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# Modeling a large AGN sample to unveil the signatures of neutrino emission

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Active galactic nuclei (AGN) are one of the most promising classes of extragalactic cosmic-ray accelerators. This has been recently strengthened by increasing indications that AGN, and in particular blazars, may be sources of IceCube neutrinos. In this talk I report on recent results from self-consistent leptohadronic modeling of a large sample of blazar AGN, where the observed multi-wavelength spectrum is described by means of a self-consistent numerical radiation model of cosmic-ray interactions. First, I discuss recent results from the modeling of a sample of 324 gamma-ray-bright blazars, of which 237 are flat-spectrum radio quasars (FSRQs). By fitting multi-wavelength observations from optical to gamma rays compiled in a previous work, we can constrain the source parameters, estimate the possible contribution from cosmic-ray protons, and predict the corresponding neutrino emission. For about one-third of the blazars in the sample, cascades from hadronic interactions can help explain observations in the X-ray band, in agreement with recent results on individual IceCube candidates. For the rest of the sources, the observed spectra are well described by purely leptonic emission. By extrapolating from these results, we can also predict the diffuse neutrino flux from the entire blazar population, which is at the level of 20% of the diffuse flux observed by IceCube. I discuss the general implications of these results for the next generation of neutrino experiments, like IceCube-Gen2. This talk is based on a recent analysis [1].

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker





PoS(ICRC2023)1544

## 1. Introduction

The origin of the cosmic rays and the astrophysical neutrinos is currently one of the central issues in high-energy astrophysics. The IceCube experiment, located at the South Pole, observes a diffuse flux of astrophysical neutrinos with energies between 100 TeV and a few PeV [2–6], thought to be emitted when cosmic rays interact with ambient radiation ($p\gamma$) or matter (pp). Crucially, although these hadronic processes should be accompanied by the emission of high-energy gamma rays, so far the cosmic neutrino sky does not seem to significantly correlate with gamma-ray-emitting sources. This suggests that the photons emitted in cosmic ray interactions are being attenuated or otherwise losing their energy, either in the astrophysical source or en route to Earth [7–11].

Blazars, active galactic nuclei (AGN) whose relativistic jet is pointing close to the line of sight, are one of the most promising candidate source classes. Multiple associations between IceCube events and individual blazars have now been reported and studied [see e.g. 12–22]. The association with highest significance thus far is that with the blazar TXS 0506+056 at the $3.5\sigma$ level [23, 24].

A feature that is shared by most phenomenological models is that the gamma rays co-produced with neutrinos through cosmic-ray interactions cascade down to the X-ray regime before leaving the source. In the GeV band the sources are typically optically thin, which means that inverse Compton emission by accelerated electrons can typically explain the GeV fluxes observed by the *Fermi* Large Area Telescope (LAT). In some cases, models can predict an optically thick environment to GeV gamma rays [e.g. 18, 25–27], inspiring concepts of GeV-gamma-ray-suppressed episodes of neutrino emission [28]. On the other hand, models suggests that somewhat extreme conditions are necessary to produce such strong suppression in the LAT band.

In this talk I discuss the recent modeling of a sample of 324 gamma-ray blazars [1], intended to shed light on the relationship between neutrino production in blazars and its possible multi-wavelength signatures. I will show how self-consistent, source-by-source cosmic-ray simulations can provide physics-driven predictions of the potential neutrino emission by fitting multi-wavelength observations.

## 2. Blazar sample

We base ourselves on the CGRaBS catalog [29], which is a radio-flux-limited sample ($F_{8.4\ \mathrm{GHz}} >$ 65 mJy) of 1625 AGN. From this catalog, Paliya et al. [30] have selected 324 sources that were present in the *Fermi*-LAT catalogs available at the time [31–33] and for which there exist also multi-wavelength observations including X-rays. We refer to references [1, 30] for more details on the data used, all of which is public.

In Fig. Fig. 1 we show the source distribution as a function of redshift and gamma-ray luminosity. The sources in the sample are shown as dark markers while, for comparison, we show as light-colored markers the overall distribution of FSRQs (left) and BL Lacs (right) detectable in gamma rays by the Fermi-LAT. As we can see by the respective histograms, our sample does not follow exactly the source population. This is taken into consideration when extrapolating the results (Sec. 4).

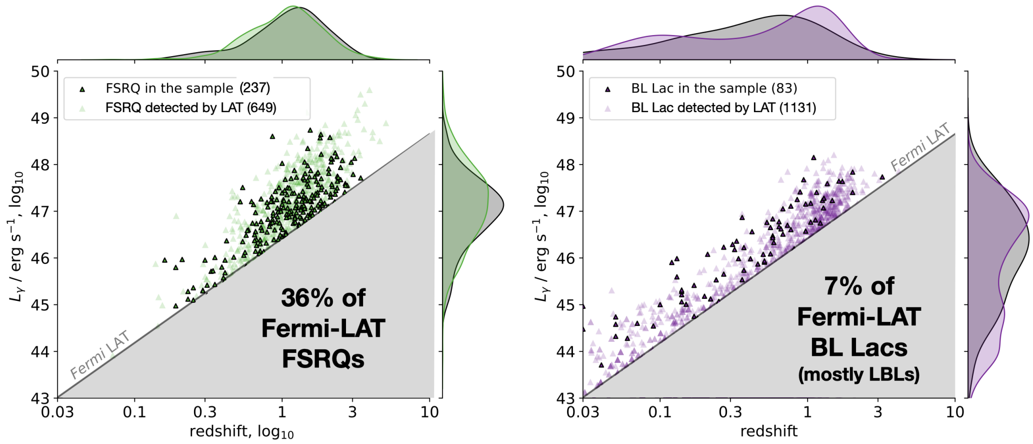


**Figure 1:** The FSRQs *(left)* and BL Lacs *(right)* in our sample are represented as dark points as a function of redshift and gamma-ray luminosity. For comparison, we show as lighter points to the distribution of the respective overall population observable by the *Fermi*-LAT, based on [34, 35]. The gray area represents the sub-threshold region for the LAT. On the margins, we have the projected distributions of the sample (black) and of the population (green on the left and purple on the right).

## 3. Multi-wavelength fits

For each source, we simulate the interactions of cosmic-ray electrons and protons accelerated in the jet interacting in a single spherical zone in the relativistic jet. For that, we use the time-dependent numerical code AM$^3$ [13]. This is a time-dependent numerical solver that self-consistently calculates the interactions between electrons, protons, photons and a homogeneous and isotropic magnetic field. The resulting steady-state emission of multi-wavelength radiation and neutrinos is then calculated in a fully self-consistent manner.

The details of the model, the simulation setup, and the optimization algorithm are provided in detail in [1].

In this context it is worth mentioning that the majority of the sources modeled are FSRQs, 241 out of 324. These sources typically have a broad-line region (BLR) surrounding the central engine, which produces significant broad line and thermal emission. If the radiation zone in the relativistic jet lies close to or within the BLR, these photon fields will be relativistically boosted into the rest frame of the jet. These external photon fields will then serve as additional target photons for interactions in the jet, which makes the FSRQ model highly sensitive to the location of the radiative zone. This is accounted for in the model by means of the dissipation radius parameter (see diagram of the jet geometry in [1]).

In Fig. 2 we show as an example two best-fit results. All results and the respective parameters are provided in [1]. Here, we break down the modeled multi-wavelength emission into the different radiation processes according to the figure legend.

For source 4C+40.25, on the left, we see that purely leptonic emission (orange curve) can explain the observed multi-wavelength fluxes above 300 GHz. We observe this to be the case for a total of 218 sources, or 66% of the sample.

On the other hand, for source PKS 1903-80, on the right plot of Fig. 2, we see that the best-fit scenario includes a contribution from cascades triggered by proton interactions (green and blue curves and respective error bands). These help explain observations both in X-rays and in gamma rays at ~100 GeV. The optical and gamma-ray peaks are well explained by leptonic emission. For about 33% of the sources in the sample, a hadronic contribution can help explain multi-wavelength observations, suggesting proton interactions and consequently neutrino emission (pink curve).

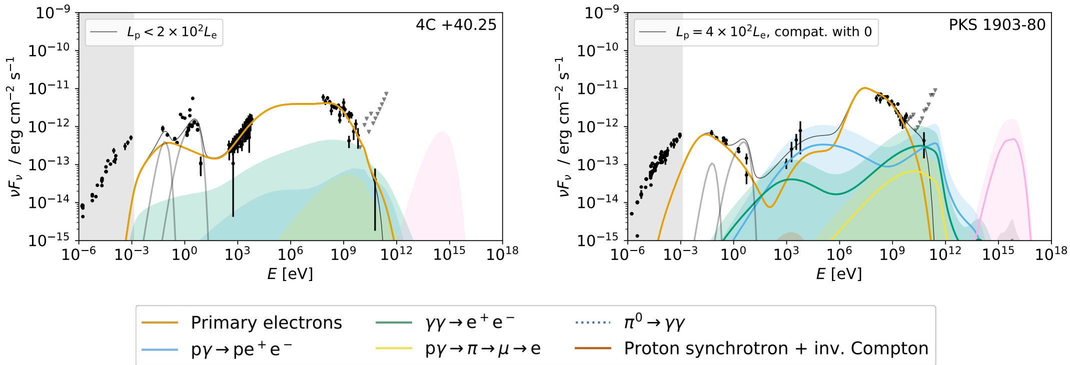


**Figure 2:** Examples of best-fit results for two sources in the sample. The color curves represent the different components of that emission, as detailed in the caption. The gray curves represent thermal emission from the dust torus and accretion disk; the black curve is the total spectrum. The pink curve on the right-hand side represents the estimated neutrino flux and the band the respective uncertainty. See [1] for further details.

## 4. Neutrino flux predictions and implications for multi-messenger searches

Using the neutrino fluxes self-consistently predicted for each source in the sample, we can now deduce the corresponding flux observed at Earth and compare to neutrino experiments. In the top plot of Fig. 3 we show the flux of muon neutrinos, compared to the sensitivities of IceCube and the future IceCube-Gen2. The model suggests that 7 of our sources may be detectable by the current IceCube, and more than 20 could be detectable in the future by IceCube-Gen2.

By convolving the fluxes with the declination-dependent effective areas, we can estimate the event rate for each source, shown in the bottom panels of Fig. 3. We can see on the left that few sources approach one event per decade in IceCube. These low rates are due to the fat that flaring events are not accounted for in this analysis, which instead focuses on average emission.

In the case if IceCube-Gen2 [37], we can see on the right panel that several sources in the sample would be detected in an average state of emission within the first decade of operation. This suggests that IceCube-Gen2 may be able to resolve this population, even if we ignore the occasional flaring events.

Finally, we can estimate the sample's contribution to the IceCube diffuse flux, shown as a solid black curve in Fig. 4. This is obtained by adding the all-flavor neutrino fluxes from all sources, as discussed previously. Comparing to the IceCube diffuse flux (black data points), we see that this contribution is estimated at the ~ 5% level.

We then extrapolate this result to the entire population of *Fermi*-LAT blazars, following the procedure detailed in [1]. The result is shown in Fig. 4 as a dotted orange curve. We can then conclude that our model predicts a neutrino flux from the *Fermi*-LAT population that is at the level

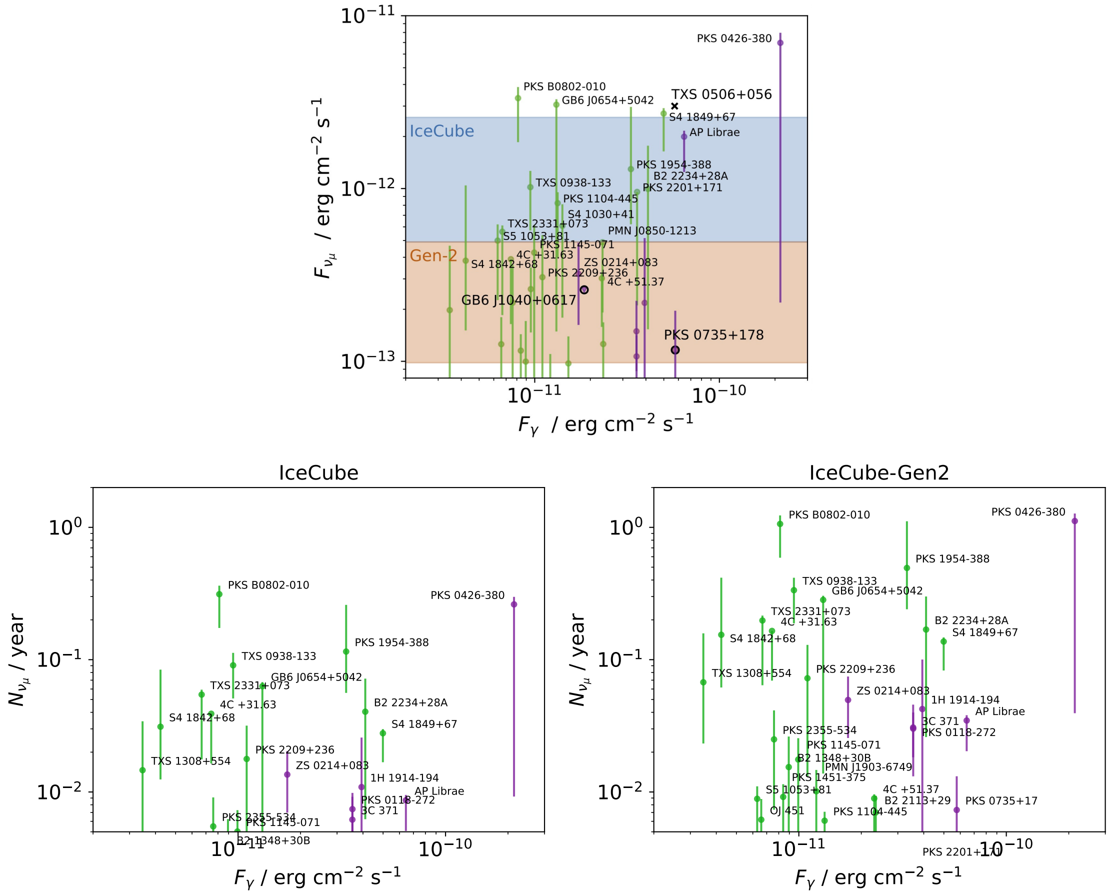


**Figure 3:** *Top:* predicted muon neutrino flux from each source, compared to the sensitivity range of IceCube [36, blue] and the future IceCube-Gen2 [37, orange]. *Bottom:* number of events per year in IceCube *(left)* and in IceCube-Gen2 *(right)* predicted by the model. Green points denote FSRQs and purple points denote BL Lacs. Plots adopted from [1].

of 20% of the diffuse flux observed by IceCube, in agreement with source stacking analyses [38], shown in the pink band with the downward arrow.

These results suggest that continued observations, together with investment in more sensitive experiments, should help us detect an increasingly significant neutrino flux from gamma-ray blazars. It is also noteworthy that the model predicts a considerable component up to ∼ 100PeV that is dominated by FSRQs, an energy regime that will be better probed by future experiments compared to the current IceCube.

## 5. Conclusion

In this talk I reported on a recent multi-messenger analysis of 324 blazars [1] belonging to the CGRaBS catalog, all detected by the *Fermi*-LAT gamma-ray telescope and all with public multi-wavelength data including X-rays. We used numerical, self-consistent and time-dependent simulations of cosmic-ray interactions in the relativistic jet. We estimated the model parameters

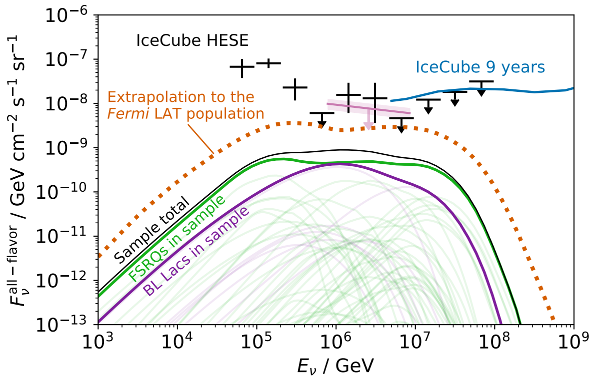


**Figure 4:** All-flavor neutrino flux expected from the entire sample (solid black curve), and the extrapolation to the entire *Fermi*-LAT population [dotted curve, see method in 1]. Also included are IceCube data in black [5], 9 year sensitivity in blue [39], and stacking limits for blazars in pink [38]. Figure adopted from [1].

by fitting the multi-wavelength emission predicted for each source to observations, as well as the respective neutrino spectrum.

For 33% of the sample, radiative emission from hadronic interactions either dominates the observed X-ray fluxes or at least improves the best fit compared to a purely leptonic scenario. For the other 218 sources, the leptonic model parameters can be constrained and upper limits can be established on the baryonic loading of the jet and the respective neutrino emission. Overall, the leptohadronic paradigm with external fields has shown to provide a solution for the entire sample.

Finally, I have shown that this sample may contribute to the diffuse flux observed by IceCube at the ~5% level. Extrapolating to the population of gamma-ray blazars we can derive a total contribution to the IceCube flux at the level of 20%, in agreement with current upper limits [38].

IceCube has already detected several neutrino events from sporadic hadronic blazar flares. These results suggest that next-generation neutrino experiments like IceCube-Gen2 can potentially probe the steady-state emission from this source population.
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## References


[1] X. Rodrigues, V. S. Paliya, S. Garrappa, A. Omeliukh, A. Franckowiak, and W. Winter *arXiv:2307.13024* (2023) .

[2] **IceCube** Collaboration, M. G. Aartsen *et al. Science* **342** (2013) 1242856.

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

[4] **IceCube** Collaboration, M. G. Aartsen *et al. Phys. Rev. Lett.* **115** no. 8, (2015) 081102.

[5] **IceCube** Collaboration, M. G. Aartsen *et al. Astrophys. J.* **809** no. 1, (2015) 98.

[6] **IceCube** Collaboration, M. G. Aartsen *et al. Phys. Rev. Lett.* **111** (2013) 021103.

[7] K. Murase, D. Guetta, and M. Ahlers *Phys. Rev. Lett.* **116** no. 7, (2016) 071101.

[8] D. Hooper *JCAP* **09** (2016) 002.

[9] F. Halzen, A. Kheirandish, T. Weisgarber, and S. P. Wakely.

[10] K. Murase *PoS* **ICRC2019** (2020) 965.

[11] F. Halzen and A. Kheirandish *Nature Phys.* **16** no. 5, (2020) 498–500.

[12] M. Kadler, F. Krauß, K. Mannheim, *et al.* *Nature Physics* **12** (Aug., 2016) 807–814.

[13] S. Gao, M. Pohl, and W. Winter *Astrophys. J.* **843** no. 2, (2017) 109.

[14] A. Keivani, K. Murase, M. Petropoulou, *et al.* *Astrophys. J.* **864** no. 1, (2018) 84.

[15] M. Petropoulou, K. Murase, M. Santander, *et al.* *Astrophys. J.* **891** (2020) 115.

[16] P. Padovani, F. Oikonomou, M. Petropoulou, P. Giommi, and E. Resconi *Mon. Not. Roy. Astron. Soc.* **484** (2019) L104.

[17] P. Giommi, P. Padovani, F. Oikonomou, T. Glauch, S. Paiano, and E. Resconi *Astron. Astrophys.* **640** (2020) L4.

[18] M. Petropoulou, F. Oikonomou, A. Mastichiadis, K. Murase, P. Padovani, G. Vasilopoulos, and P. Giommi *Astrophys. J.* **899** no. 2, (2020) 113.

[19] A. Franckowiak, S. Garrappa, V. Paliya, *et al.* *Astrophys. J.* **893** (2020) 162.

[20] X. Rodrigues, S. Garrappa, S. Gao, V. S. Paliya, A. Franckowiak, and W. Winter *Astrophys. J.* **912** no. 1, (2021) 54.

[21] S. Gasparyan, D. Bégué, and N. Sahakyan *Mon. Not. Roy. Astron. Soc.* **509** no. 2, (2021) 2102–2121.

[22] N. Sahakyan, P. Giommi, P. Padovani, M. Petropoulou, D. Bégué, B. Boccardi, and S. Gasparyan *Mon. Not. Roy. Astron. Soc.* **519** no. 1, (2022) 1396–1408.

[23] **IceCube Collaboration** Collaboration, M. Aartsen, M. Ackermann, J. Adams, *et al.* *Science* **361** no. 6398, (2018) .

[24] **IceCube Collaboration** Collaboration, M. Aartsen, M. Ackermann, J. Adams, *et al.* *Science* **361** no. 6398, (2018) 147–151.

[25] X. Rodrigues, S. Gao, A. Fedynitch, A. Palladino, and W. Winter *Astrophys. J.* **874** no. 2, (2019) L29.

[26] A. Reimer, M. Boettcher, and S. Buson *Astrophys. J.* **881** no. 1, (2019) 46. [Erratum: Astrophys.J. 899, 168 (2020)].

[27] R. Xue, R.-Y. Liu, Z.-R. Wang, N. Ding, and X.-Y. Wang *Astrophys. J.* **906** no. 1, (2021) 51.

[28] E. Kun, I. Bartos, J. Becker Tjus, P. L. Biermann, A. Franckowiak, F. Halzen, and G. Mezo.

[29] S. E. Healey, R. W. Romani, G. Cotter, P. F. Michelson, E. F. Schlafly, A. C. S. Readhead, P. Giommi, S. Chaty, I. A. Grenier, and L. C. Weintraub *Astrophys. J. Suppl.* **175** (2008) 97.

[30] V. S. Paliya, L. Marcotulli, M. Ajello, M. Joshi, S. Sahayanathan, A. R. Rao, and D. Hartmann *Astrophys. J.* **851** no. 1, (2017) 33.

[31] **Fermi-LAT** Collaboration, A. A. Abdo *Astrophys. J.* **715** (2010) 429–457.

[32] M. Ackermann, M. Ajello, A. Allafort, *et al.* *ApJ* **743** no. 2, (Dec., 2011) 171.

[33] **Fermi-LAT** Collaboration, F. Acero *et al.* *Astrophys. J. Suppl.* **218** no. 2, (2015) 23.

[34] M. Ajello *et al.* *Astrophys. J.* **751** (2012) 108.

[35] M. Ajello *et al.* *Astrophys. J.* **780** (2014) 73.

[36] **IceCube** Collaboration, M. G. Aartsen *et al.* *Astrophys. J.* **835** no. 2, (2017) 151.

[37] **IceCube-Gen2** Collaboration, M. G. Aartsen *et al.* *J. Phys. G* **48** no. 6, (2021) 060501.

[38] **IceCube** Collaboration, M. G. Aartsen *et al.* *Astrophys. J.* **835** no. 1, (2017) 45.

[39] **IceCube** Collaboration, M. G. Aartsen *et al.* *Phys. Rev. D* **98** no. 6, (2018) 062003.