Using End-to-End Optimized Summary Statistics to Improve the Measurement of Neutrinos from the Galactic Plane with IceCube

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Abstract: Characterizing the astrophysical neutrino flux with the IceCube Neutrino Observatory traditionally relies on a binned forward-folding likelihood approach. Insufficient Monte Carlo (MC) statistics in each bin limits the granularity and dimensionality of the binning scheme. A neural network can be employed to optimize a summary statistic that serves as the input for data analysis, yielding the best possible outcomes. This end-to-end optimized summary statistic allows for the inclusion of more observables while maintaining adequate MC statistics per bin. This work will detail the application of end-to-end optimized summary statistics in analyzing and characterizing the galactic neutrino flux, achieving improved resolution in the likelihood contours for selected signal parameters and models.

Galactic Plane with IceCube

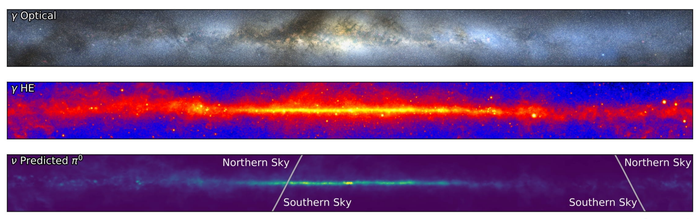
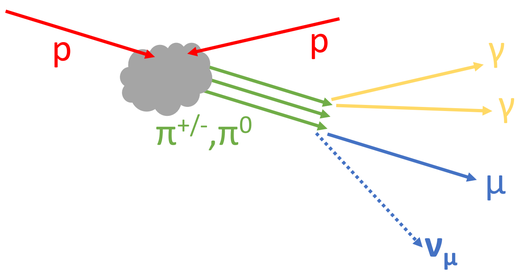


Image from [1]



Cosmic ray protons interact with gas in the Galaxy. The resulting pions decay into gamma rays and neutrinos.

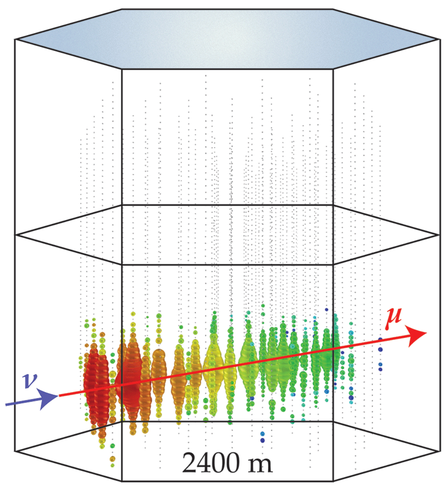


Illustration: Adapted from APS/Joan Tycko; Neutrino event: IceCube

More than 5000 light sensors (DOMs) can detect the Cherenkov light from neutrino interactions in the ice at the South Pole. For this analysis only tracks from the northern hemisphere are included, using the Earth as a shield against atmospheric muons.

From the light detected by the DOMs, event information is reconstructed, e.g., the energy and arrival direction of the neutrino. Those are used to differentiate galactic neutrinos from atmospheric or other astrophysical neutrinos. This is done using a forward folding likelihood approach.

Summary Statistics

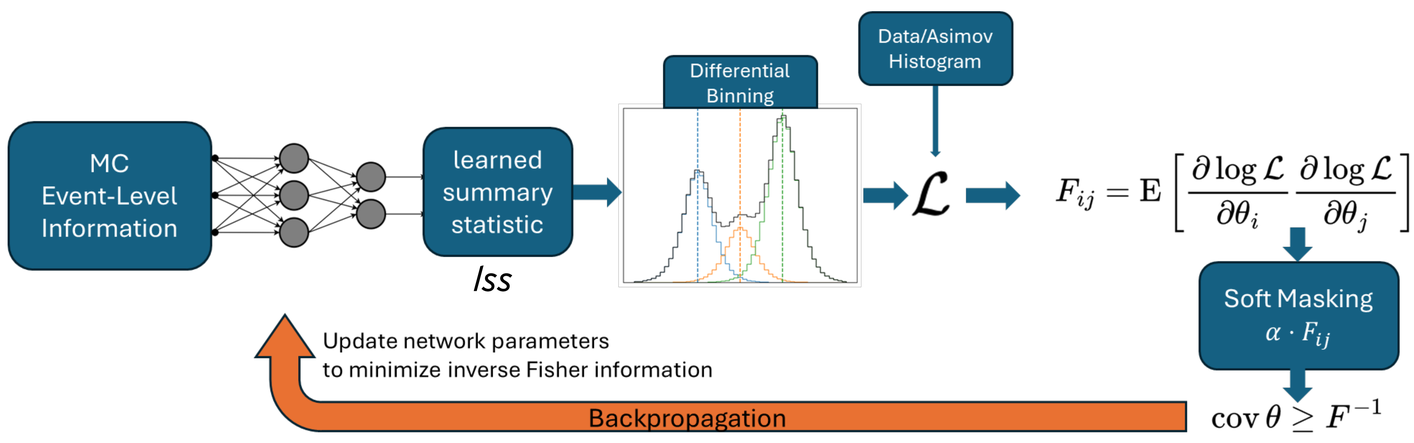
$\mathcal{L}$

Maximize likelihood to find estimate for signal parameters

MC → Expectation

Signal parameter θ
Nuisance parameter η

Workflow



Fisher Information

Estimate Likelihood contour using Fisher Information & Cramér Rao bound

$$F_{ij} = E\left[\frac{\partial \log \mathcal{L}}{\partial \theta_i} \cdot \frac{\partial \log \mathcal{L}}{\partial \theta_j}\right]$$

$$\mathrm{cov}\,\boldsymbol{\theta} \geq F^{-1}$$

For Poisson likelihood:

$$F_{ij} = \frac{1}{\lambda}\frac{\partial \lambda}{\partial \theta_i}\frac{\partial \lambda}{\partial \theta_j}$$

Soft Masking

During training, the Fisher Information per bin is multiplied with a masking factor α_k to remove bins with insufficient MC statistics.

$$\alpha_k = 1 - \left(1 + \exp\left(\frac{\delta_k - t}{z}\right)\right)^{-1}$$

δ_k is the relative uncertainty on the expectation value in that bin and gets smaller with more MC statistics. t and z are tunable hyperparameters.

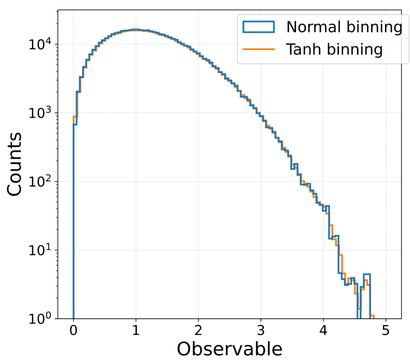
Differential Binning

Obtain the expectation value in each bin using the per event weights w_i and the indicator function I:

$$\lambda_k(\theta) = \sum_i w_i(\theta) \cdot I(lss_i)$$

Differential indicator function used here:

$$\mathrm{I_i} = tanh\left(\frac{\left(lss_d - b_{i_d}^{(d)}\right)}{s_d}\right) \cdot tanh\left(\frac{\left(b_{i_{d+1}}^{(d)} - lss_d\right)}{s_d}\right) + 1$$

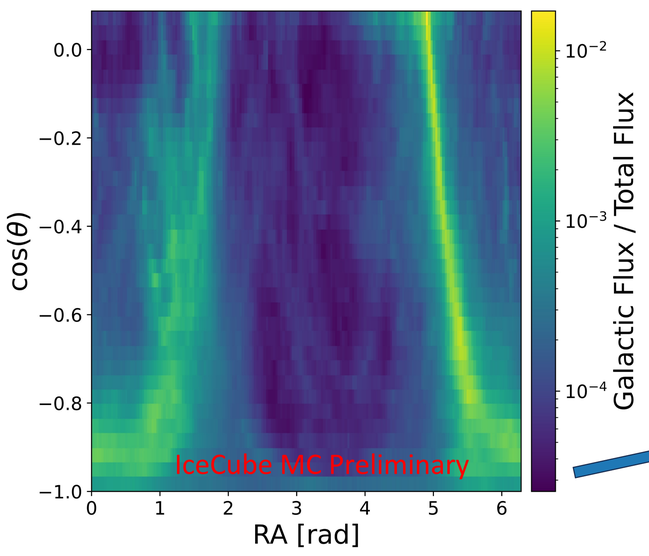


The differential binning method using tanh successfully approximates the original histogram. Here the slope parameter *s* was chosen to be the bin width of the original binning.

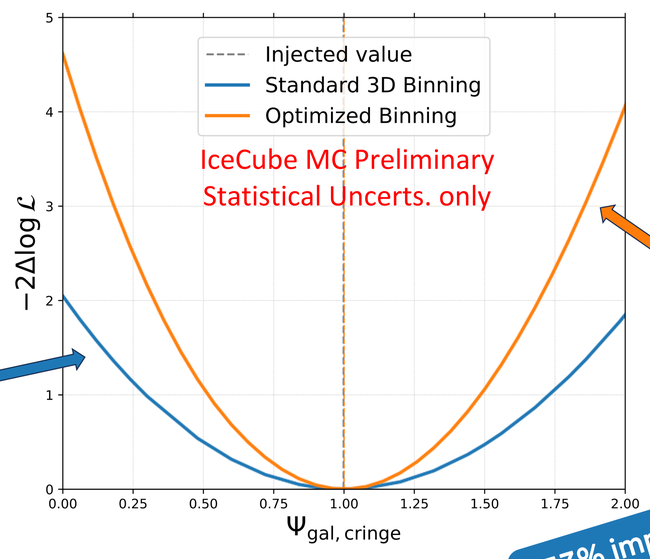
A multidimensional binning is obtained by calculating the outer product over the individual dimensions

$$I_{i_1,\ldots,i_D}(lss_1, \ldots, lss_D) = \bigotimes_{d=1} I_{i_d}(lss_d)$$

First MC only Results

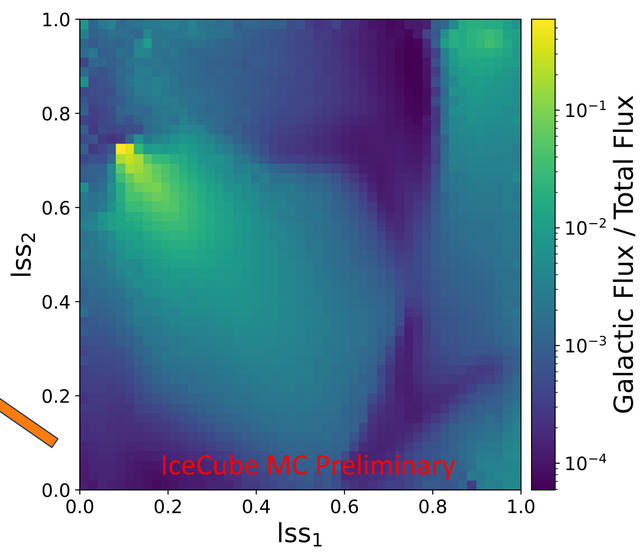


2D Projection of Standard Binning
Using 45 bins in log(energy),
33 bins in cos(zenith),
180 bins in right ascension



Normalization of the galactic template using the CRINGE model[2]

~33% improvement on 1σ intervall



Optimized Binning
Using 40x40 bins
Inputs: Energy, zenith, right ascension, angular uncertainty + other reconstruction quality parameters

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[1]IceCube Collaboration*†, Observation of high-energy neutrinos from the Galactic plane. Science380,1338-1343(2023). DOI:10.1126/science.adc9818
[2]Schwefer, G., Mertsch, P., & Wiebusch, C. W. (2023). *Diffuse emission of Galactic high-energy neutrinos from a global fit of cosmic rays. The Astrophysical Journal, 949*(1), 16. DOI:10.3847/1538-4357/acc1e2

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