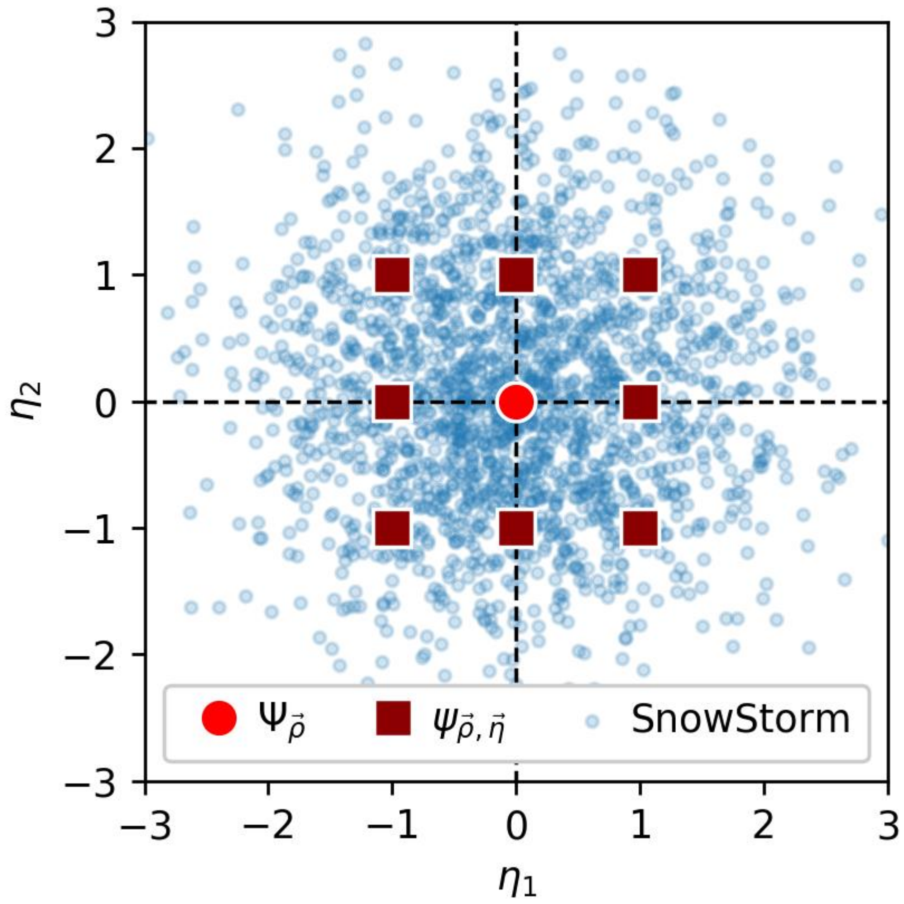
- Most signal and background parameters can be accounted for by re-weighting the MC simulation accordingly: forward-folded fit (e.g., flux normalizations)

- Systematic uncertainties that change the detector response (e.g., properties of the glacial ice, photon sensitivity of the DOMs) need multiple dedicated simulation sets
  - Production of those can be computationally expensive
  - Must find a common basis of dedicated sets that will be used by all event selections that will be combined

The SnowStorm MC Method

"Classic approach":
- Interpolate between multiple discrete simulation sets each using different detector response parameters scattered around a central "baseline" model/set (red)
  - Computationally expensive to produce multiple of these sets with high statistics

SnowStorm Simulation Method (arxiv:1909.01530):
- Continuous variation of nuisance parameters by choosing a different detector response model for each event during simulation based on a pre-defined distribution (blue)
  - Single, multi-dimensional SnowStorm ensemble that includes all (allowed) combinations of nuisance parameters



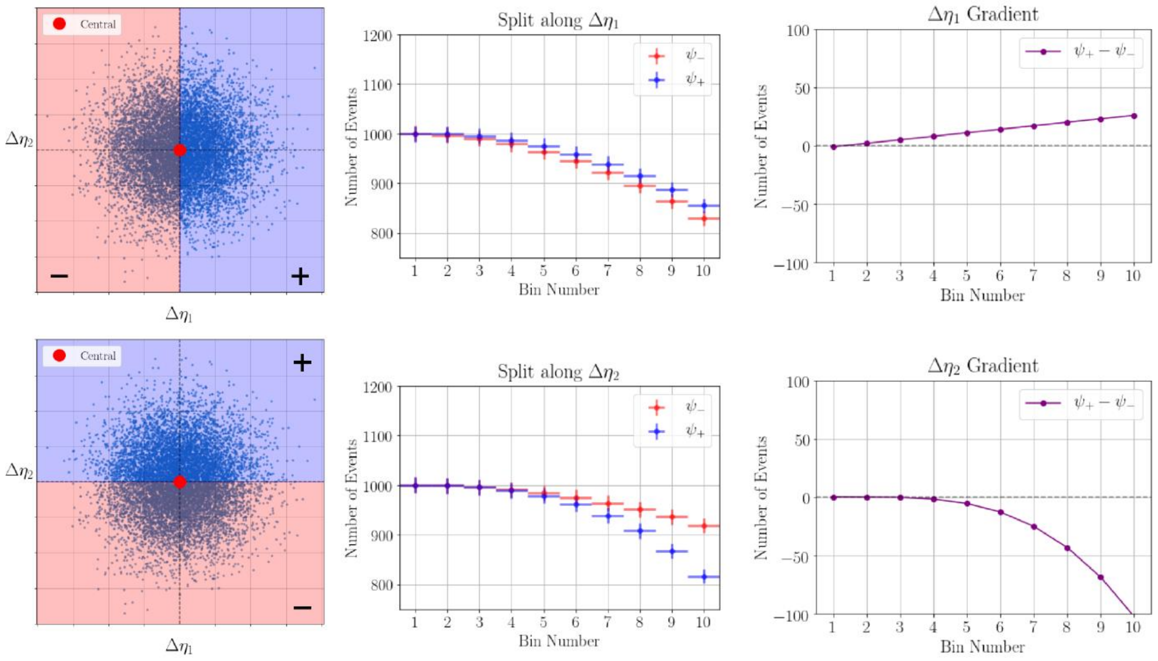
DOI:10.1088/1475-7516/2019/10/048

Application of SnowStorm MC in an Analysis

Extract "nuisance parameter gradient vector" by splitting the SnowStorm ensemble:

- Assuming linearity this can be done independently for each parameter
  - Parameters that don't affect a certain event selection can be "averaged out"
- Gradient vector = change in number of expected events in each bin
  - Proportional to the difference of the "upper/+" and "lower/-" split

➢ Here: **First time application of the SnowStorm method to a high-energy neutrino analysis**
  - ➢ Adapt the simulation technique for efficient high-energy MC production
  - ➢ Verification of the method in the context of high-energy neutrino event selections



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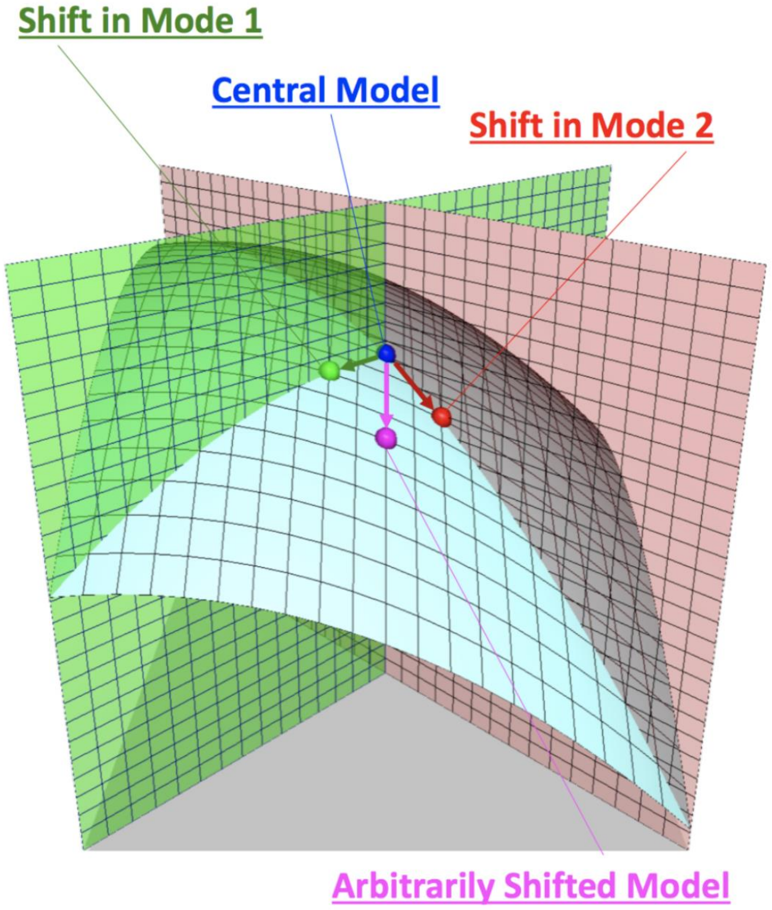
Application of SnowStorm MC in an Analysis

This gradient vector can be used to obtain the prediction for an arbitrarily chosen detector response model:

$$\Psi_{\vec{\rho},\vec{\eta}} = \Psi_{\vec{\rho}} + \vec{\eta} \cdot \vec{G}_{\vec{\eta}}$$

Use the same SnowStorm event ensemble to extract the gradient vectors for all different event selections
→Consistent treatment of the detector systematic uncertainties in a combined analysis by using only a single MonteCarlo simulation set

- Verification of the SnowStorm method for a high-energy analysis: through-going muon tracks



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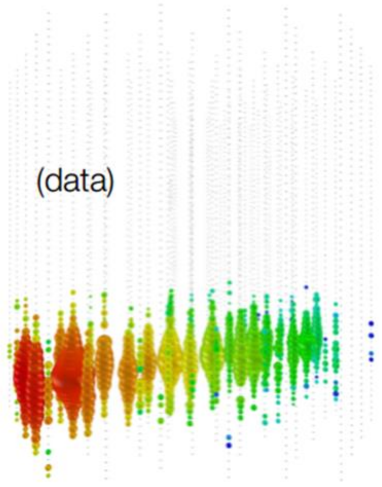
The Through-going Muon Track Sample

- Event selection focused on track like event signatures:
  - Mostly through-going muon tracks from charged current muon neutrino interactions
  - Small additional contribution from muonic tau decays from tau neutrino interactions
- High purity sample (> 99.8%)
  - Using the Earth as a shield against muons from cosmic-ray-induced air showers
  - Additional BDT further separating well reconstructed neutrino-induced muon tracks from mis-reconstructed atmospheric muons
- High statistic sample of more than 600,000 events from 9.5yrs of IceCube's neutrino data



- Track-like events
  - $\nu_\mu + N \rightarrow \mu + X$
- Very good angular resolution, typically <1°

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The Through-going Muon Track Analysis

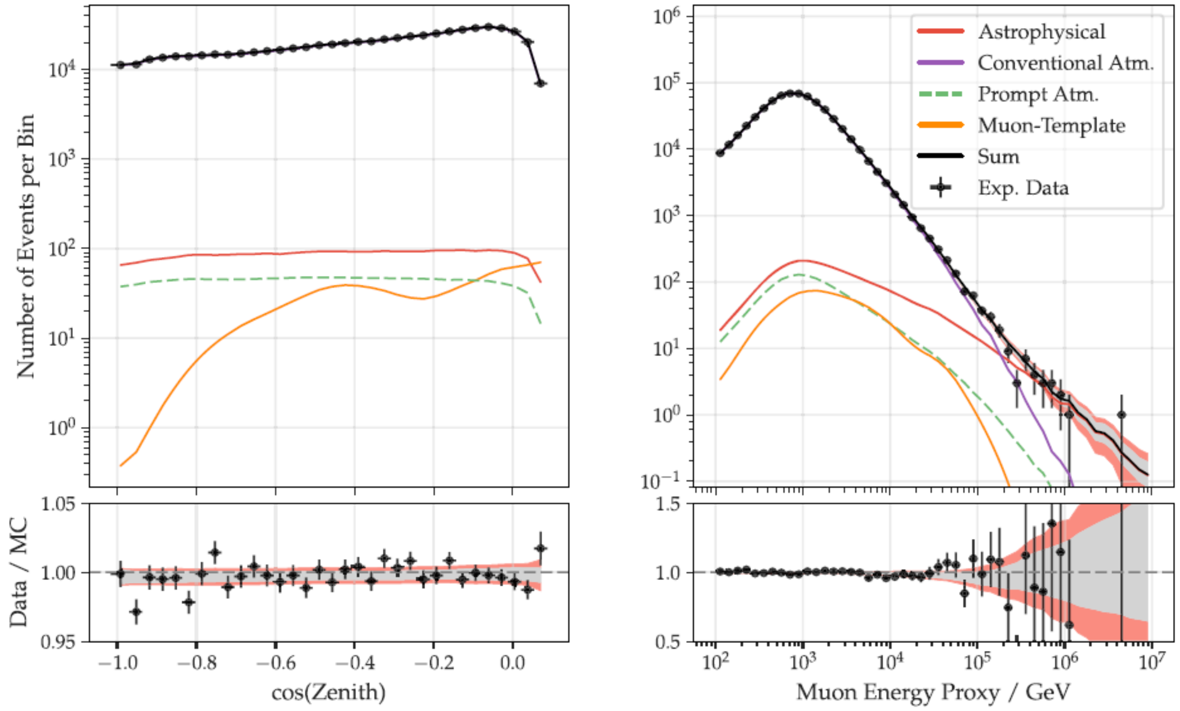
Forward-folded Poisson Likelihood fit for the astrophysical neutrino spectrum in a 2D histogram of reconstructed muon energy and zenith angle

Total flux given by the sum of four individual flux components:

- Conventional atmospheric neutrinos
- Prompt (atmospheric) neutrinos from decay of heavy charmed hadrons

→ Both flux predictions are calculated using the MCEq package

- Atmospheric muons
  - Subdominant contamination
- Astrophysical neutrino signal
  - Cumulative isotropic flux from all sources of high-energy astrophysical neutrinos



DOI: 10.3847/1538-4357/ac4d29

Verification of the Analysis Framework for the Combined Analysis

In preparation of a combined fit of IceCubes neutrino data:

- ✓ Development of an analysis framework that can fit for multiple analysis histograms at the same time
- ✓ Production of a SnowStorm event ensemble simulation set
- ✓ Use of this SnowStorm event ensemble to model systematic uncertainties in the (combined) analysis

- ➢ Verification of the framework and the updated detector response uncertainty treatment (SnowStorm)
  → First step: use the newly developed framework to (re) run the 9.5yr fit of through-going muon track data
- ➢ Next step: use the framework for a combined fit of through-going muon tracks and cascades

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- Next step: use the framework for a combined fit of through-going muon tracks and cascades

In preparation for the (later) combined fit:

- Updated to most recent version of MCEq for calculating the conventional and prompt atmospheric flux contributions
- Updated the baseline detector response and glacial ice model
- Use of a single SnowStorm event ensemble for the treatment of detector systematic uncertainties
- Use only IceCube data from 2010 onwards
  - IC79 and IC86 detector configuration
  - Same data that will be used in the later combined through-going tracks and contained cascades fit

Verification Results: Through-going Muon Track Fit

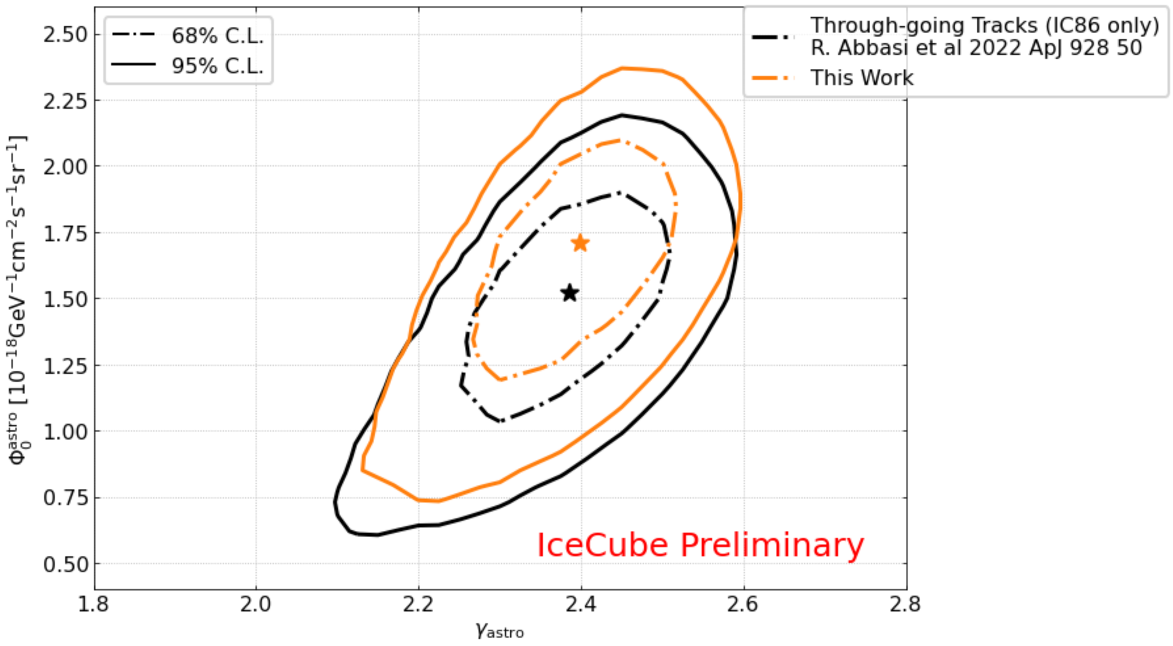
Profile likelihood for the single power-law model of the astrophysical neutrino flux:

- Black: R. Abbasi et al 2022 ApJ 928 50, but only using IC79 + IC86 data
- Results of the new framework using the SnowStorm event ensemble for the detector response modelling
  - This includes the updates with respect to the baseline detector model and the updated MCEq version (previous slide)

✓ Very compatible results

✓ Slight shift exactly as expected based on pseudo-experiments (not shown here)

✓ Successful application of the updated framework and treatment of detector systematic uncertainties



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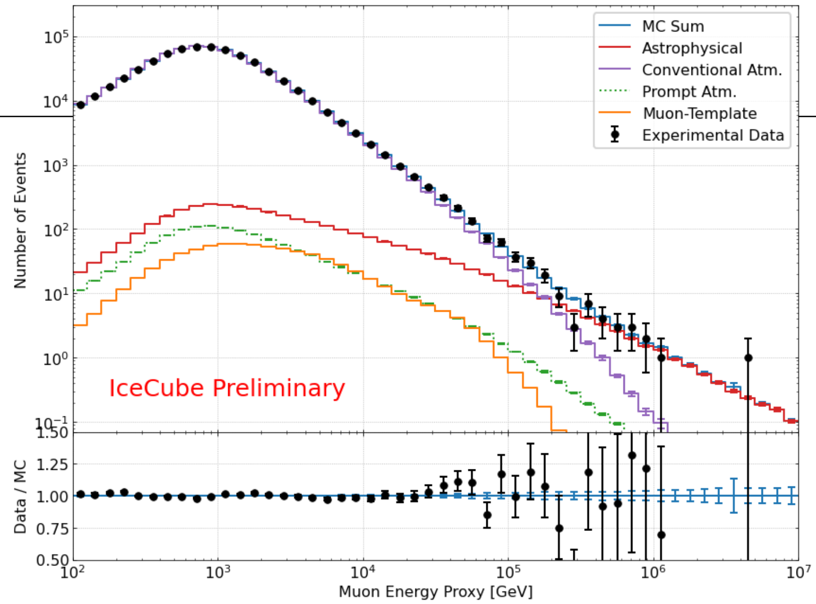
Verification Results: Through-going Muon Track Fit

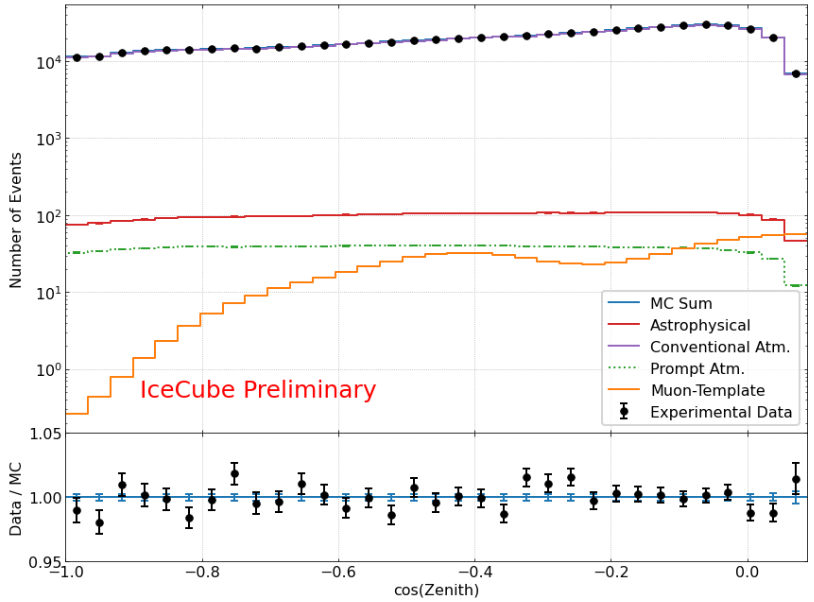
One dimensional best-fit distributions for reconstruceted muon energy (top) and zenith angle (bottom).

Different flux components shown in colors. For prompt, the nominal prediction is shown, although the best-fit normalization is zero

- The error-bars show statistical uncertainty of the simulated data

✓ Good data/MC agreement





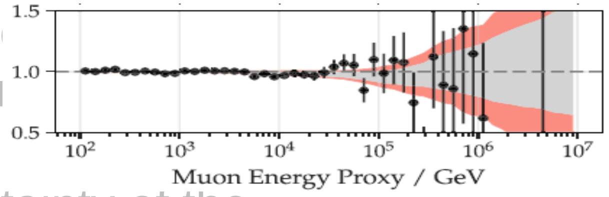
Framework Verification Results

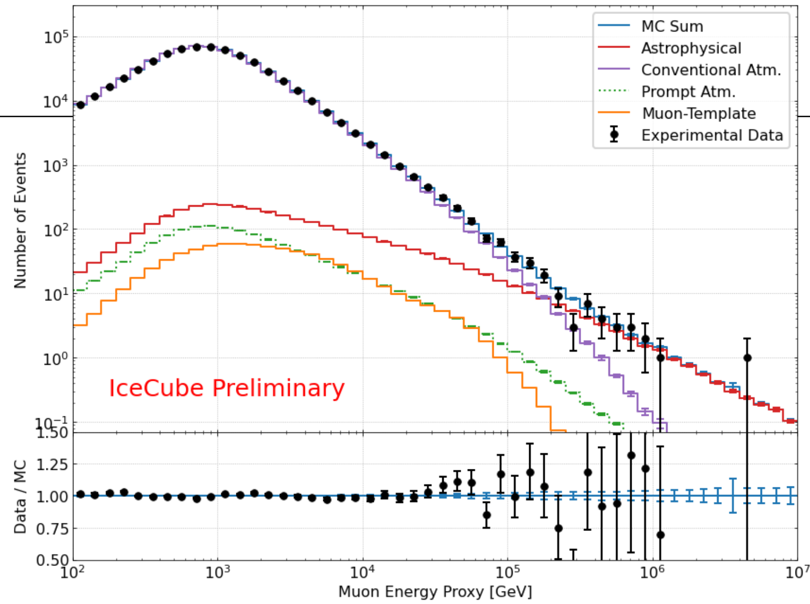
One dimensional best-fit distributions for reconstruceted muon energy (top) and zenith angle (bottom).

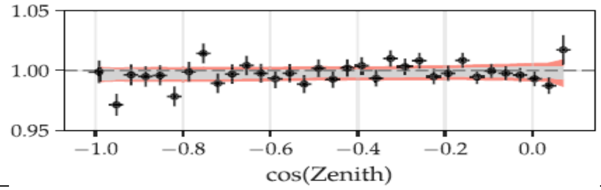
Different flux components shown in col… prompt, the nominal prediction is show… best-fit normalization is zero

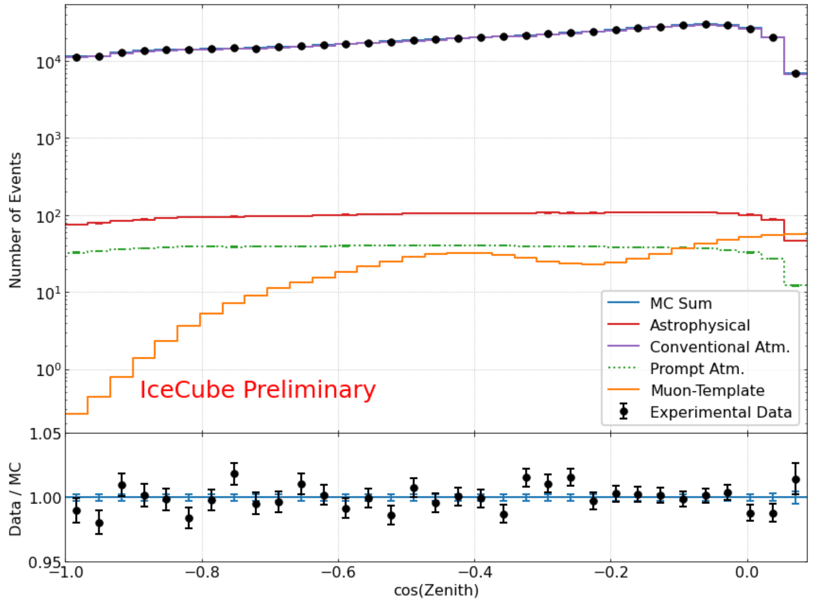
- The error-bars show statistical uncertainty of the simulated data

✓ Good data/MC agreement
✓ Very much in agreement with the 9.5yr result









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Summary

Development of a framework for a combined analysis of multiple of IceCube's detection channels:

- ✓ Using the SnowStorm MC method for simulating the effect of detector systematic uncertainties and propagating them to the analysis
- ✓ Allows combining multiple analysis histograms in a single likelihood fit

- ✓ Successful validation of this new framework and technique for high-energy analysis of the diffuse astrophysical neutrino flux

Summary and Outlook

Development of a framework for a combined analysis of multiple of IceCube's detection channels:

✓ Using the SnowStorm MC method for simulating the effect of detector systematic uncertainties and propagating them to the analysis

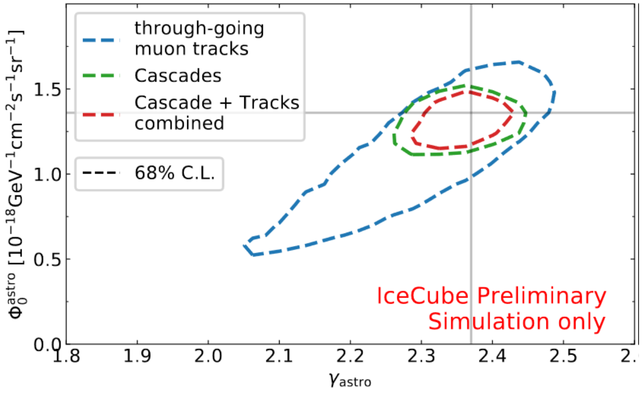
✓ Allows combining multiple analysis histograms in a single likelihood fit

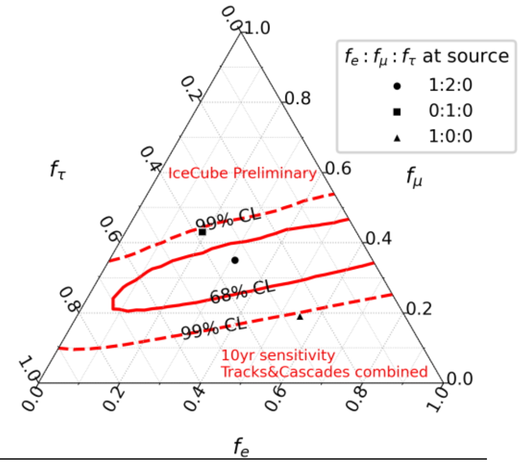
✓ Successful validation of this new framework and technique for high-energy analysis of the diffuse astrophysical neutrino flux

✓ Framework for next generation of combined analyses for the high-energy diffuse flux

Use the framework and method to perform a combined fit of through-going muon tracks and contained cascades

- Improve the measurement of the astrophysical neutrino flux properties and challenge the single power-law flux model
- Fit for the astrophysical neutrino flux flavor composition
  - Not possible with either tracks/cascades alone





Appendix