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Investigating the AGN-neutrino connection with public IceCube data

Julian Kuhlmann[1,*] and *Francesca* Capel[1]

[1]Max Planck Institute for Physics
Boltzmannstraße 8, 85748 Garching

Abstract. We present the first application of a newly developed hierarchical Bayesian analysis framework for the detection of point-like sources of high-energy neutrinos. We verify that we are able to reproduce the results of the standard frequentist approach for the case of NGC 1068, a Seyfert II galaxy. Our results are robust against reasonable variations of the spectral index prior. However, simulated event rates of mainly atmospheric events do not agree with measurements, presumably due to the binning of the provided instrument response function. We propose an adaptation for the issue and draw a coherent picture of the impact on point source analyses. For future studies moving from finding to characterising sources of high-energy neutrinos the accuracy of the detector response is pivotal for drawing conclusions about the source spectrum.

1 Introduction

In 2013 the IceCube neutrino observatory [1] first observed astrophysical neutrinos with a partial detector configuration [2]. Since completion, a diffuse flux of astrophysical neutrinos has been found [3], transient events of blazars have been observed [4] and Seyfert galaxies are emerging as the first source class [5, 6]. NGC 1068, an x-ray bright Seyfert II galaxy at a distance of $\sim 11\,\mathrm{Mpc}$, coincides with the hottest spot in sky scans for point sources and in catalog searches when included, e.g. [7].

Making use of 10 years of public IceCube data [8], we apply a novel Bayesian hierarchical framework for fitting point sources [9] to the case of NGC 1068. In this framework we model source components and detection effects as a mixture of inhomogeneous Poisson point processes and explore the parameter space through a Hamiltonian Monte Carlo algorithm. Model components are an atmospheric neutrino background, astrophysical diffuse emission and a proposed point source. The latter two are modelled as power-laws, while the atmospheric background's spectral shape is fixed and derived from MCEq [10]. In this proceeding, we investigate the influence of different priors, as well as the binning of the instrument response function (IRF). The latter induces a mismatch between expected and observed event rates, for which we propose an interim solution.

2 Bayesian analysis of NGC 1068

We select data in a circular region of interest (ROI) of 4.98° radius, avoiding contamination by atmospheric muons below −5° declination, around the source location of NGC 1068,

*e-mail: kuhlmann@mpp.mpg.de

RA = 40.67°, DEC = −0.01°. Free source parameters are the luminosity L and power-law spectral index γ, allowed to vary between 1 and 4. From both L and γ we can derive an expected number of source events, $\bar{n}$. For the parameterisation of background models and choice of priors we refer to [9]. Furthermore, we do not marginalise over neutrino energies as is done in standard methods [11], but model them as latent parameters, leading to $\mathcal{O}(10^3)$ free model parameters. We compare our results against maximum likelihood estimates (MLEs) obtained using `SkyLLH` [11, 12], which implements a frequentist approach to determining source properties.

2.1 Priors

First, we analyse the impact of using informative priors on the spectral index. Assuming we have a theoretical prediction for the spectral shape, we are able to strongly constrain the spectral index. We can then investigate if such a point source is present, imposing an uninformative prior on the luminosity. We perform two fits to the data: one with an uninformative normal prior on the spectral index, $\mathcal{N}(2.5, 1.5)$, and one taking the recent results of IceCube [7] as prior input, $\mathcal{N}(3.2, 0.2)$. Marginal posterior densities of $\bar{n}$ and γ are shown in Fig. 1. In both cases our results are compatible with MLEs found using `SkyLLH`. The $\bar{n}$ posterior is unaffected by the varying spectral index prior and in both cases slightly underestimates the number of source events. For the uninformative prior, the γ posterior peaks at ~ 2.8 and the MLE lies in the posterior's tail. In the informative case, the posterior pulls away to harder indices, hinting that the data itself is very much informative in its own right. We conclude that the spatial clustering of events itself can provide a constraint on the number of clustered events, while their energies impose a subdominant constraint on $\bar{n}$.

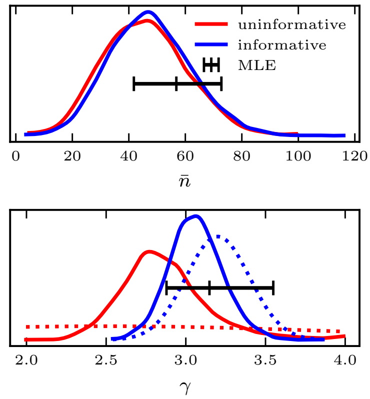

Figure 1: Posterior distributions (solid lines) and prior distributions (dotted). MLEs with 1σ uncertainties are shown in black.

2.2 Modifying the instrument response function

To account for the dominant contribution of atmospheric muons from the Southern sky, IceCube utilises different event selections above and below a declination of −5° [8]. Yet, the provided IRFs average over this discontinuity from −10° to 10° declination. We analyse the consequences of this binning choice and propose an interim solution to increase the sensitivity of analyses.

We calculate expected event rates for the detector configuration "IC86_II" between −5° and 10° declination by forward folding the atmospheric neutrino spectrum through the detector response. We compare the measured event rates to predicted ones, using the provided ("default") IRFs, in Fig. 2. Around TeV energies event rates are 25% higher than expected, below rates are lower by up to 50% than simulations suggest. In `SkyLLH` this issue does not arise due to the entire dataset being used to generate the background distribution. In contrast, we forward-model all backgrounds and point sources. While this enables us to model neutrino energies as free parameters, it prevents us from directly generating the background distribution from the data itself.

We propose to modify the IRFs between 10^2 GeV and 10^3 GeV neutrino energy by applying a linear transformation to the bins of reconstructed energies $\hat{E}$. By building a binned

Poisson likelihood of predicted and measured event rates we can fit the linear parameters and construct a modified IRF, predicting event rates closer to the observations.

Predicted event rates using this modified IRF are shown for comparison in Fig. 2. Relative deviations are now on the level of 10% at the energies of maximum event rates. While this approach is somewhat arbitrary in the choice of transformation, it is data-driven and tries to be minimally invasive in the IRF. Furthermore, determining parameters of the linear transformation requires large runtimes despite parallelisation and tested optimisers are prone to ending in local maxima of the likelihood. We therefore restrict the following analysis to the detector configuration "IC86_II", where, due to the large statistics available, the result is robust.

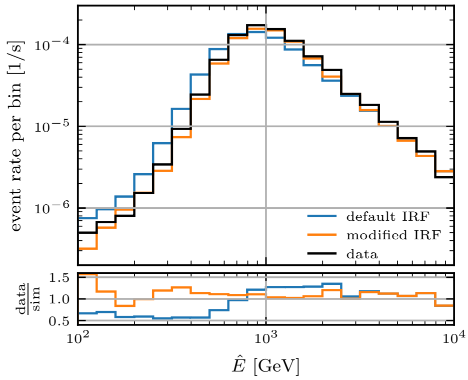

Figure 2: Measured and simulated event rates. Bottom panel shows ratio between simulation and data.

To isolate the effect of the modification of IRFs on the result of point source searches, we first fit a model to NGC 1068 using the unmodified IRFs and an uninformative spectral index prior. The 68% credible region of the resulting joint posterior of $\bar{n}$ and γ is shown as salmon-coloured contour in Fig. 3. For comparison, confidence levels obtained with SkyLLH (using the unmodified IRFs) are shown as grey lines. We already see that the MLE is now contained within the 68% credible region, whereas it was on the edge when utilising the entire data set. Finally, we fit a model using the modified IRFs (blue contour), again placing an uninformative prior on the spectral index. We are almost able to reproduce the result of SkyLLH. The number of excess events remains slightly underestimated, but the index is fully consistent, including the flat profile to very soft indices of ~ 4.

In marginalising over the neutrino energies, the summed event rates depicted in Fig. 2 directly enter the likelihood for the atmospheric background component. As a result of mismodelling, we underestimate the atmospheric component at energies above $\hat{E} \approx 7 \times 10^2$ GeV and overestimate it below. Assuming the spatial information can put some constraint on $\bar{n}$ (consistent with the results of Sec. 2.1), we attribute higher energy background events to the point source and, vice versa, associate lower energy events with the background, leading to a harder inferred spectral index.

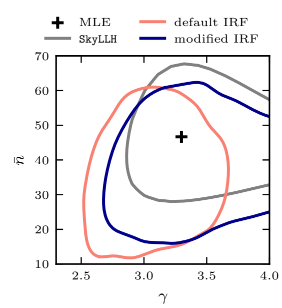

Figure 3: Joint posteriors of $\bar{n}$ and γ, using data of IC86_II only.

3 Conclusions

We analyse 10 years of public IceCube data for neutrino emission from the direction of NGC 1068 utilising a novel Bayesian analysis framework. To a good extent we are able to reproduce published results. We find that the data itself is informative enough to overrule a constraining prior distribution while the excess number of events is stable against this modelling choice. An apparent mismatch between data and simulation may be responsible for NGC 1068's inferred spectral index being harder than found by IceCube. A resolution of the difference presented, changing parts of the instrument response to predict event rates closer to the measurement. We show that with such modifications we are able to obtain parameter estimates closer to those found using the standard method. Due to the limited energy resolution of track events spectral modelling is already challenging, but exacerbated by suboptimally binned instrument responses. Improving the amount of information included in future data releases will allow better reproducibility of results by forward modelling methods that model background components separately.

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