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Impact of key modelling aspects on blazar–neutrino associations

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Blazars are promising candidates for astrophysical neutrino sources. Multi-messenger lepto-hadronic models based on proton–photon ($p\gamma$) interactions predict spectra that peak at high energies, whereas statistical searches often assume a power-law shape, emphasising lower energies. We investigate how these spectral assumptions impact neutrino–blazar associations by incorporating physically motivated spectra into our Bayesian point-source framework. Using recent predictions, we analyse 10 years of IceCube data and identify five candidate sources. Our results show that $p\gamma$ spectra suppress low-energy associations but may enhance high-energy ones. Strong associations then imply that energetic neutrino events likely have much higher true energies than those inferred under a power-law assumption. This is particularly relevant in light of the recent KM3NeT detection of the highest-energy neutrino, reinforcing the need for theory-driven models to interpret multi-messenger signals. For the first time we include angular systematic uncertainties in our fits and show that they have a strong impact on the results and subsequent interpretation.

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1. Introduction

While IceCube has discovered an astrophysical flux of neutrinos [1–3], individual sources of high-energy neutrinos are challenging to identify. At TeV energies, Seyfert galaxies are emerging as the first source population [4]. Most prominently among them is NGC 1068 as the first point source beyond 4σ significance [5]. At higher energies blazars have been suspected to be the dominant source class, yet catalog searches only find upper limits, e.g. [6]. Typically, power laws are used to test point source contributions to the data, with spectral index being a free parameter [5]. Numerical modelling of the proposed emission regions shows that this might not be a good choice, as predicted spectra tend to have a distinct peak in energy flux, see [7] for the case of blazars. The power law shape puts the emphasis on lower energies, where the contribution of the strong atmospheric background complicates the classification of astrophysical events.

Studies independent of the IceCube collaboration have, until recently, been limited by the availability of data and analysis tools. They therefore tend to be restricted to analysing spatial correlations between reconstructed event directions or hotspots and proposed sources or catalogs thereof. The events' energies are either not considered, as in hotspot searches, or only superficially included by means of high-energy event selections. Hence information on the physical connection is lost and interpreting the results becomes more difficult.

However, claims of association between IceCube's high-energy alert events [8] and blazars [9] have led to further analysis of the proposed source counterparts, generating a wealth of relevant information, e.g. [10]. In an effort to understand the possible connections, collected multi-wavelength data has been utilised in lepto-hadronic one-zone modelling of the suggested emission region in blazar jets, leading to the calculation of neutrino spectra expected from proton-gamma ($p\gamma$) interactions [11].

Going beyond the power-law spectrum, we employ such neutrino spectra (hereafter "$p\gamma$ spectra") in point source fits to publicly available IceCube track data [12]. The free parameters of the $p\gamma$ spectrum are the normalisation and the energy E_{peak} at which the energy flux peaks. The framework used is `hierarchical_nu`[1], a Bayesian hierarchical analysis framework aimed at characterising the point sources of high-energy astrophysical neutrinos. For details we refer to [13–15]. The Bayesian viewpoint allows for prior distributions to be multiplied to the likelihood, reflecting prior knowledge. Depending on the shape of the prior, and the information content of the data, observations can overrule the prior information. Further, we quantify individual events' connections to the proposed point source by posterior-averaged association probabilities, Pr_{assoc}. We additionally include an angular systematic uncertainty that we infer from events shared between data sets, in particular IceCube's public track data [12] and IceCat-1 alert events [8]. Similar approaches have been used in the past in correlation studies between source catalogs and individual events [9, 16]. The `hierarchical_nu` frameworks enables us to incorporate a free parameter describing the angular systematic uncertainty directly in the fits.

We detail our source and data selection in Section 2, the application to blazars with a focus on the impact of the spectral model choice in Section 3, and the further impact of possible angular systematics in Section 4. Finally we discuss our findings in Section 5 and conclude in Section 6.

[1] https://github.com/cescalara/hierarchical_nu

2. Source and data selection

We analyse 10 years of IceCube public track data for the contribution of blazars that have been linked to IceCube's high-energy alert events. To quantify the claimed link between source and alert event we have to identify the track events corresponding to the issued alerts. This step is necessary as IceCube only provides an effective area but no complete instrument response function in the alert event case required for a full analysis. In particular, the provided alert energies are estimated neutrino energies, inferred with an assumed power law of index −2.19. The forward folding approach we take requires reconstructed muon energies and an energy resolution. We establish the following procedure to identify the track event corresponding to an alert. Tracks are selected within a radius of 5° of an alert. Candidate tracks are narrowed down by selecting tracks arriving at the time of the alert, allowing for an absolute difference of 10^{-4} s. If more than one track survives this cut, we choose the highest energy one, if no track remains we increase the search radius. For some sources the associated alert lies outside of the time range covered by the public track data and no matching track can be found. We analyse 29 sources in the Northern Sky, for 26 of them we can identify the track event corresponding to the linked alert event. Only 13 of these alerts are unique, as some sources are directionally close to the same alert. For fits we select track events within a region of interest (ROI) with a radius of 5° around the proposed point source above a reconstructed muon energy of 300 GeV.

3. Application to blazars

For each source we perform two fits: one with an uninformative prior on E_{peak} (Fit #1) and one with an informative prior (Fit #2), based on each source's predicted E_{peak} [11]. Luminosity priors are chosen to be weakly informative. In addition to the point source, we model an astrophysical diffuse background and an atmospheric background. The fit of the model to the data is performed using a Hamiltonian Monte Carlo algorithm, implemented in `stan` [17], to find the posterior distribution of the parameters of interest. To make comparisons to previous results we also run fits using a power law (for details see [18]). Of the 29 sources selected, we find five showing evidence of neutrino emission, among them TXS 0506+056. The peaks of the energy fluxes that are only informed by the data lie around 10 TeV to 1 PeV, with the 68% credible interval extending over 1.2dex in energy for the well constrained sources 4FGL J1528.4+2004 and TXS 0506+056. As expected, employing informative priors on E_{peak} centred at high energies leads to peak energy fluxes and neutrino energies from 10 PeV to 100 PeV. We find the largest association probability of any event

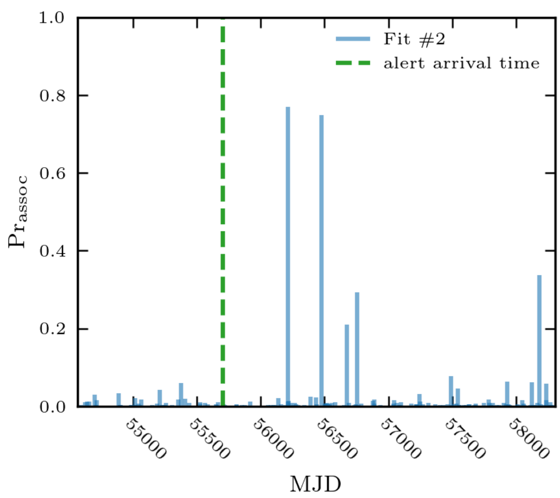

Figure 1: Events' Pr_{assoc} to 4FGL J1528.4+2004 ordered by their arrival time.

$\mathrm{Pr}_{\mathrm{assoc}} \gtrsim 0.9$ to TXS 0506+056 (the event being the alert IC170922A), independently of the used prior. For 4FGL J1528.4+2004 we associate two events at 15 TeV and 25 TeV reconstructed muon energy at 80% to 90%, but not the proposed alert event. We show each events' $\mathrm{Pr}_{\mathrm{assoc}}$ against their arrival time for this source in Fig. 1. The two associated events were detected with a time difference of 264 days, hinting at a possible flare of the source. A further three sources can be associated to one event each with $\mathrm{Pr}_{\mathrm{assoc}} > 50\%$. In all cases this is their respective alert event to which they have been previously linked by Ref. [9].

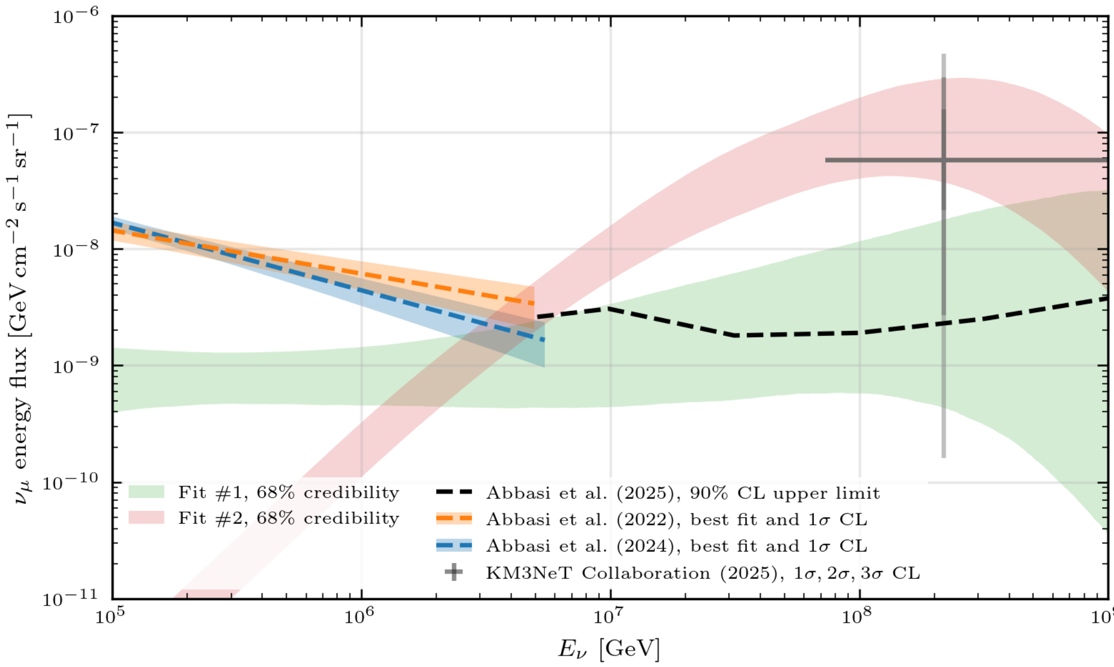

Figure 2: Combined neutrino energy flux of all considered sources, normalised to the entire sky. Single data point shows flux of [19] with $1, 2, 3\sigma$ uncertainties. Also shown are diffuse fluxes of [20], [21] and upper limits of [22].

The resulting energy fluxes generally agree with the predictions made in Ref. [11]. One exception is 4FGL J0854.0+2753. At its declination of 27°, IceCube's effective area decreases with increasing neutrino energy. With the particularly high predicted value of $E_{\mathrm{peak}} \sim 200$ PeV an accordingly high flux is needed to counteract the low effective area. Hence the posterior is concentrated three orders of magnitude higher in energy flux than predicted. Further investigation is beyond the scope of this work.

The combined flux of all blazars, shown in Fig. 2, is compatible with diffuse fits of IceCube at energies up to ~ 5 PeV [20, 21]. At higher energies our results exceed the extrapolated fluxes, as well as limits of dedicated searches at energies beyond the PeV-scale [22], but are compatible with recent results of the KM3NeT collaboration [19]. Comparisons are, however, not straightforward as different model assumptions have gone into said fits.

4. Angular systematics

By the described procedure of matching alert events with public tracks, we find a distribution of opening angles between pairs of such events, as shown in Fig. 3. Fitting an exponentially modified Gaussian distribution, we introduce a new parameter quantifying the angular systematic uncertainty, σ_{sys}, on which we impose the fitted distribution as a prior. We then replace the per-event angular uncertainty σ_{stat} by $\sqrt{\sigma_{\text{stat}}{}^2 + \sigma_{\text{sys}}{}^2}$.

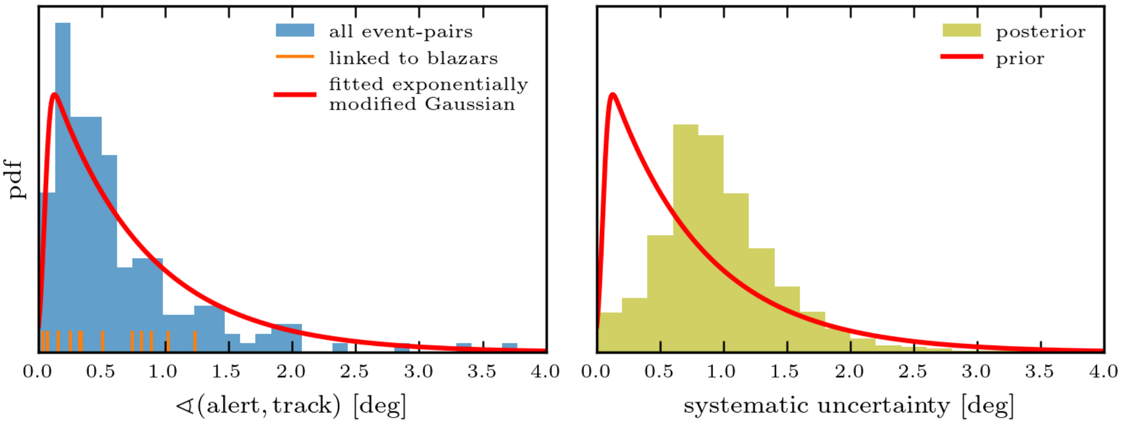

Figure 3: Left panel: Distribution of opening angles of matched alert-track pairs. Events linked to sources considered in this work are marked by orange dashes. **Right panel:** Posterior distribution of σ_{sys} in fit to 4FGL J1554.2+2008.

Comparing to the fits without this additional systematic treatment, we observe three possible effects. For sources whose high-Pr_{assoc} events coincide with the point source location, e.g. TXS 0506+056, the point source contribution to the entire model decreases. This is due to the spatial likelihood profile becoming wider, but more importantly flatter, when increasing the angular uncertainty. The decrease of, e.g., Pr_{assoc} is on the order of 5-10 percentage points for the uninformative E_{peak} prior, and up to 15 percentage points for the informative prior. In cases with an angular uncertainty region at the edge of compatibility with the point source, the opposite effect is seen, and the association of the event to the point source increases, in one case from 20% to 60%.

For 4FGL J1554.2+2008 the association of two events, one of which is an alert counterpart, hinges on the additional angular systematic, as shown in Fig. 4. The events arrive with a delay of 285 days. Here, it is also apparent that the σ_{sys} posterior pulls away from the prior to larger angles, as seen in Fig. 3. A side effect is the increased amount of low-energy events being attributed at percent-level to the point source, which is partly counteracted by the informative E_{peak} prior.

5. Discussion

We have analysed a sample of blazars that have been linked to IceCube alert events and find five sources with evidence for neutrino emission. Using physically motivated spectra expected of the emission mechanism in blazar jets, we find neutrino energies ranging from tens to hundreds of PeV when imposing informative priors on the peak energy. Despite not being able to associate

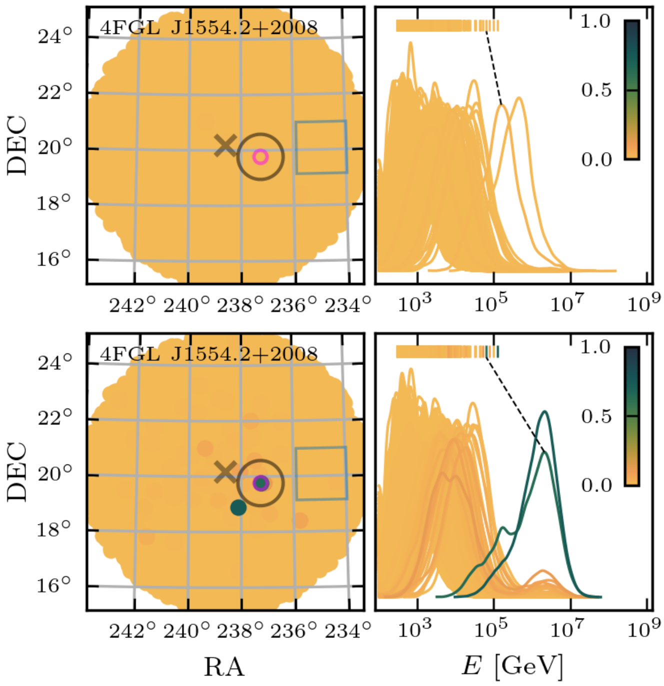

Figure 4: Upper: Default analysis. **Lower:** Analysis including angular systematics. Analysis of 4FGL J1554.2+2008. The colour of markers and lines reflects $\mathrm{Pr}_{\mathrm{assoc}}$. The left panels show a scatter plot of analysed events, projected onto the sky. The markers' size is arbitrary. The ROI is centered on 4FGL J1554.2+2008, marked by a cross. The blue box shows the rectangular boundary of the IceCat alert's 90% containment. The red circle marks the corresponding track with its 90% containment shown as a grey circle. The right panels show each event's marginalised true neutrino energy posterior, transformed to $\log_{10}(E/\mathrm{GeV})$. The upper axis shows reconstructed muon energies. The dashed line connects reconstructed energy and energy posterior of the track matched to the alert.

the proposed alert event to 4FGL J1528.4+2004, we identify two other events at $\mathrm{Pr}_{\mathrm{assoc}} \sim 80\%$. The predicted peak flux is compatible at 90% credibility with our results, the 68% credible region lies one to two orders of magnitude higher in energy flux. These events arrive within 264 days of each other, therefore a detailed, time-resolved study of the related multi-wavelength emission might provide an insight to the origin of the events. However, this approach is typically limited by the availability of simultaneous observations across the electromagnetic spectrum.

For the first time in our framework, we include systematic uncertainties in the angular reconstruction into our fits. By introducing a parameter σ_{sys} we are able to identify another potential source of neutrinos, 4FGL J1554.2+2008, with two events associated at $\mathrm{Pr}_{\mathrm{assoc}} \sim 70\%$ and their detection separated by 285 days. The initial link between the sources analysed here and IceCube's alert events showed the highest significance when accounting for systematic uncertainties by enlarging the error contours by a scaling factor [9]. Our results support the hypothesis that previously unaccounted for systematics should be considered in point source searches.

The IceCube collaboration has implemented a KDE parameterisation of the angular uncertainty which is more accurate, and a different reconstruction algorithm, see the supplementary material of Ref. [5]. Additionally, the published likelihood contours of alert events show substantial eccentricity [8], rendering the circularisation of uncertainties used in Ref. [12] an approximation. The inclusion of angular systematics here is just a first step towards a comprehensive approach in point source analyses. While the summed flux of all sources is compatible with existing power-law fits, it exceeds flux limits beyond PeV energies. The inclusion of angular systematic effects leads to more sources with $\mathrm{Pr}_{\mathrm{assoc}} \gtrsim 0.5$ and increases the tension with flux limits. Direct comparisons are, however, non-trivial as mentioned above.

6. Conclusions

We show that the inclusion of more information, here the spectral model and an informative prior on spectral parameters, as well as systematic uncertainties, can markedly alter the results of point source searches. Our combined flux predictions are purely constrained by the model assumptions and the public track dataset used. Other event samples, such as cascades or starting events, have better energy resolution and could provide independent constraints on the high-energy flux. We plan to explore these constraints in future work as the relevant information becomes available. `hierarchical_nu` is ideally suited for these tasks due to its modular framework capable of handling different detectors and data sets in joint fits.

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References

[1] M.G. Aartsen et al., *Phys. Rev. Lett.* **111** (2013) [1304.5356].

[2] M.G. Aartsen et al., *Science* **342** (2013) [1311.5238].

[3] M.G. Aartsen et al., *Phys. Rev. Lett.* **113** (2014) 101101 [1405.5303].

[4] R. Abbasi et al., *ApJ* **988** (2025) 141 [2406.07601].

[5] R. Abbasi et al., *Science* **378** (2022) 538 [2211.09972].

[6] R. Abbasi et al., *ApJ* **938** (2022) 38 [2207.04946].

[7] F. Oikonomou, *PoS* **ICRC2021** (2022) 030.

[8] R. Abbasi et al., *ApJS* **269** (2023) 25 [2304.01174].

[9] P. Giommi et al., *MNRAS* **497** (2020) 865–878 [2001.09355].

[10] S. Paiano et al., *MNRAS* **504** (2021) 3338 [2104.05290].

[11] X. Rodrigues et al., *A&A* **689** (2024) A147 [2406.06667].

[12] IceCube Collaboration, *Icecube data for neutrino point-source searches years 2008-2018*, 2021. 10.21234/CPKQ-K003.

[13] F. Capel et al., *PoS* **ICRC2023** (2023) 1576.

[14] F. Capel et al., *hierarchical_nu: A hierarchical Bayesian approach to point source analysis in high-energy neutrino telescopes*, 2024. 10.5281/zenodo.13760504.

[15] F. Capel et al., *ApJ* **976** (2024) 127 [2406.14268].

[16] A.V. Plavin et al., *MNRAS* **523** (2023) 1799 [2211.09631].

[17] Stan Development Team, *Stan Modeling Language Users Guide and Reference Manual*, 2025.

[18] J. Kuhlmann and F. Capel, *Under review at ApJ* [2503.04632].

[19] S. Aiello et al., *Nature* **638** (2025) 376.

[20] R. Abbasi et al., *ApJ* **928** (2022) 50 [2111.10299].

[21] R. Abbasi et al., *PRD* **110** (2024) 022001 [2402.18026].

[22] R. Abbasi et al., *Phys. Rev. Lett.* **135** (2025) 031001 [2502.01963].