Angular dependence of the atmospheric neutrino flux with IceCube data

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The IceCube Collaboration

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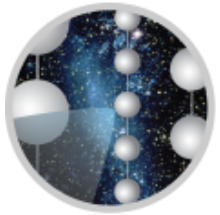

IceCube Neutrino Observatory

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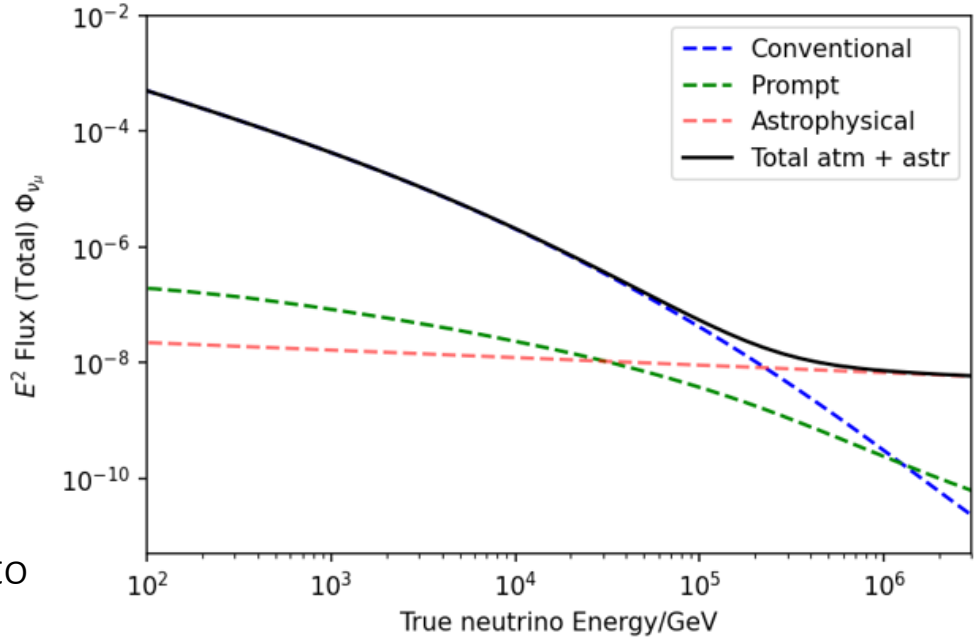
Neutrino flux and its components

The total neutrino flux arriving to Earth is comprised from several sources separated depending on their creation process. We differentiate three components;

- **Conventional:** decay of long-lived particles, majorly π and K
- **Prompt:** decay of short-lived particles usually charmed
- **Astrophysical:** created at astrophysical sources in different mechanisms

Components jointly comprise the total muon neutrino flux aimed to be determined in a model-independent approach in this analysis.



[Expectancy simulated with MCEq]

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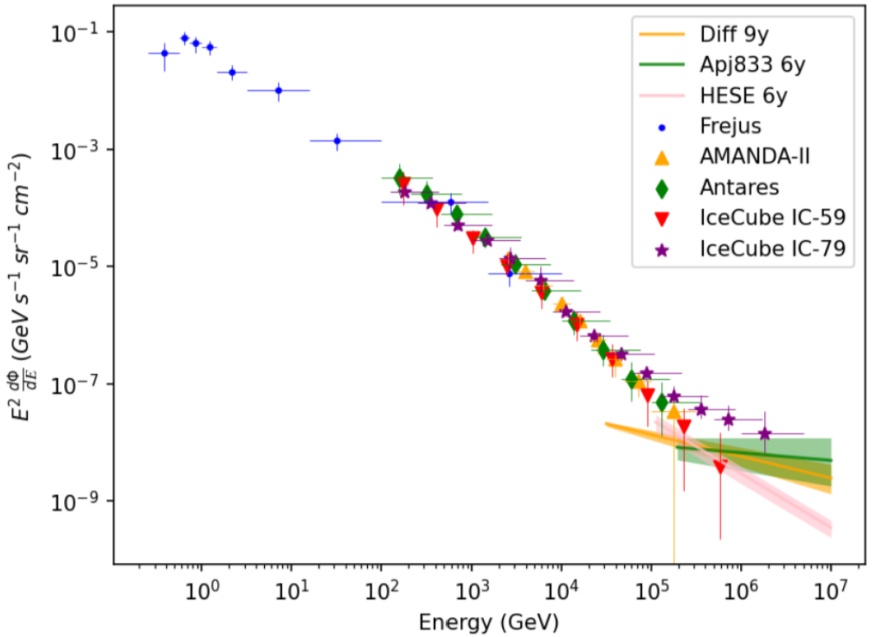
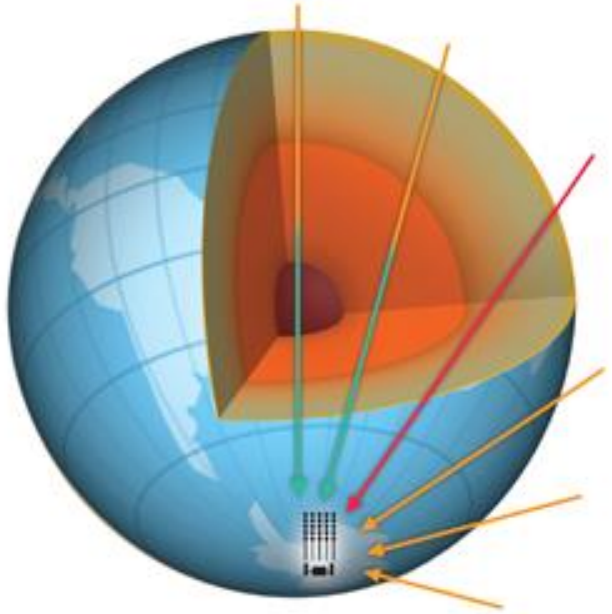
Experimental results of the muon neutrino flux up to date.



Angular dependence

Differences in primary particles of the three components inevitably lead to a zenith dependance arising in Earth's atmosphere.

- **Conventional:** longer mean free path of primaries
- **Prompt:** short mean free path, atmospheric effects irrelevant
- **Astrophysical:** primaries at source, atmospheric effects irrelevant



Credit: IceCube Collaboration

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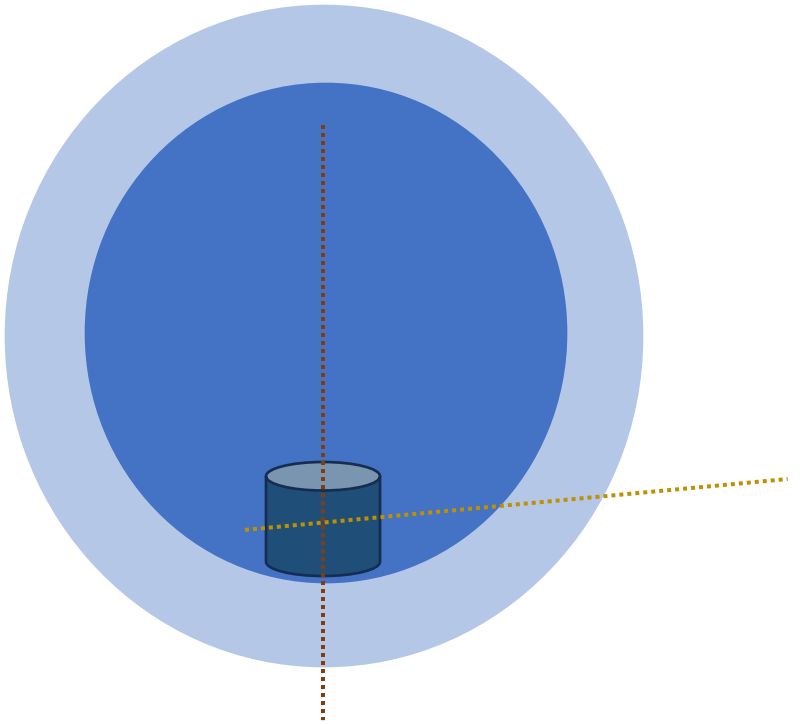

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Longer path in low air density --> fewer secondary interactions --> lower energy loss --> higher energy neutrinos

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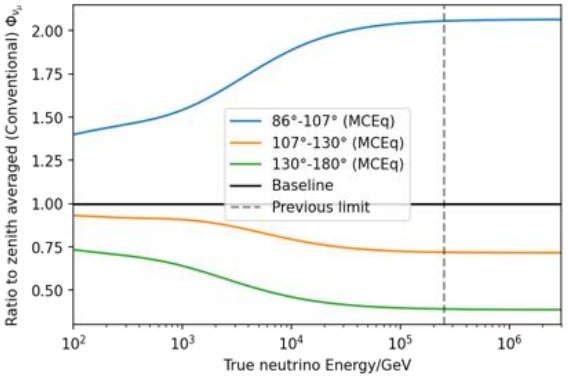
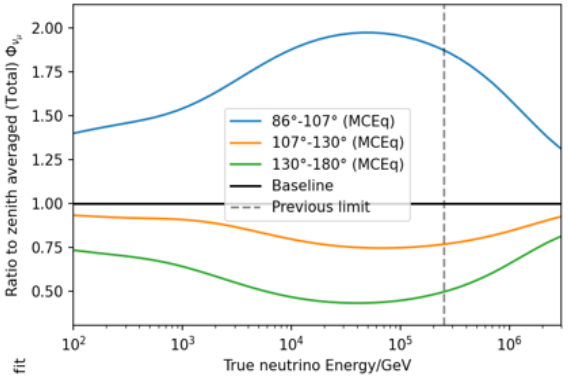
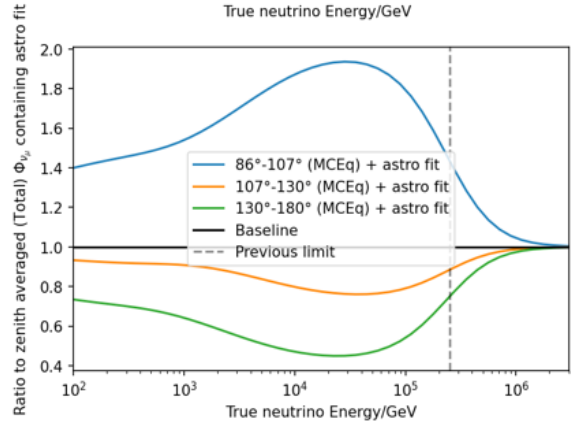


Conventional



Conventional + prompt



Conventional + Prompt + Astrophysical

Unfolding

Model-independent approach to reconstructing convolved variables of interest.

Detector response

Neutrino energy spectrum

Observables ← $g(y) = \int A(x,y)\, f(x)\, \mathrm{d}x + b(y)$ → Background

Discretization

$$\vec{g} = \mathbf{A}\vec{f}\,.$$

Poisson likelihood definition, simplifying

$$l(\vec{g}\,|\,\vec{f}\,) = \sum_{u=1}^{m}\left(g_u \ln\left((\mathbf{A}\vec{f}\,)_u\right) - (\mathbf{A}\vec{f}\,)_u\right) + R(\vec{f}\,)$$ →

Tikhonov regularization: solution assumed to be smooth

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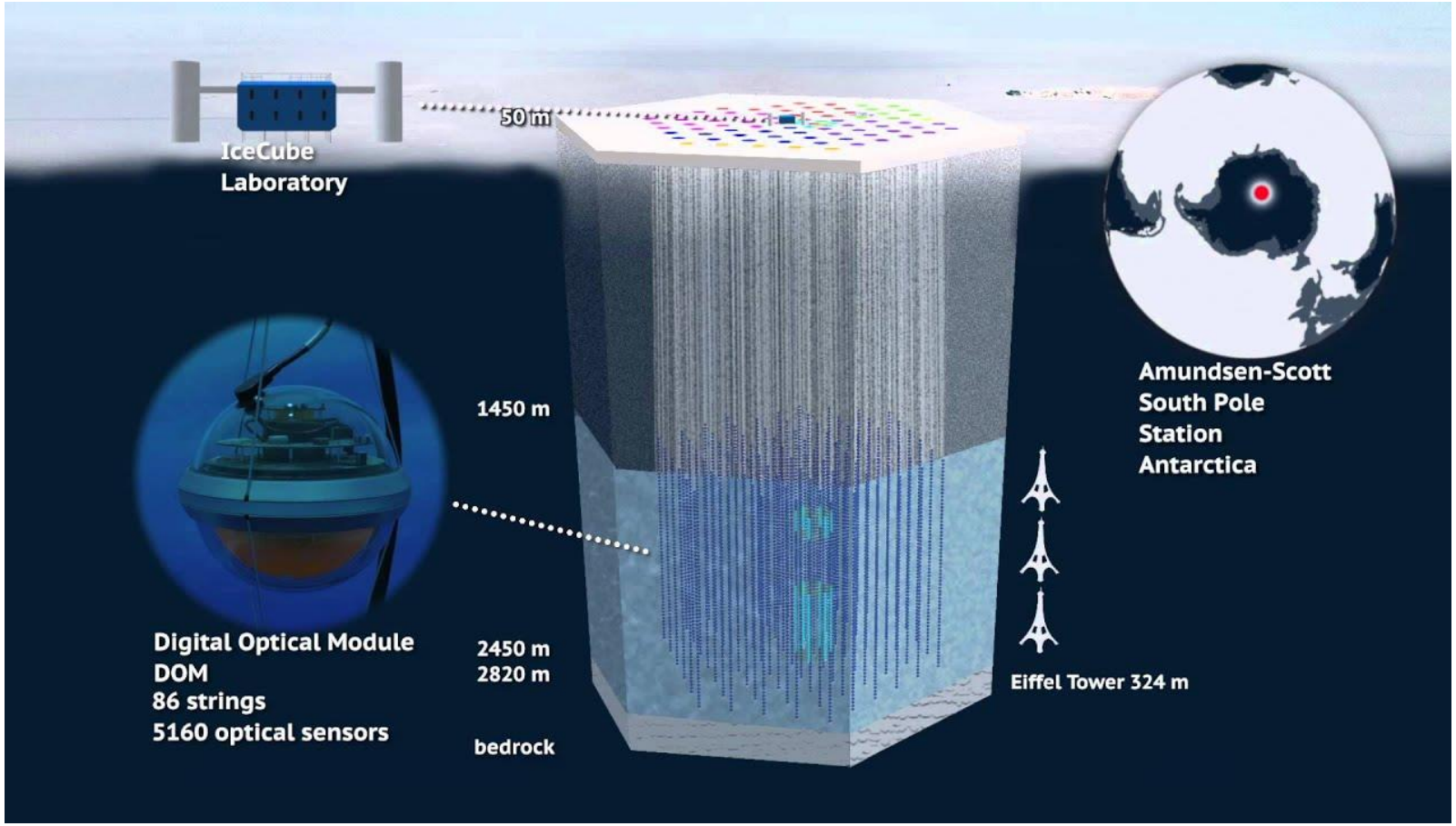
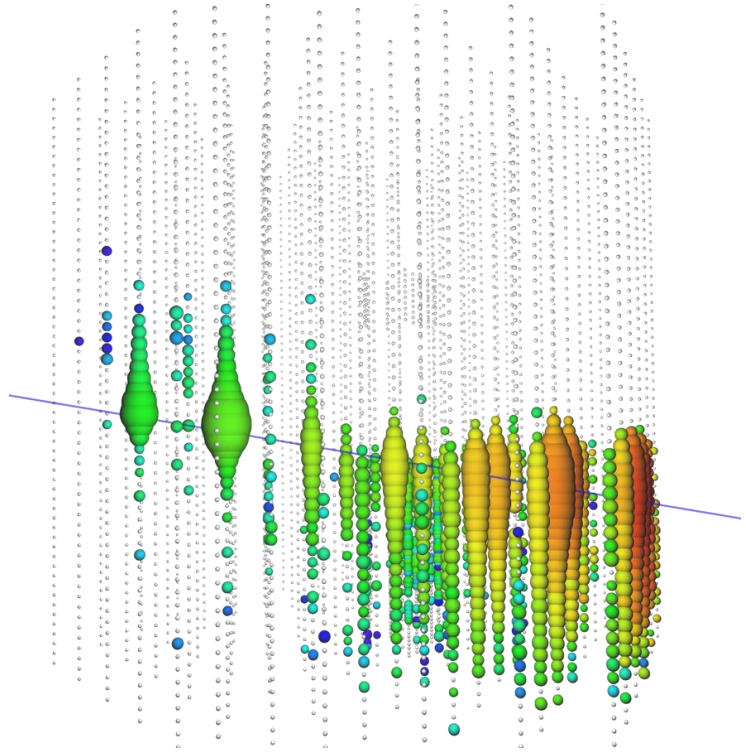
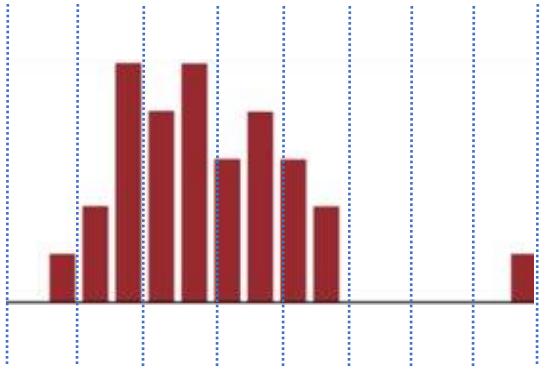




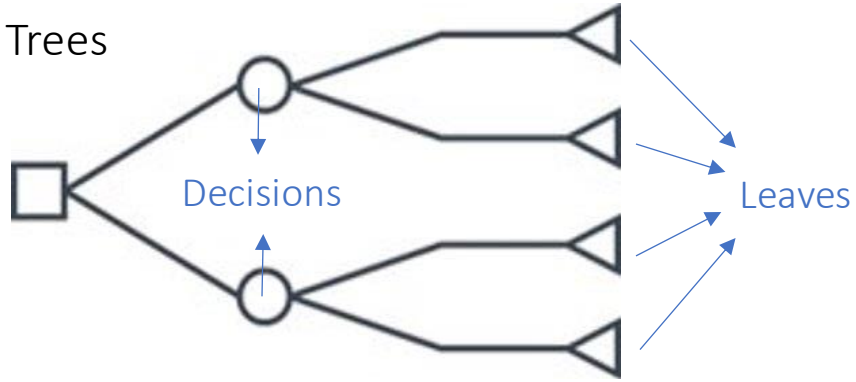
Credit: IceCube Collaboration

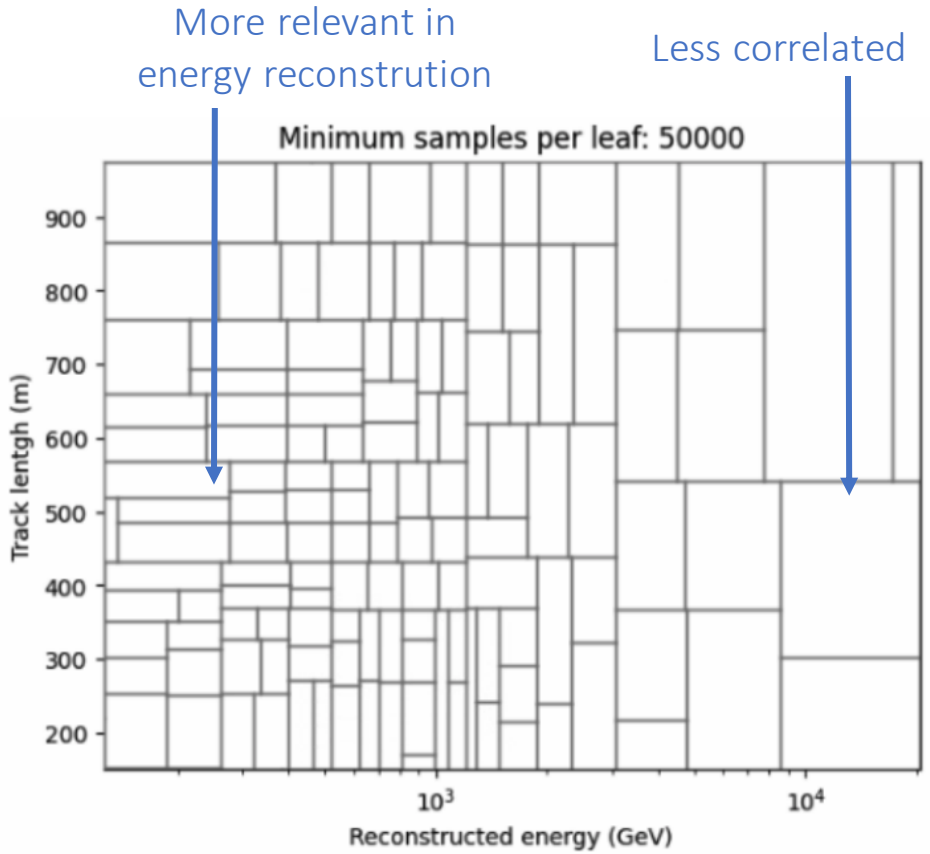
Rebinning the observable space

Finding optimal binning scheme based on the distribution of observables used in unfolding with the goal of ensuring enough statistics and proper information gain.



- Utilizing Decision Trees





Example rebinning scheme. The Trees create denser cuts in regions with higher information gain.

Application of unfolding

Proof of concept: a pseudosample imitating the expectation for the 11 year dataset is unfolded with Markov Chain Monte Carlo walkers.

- Observables chosen in a three-fold feature selection process and rebinned with the aforementioned process.

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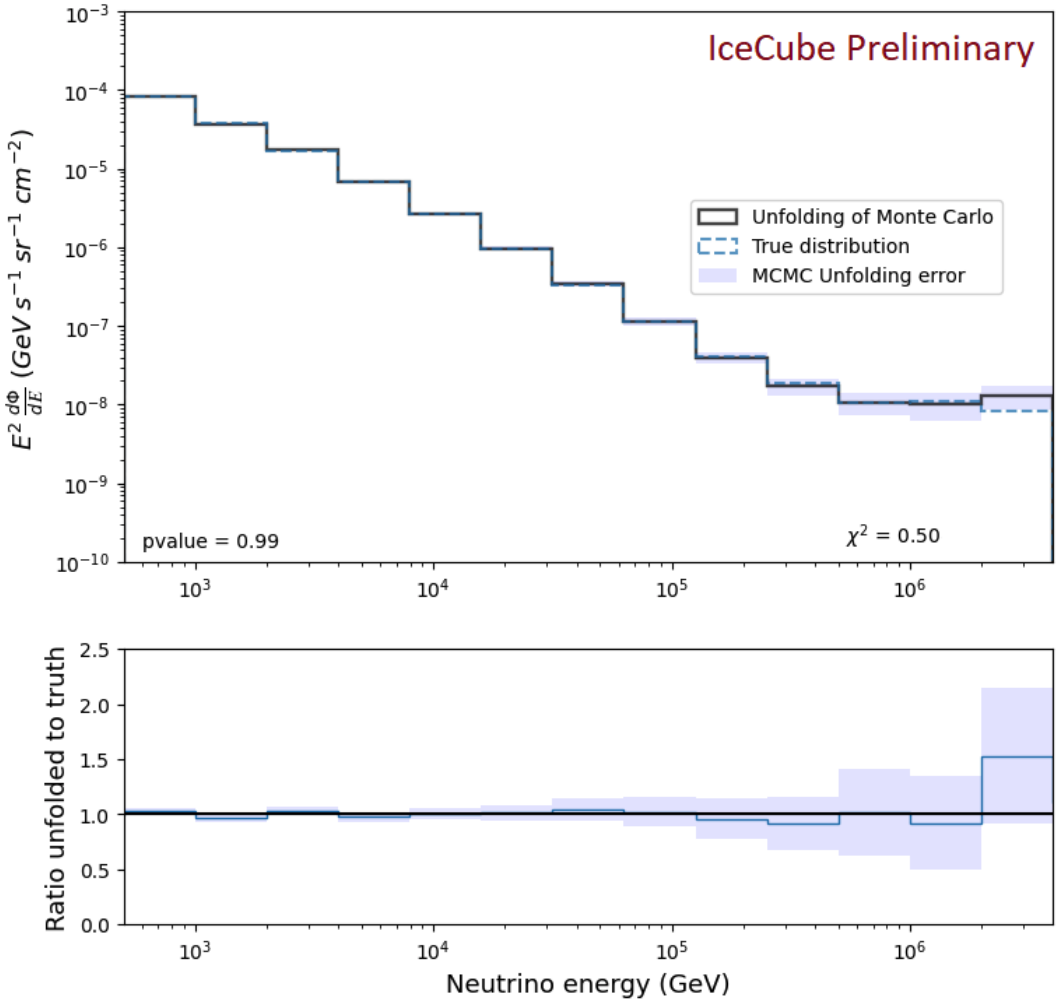
- Observables chosen in a three-fold feature selection process and rebinned with the aforementioned process.
- Unfolding repeated for randomized trials, all reconstructions in good agreement with the corresponding true values and with low statistical uncertainty.



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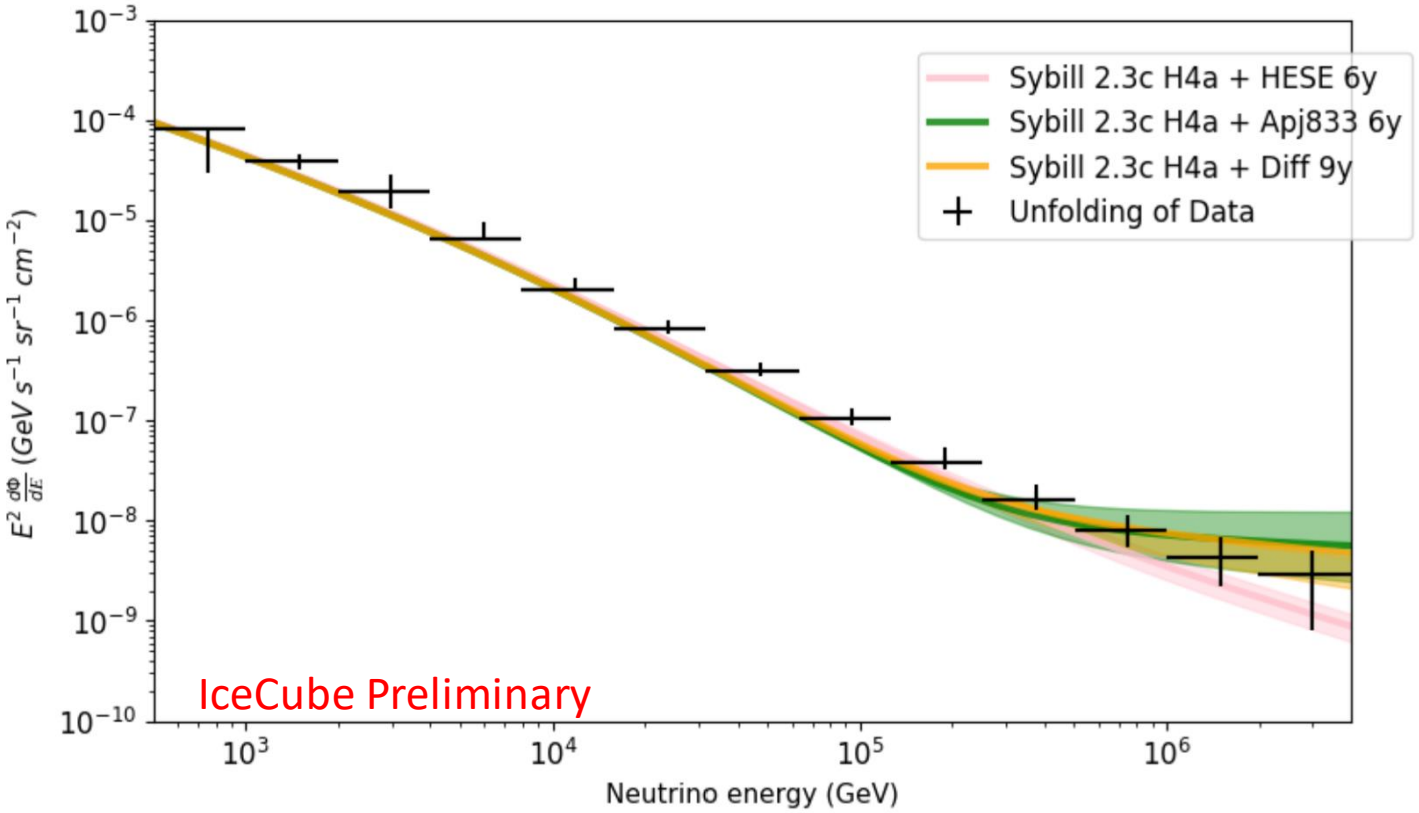
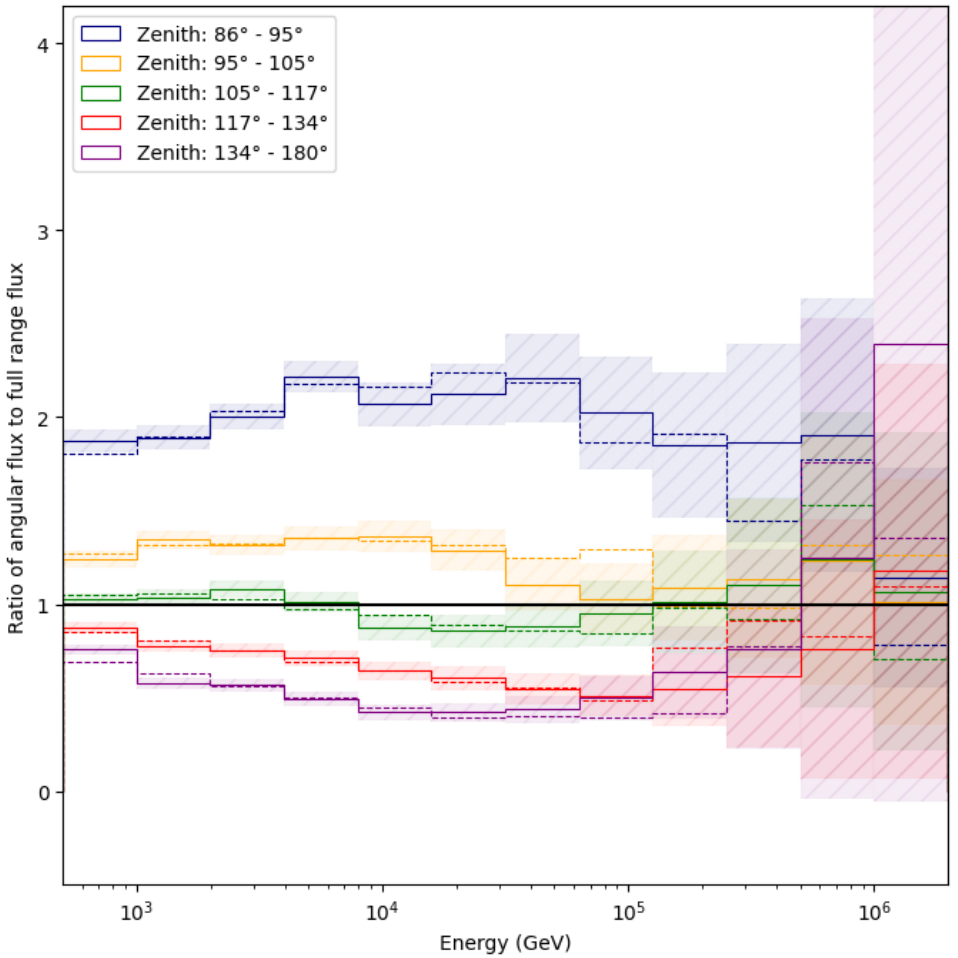


- Results of unfolding 11 years of data
- Atmospheric dominated energy region in good agreement with models.
- Astrophysical dominated region in good agreement with astrophysical fits from other IceCube analyses.
- Crossover region is overestimated in comparison with atmospheric model and astrophysical fit combined prediction.

Angular unfolding

- Five angular bins determined to approximately contain the same number of events, compared to the *baseline* spectrum that covers the full angular range.
- Slightly higher statistical uncertainty due to lower number of events in zenith bins In comparison to expected uncertainty of the full dataset.
- Discrimination of zenith fluxes possible up to 1 PeV with the assumed model and lifetime.



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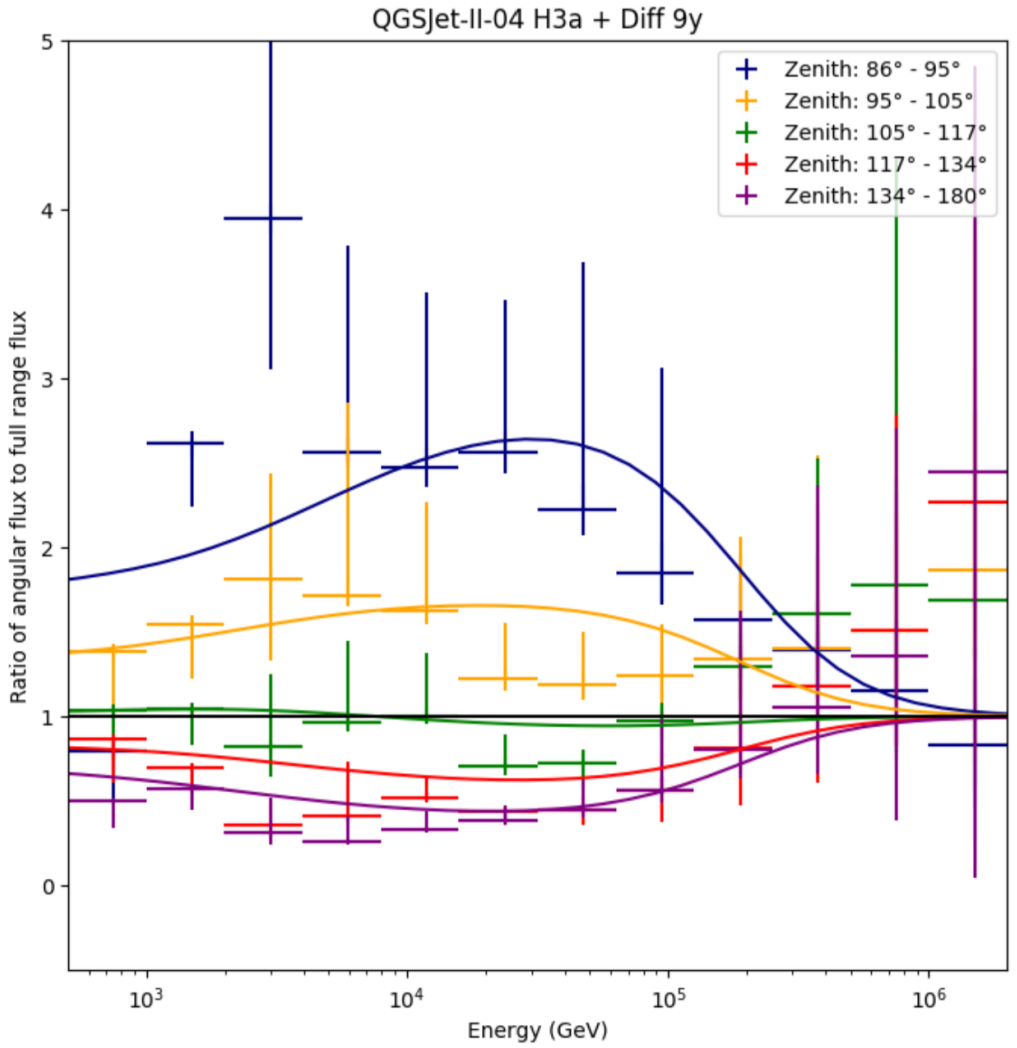
- Discrimination of zenith fluxes possible up to 1 PeV with the assumed model and lifetime.
- Results show support for the assumed anisotropic behaviour coming from the conventional contribution.



Conclusion and Outlook

- Presented a rebinning approach applicable to both unfolding and any other areas with the goal of equalizing statistical errors across the entire sample.
- Presented a bin-wise model-independent unfolding algorithm with promising results in flux measurement.
- Flux unfolding in good agreement with predictions, lowest statistical error in measurements up to date.
- Angular unfolding proven as concept, the expected anisotropic behaviour confirmed on the case of five zenith band unfolding in this work. Unfolding possible up to PeV energies.

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Thank you for your attention!