PROCEEDINGS OF SCIENCE

Exploring the detection prospects of NGC 1068-like neutrino sources against the backdrop of their astrophysical population

Lena Saurenhaus* **and Francesca Capel**

Max Planck Institute for Physics,
Föhringer Ring 6, 80805 München, Germany

E-mail: lsaurenh@mpp.mpg.de, capel@mpp.mpg.de

Active galactic nuclei (AGN) are considered possible sites of hadronic particle acceleration and are, therefore, promising neutrino source candidates. The IceCube Collaboration recently reported an excess of neutrino events in the 1.5 - 15 TeV range associated with the nearby Seyfert II galaxy NGC 1068, which hosts an intrinsically luminous AGN that is heavily obscured by gas and dust. Due to the lack of observable gamma-rays in this energy range, it seems that these neutrinos are most likely produced in photohadronic interactions in the vicinity of the central black hole. Motivated by this result, we explore the prospects of observing other hidden neutrino sources with similar neutrino production mechanisms. For this purpose, we use Monte Carlo simulations based on multi-wavelength observations of this class of sources. Applying approximate methods for point source searches combined with publicly available detector information, we then make predictions about the detectability of the resulting neutrino emission with IceCube and planned next-generation detectors, such as IceCube-Gen2 and KM3NeT. Connecting our findings on the diffuse flux from the source population as a whole to the possibility of detecting nearby individual neutrino sources allows us to draw a coherent picture of the contribution of these sources to astrophysical neutrino observations.

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

*Speaker

PoS(ICRC2023)1509

1. Introduction

Ten years ago, the first detection of a diffuse flux of astrophysical neutrinos was reported by the IceCube Collaboration [1, 2]. These neutrinos are most likely produced in hadronic interactions of cosmic rays with matter or radiation in or close to their sources. In those interactions, neutral and charged mesons are created that subsequently decay into neutrinos and γ-rays. Thus, we would expect astrophysical neutrinos to be accompanied by a flux of high-energy γ-rays of approximately the same order of magnitude as the neutrino flux. However, in order not to overproduce the diffuse extragalactic γ-ray flux measured by Fermi-LAT, the majority of the sources of TeV-PeV neutrinos have to be so-called hidden neutrino sources, opaque to GeV-TeV γ-rays [3]. Particularly promising source candidates that could meet this requirement are active galaxies hosting an active galactic nucleus (AGN). These galaxies are powered by the accretion of matter onto a supermassive black hole in their centre and emit intense electromagnetic radiation over a wide range of wavelengths.

Recently, the IceCube Collaboration reported evidence of neutrino emission from the nearby Seyfert galaxy NGC 1068 [4]. Analysing data recorded between 2011 and 2020, they found an excess of 79 neutrinos at TeV energies with a global significance of 4.2σ associated with the galaxy. NGC 1068 is a well-studied Compton-thick Seyfert II galaxy that is located at a distance of (10.1 ± 1.8) Mpc [5, 6] and has an intrinsic X-ray luminosity of 3.5×10^{43} erg s^{-1} in the 2-10 keV range[1]. This makes it the most intrinsically luminous X-ray source in the Northern sky. The lack of observed γ-ray emission above 200 GeV implies that NGC 1068 is a hidden neutrino source [8].

Several theoretical models have been proposed to explain the neutrino emission from NGC 1068 [9–11]. All of these models suggest that the neutrino emission originates from the innermost region of the AGN, the so-called corona. The corona is a hot plasma of electrons surrounding the central region of the accretion disk and is very luminous in X-rays. These X-rays are mainly produced via multiple inverse Compton scatterings of optical and UV disk photons by hot electrons in the corona. To produce the observed neutrinos, protons have to be accelerated up to TeV-PeV energies inside the AGN corona. Then, the accelerated particles interact via $p\gamma$ interactions with the coronal X-rays or via pp interactions with the surrounding gas, which leads to the production of high-energy neutrinos and γ-rays. Neutrinos are only weakly interacting and can escape from the corona, while the γ-rays are attenuated in $\gamma\gamma$ interactions with X-rays and contribute instead to the emission in the MeV range via electromagnetic cascades.

Besides particle acceleration in the corona, other possible mechanisms for neutrino production in NGC 1068 have been explored. However, it was found that neither the intense starburst activity [10] nor particle acceleration in an outflow [12, 13] could account for the neutrino emission. Instead, these phenomena could explain the γ-ray emission at $\sim$ GeV energies observed by Fermi-LAT [14].

Here, we investigate the contribution of the neutrino flux from Seyfert galaxies to astrophysical neutrino observations taking into account the neutrino emission from other nearby possible point sources besides NGC 1068 as well as a population of Seyfert galaxies. To predict the neutrino spectrum of a single source based on its X-ray properties, we use a simple spectral model presented in Section 2. In Section 3, we discuss the chosen nearby sources and the properties of the source population. In Section 4, we present our findings on the expected neutrino flux from the nearby sources and the source population and assess its detectability. Finally, we conclude in Section 5.

[1]From [7] and rescaled for a distance of 10.1 Mpc.

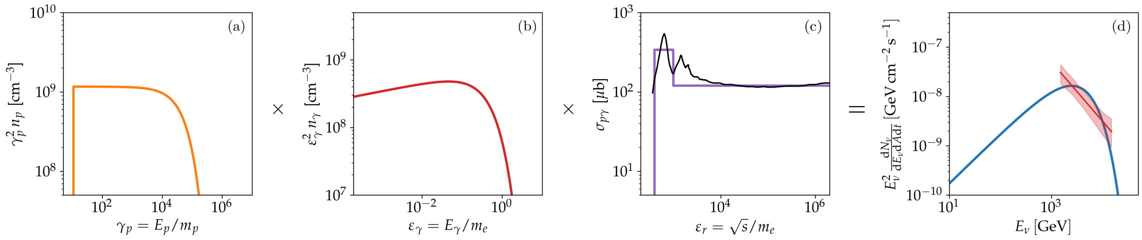

Figure 1: Schematic overview of the spectral model used to calculate the neutrino spectrum of a Seyfert galaxy, here for NGC 1068. **(a)** Primary proton spectrum for $E_{p,\max} = 50\,\text{TeV}$. **(b)** Coronal X-ray spectrum. **(c)** Photomeson production cross section (black line) approximated by a simple step function (purple line). **(d)** Resulting neutrino spectrum per flavour. The IceCube best-fit spectrum of NGC 1068, including the 95% confidence region, is shown in red [4]. The figure is motivated by the schematic in [15].

2. Spectral model for neutrino emission from NGC 1068-like sources

To compute the neutrino spectrum of a Seyfert galaxy with specific X-ray properties, we use a relatively simple spectral model. As proposed in [11], we assume that neutrinos in Seyfert galaxies are mainly produced in photohadronic interactions of accelerated protons with X-rays in the corona and neglect hadronuclear interactions. As shown in Fig. 1, our model has three different ingredients: the primary proton spectrum (panel (a)), the X-ray spectrum of the corona (panel (b)), and the cross section for photomeson production as a function of the centre-of-mass energy (panel (c)).

For the proton spectrum, we use a power law with spectral index -2 and an exponential cutoff, $n_p(\gamma_p) = A_p \gamma_p^{-2} \exp\left(-\gamma_p/\gamma_{p,\max}\right)$, where $\gamma_p = E_p/m_p$ is the Lorentz factor of the proton and A_p is a normalisation constant. The X-ray spectrum of the corona is also modelled as a power law with an exponential cutoff of the form $n_\gamma(\varepsilon_\gamma) = A_\gamma \varepsilon_\gamma^{-\Gamma} \exp\left(-\varepsilon_\gamma/\varepsilon_{\gamma,\max}\right)$ with $\varepsilon_\gamma = E_\gamma/m_e$. Following the calculation in [11], the spectral index Γ, the cutoff energy $\varepsilon_{\gamma,\max}$, and the normalisation A_γ are functions of the X-ray luminosity so that the coronal X-ray spectrum of a source is entirely determined by its X-ray luminosity. In our model, we can safely neglect disk photons in the optical and UV range as possible targets for $p\gamma$ interactions. They only become relevant at primary proton energies of $\sim 1\,\text{PeV}$ or higher.

The cross section for photomeson production, which is needed to calculate the spectrum of the neutrinos produced in the interactions of the accelerated protons with the coronal X-rays, is a complex superposition of many different resonances. To simplify our calculation, we approximate the cross section by a step function. Following the calculation outlined in Chapter 9 of [16] and additionally taking into account the distance of the source and energy losses due to the adiabatic expansion of the Universe, we can then derive the neutrino flux at Earth as a function of observed neutrino energy as shown in panel (d) of Fig. 1. The resulting spectrum roughly follows a power law up to a peak energy of $E_{\nu,\text{peak}} \simeq 0.05 E_{p,\max}$, where $E_{p,\max}$ is the cutoff energy of the proton spectrum, and decreases steeply at higher energies.

In general, if only the X-ray luminosity of a source is known, our model has two unconstrained parameters, A_p and $E_{p,\max}$. The fact that NGC 1068 is the intrinsically brightest Seyfert galaxy in 2-10 keV X-rays and also the only one so far associated with neutrinos detected by IceCube suggests that there is a correlation between the intrinsic X-ray luminosity L_X of a source and

Table 1: Properties of the considered nearby Seyfert galaxies as reported in the BASS catalogue [17] as well as the expected number of neutrino events N_ν in 10 years of IceCube and the corresponding local p-value for each of the sources. For NGC 1068, we employ the X-ray luminosity reported in [7] and the luminosity distance from [6] instead. For all other sources, the luminosity distance is calculated from the redshift.

source	z	d_L [Mpc]	δ [deg]	$\log L_X$ [erg s^{-1}]	N_ν	local p-value
NGC 1068	0.00303	10.1	-0.013	43.54	40.0	7×10^{-5}
CGCG 164-019	0.0296	130.0	27.03	44.57	3.4	0.4
NGC 7212	0.0267	117.0	10.23	44.41	2.8	0.4
NGC 1275	0.0166	72.2	41.51	43.98	2.8	0.4
NGC 1194	0.0136	58.9	-1.10	43.69	1.7	0.4
NGC 5506	0.00609	26.3	-3.21	42.99	1.0	0.5
NGC 4151	0.00314	15.8	39.51	42.20	1.3	0.5
CGCG 420-015	0.0294	128.7	4.06	44.00	0.8	0.5

its neutrino luminosity L_ν. However, the exact relation between L_X and L_ν remains unknown. Therefore, we make the simple assumption that L_ν is proportional to L_X, $L_\nu = \alpha L_X$. The proportionality constant depends on the X-ray and the neutrino luminosity of NGC 1068 and is given by $\alpha = L_\nu^{1068}/L_X^{1068} \simeq 0.041$. This relation allows us to determine the normalisation of the neutrino spectrum and, thus, also the normalisation of the proton spectrum of a source for which only L_X is known.

To constrain the cutoff energy $E_{p,\max}$ of the proton spectrum, we compare our model neutrino spectra for NGC 1068 for different values of $E_{p,\max}$ to the best-fit power-law spectrum reported by IceCube [4]. As shown in panel (d) in Fig. 1, we found that for a cutoff energy of $E_{p,\max} \simeq 50$ TeV the model neutrino spectrum agrees reasonably well with the IceCube power law. For the following calculations, we assume that all sources, independent of their X-ray luminosity, have the same cutoff energy of $E_{p,\max} = 50$ TeV.

3. Individual point sources and a population of sources

Besides NGC 1068, we also consider seven other Seyfert galaxies from the BAT AGN Spectroscopic Survey (BASS) [17] that are located in the Northern hemisphere and have a high intrinsic X-ray flux in the 2-10 keV range. All considered individual sources and their properties are listed in Table 1.

In addition to those nearby point sources, we also consider the cumulative neutrino emission from an entire population of Seyfert galaxies. To describe the cosmological evolution of this source population, we assume a pure density evolution where the luminosity function is the same for all redshifts and only the number density of sources evolves with redshift. We consider it essential to include AGNs of all column densities, especially Compton-thick (CTK) AGNs because the column density along the line of sight only impacts the observed X-ray flux but not the neutrino luminosity of a source. The evolution of non-blazar AGNs, including heavily obscured CTK AGNs, has been examined in [18] and [19]. However, their high obscuration in X-rays makes them challenging to detect, and their cosmological evolution has large uncertainties.

We simulate a population of Seyfert galaxies together with their X-ray properties up to a redshift of $z = 5$, making use of the python package `popsynth` [20]. For that, we use the density evolution and the luminosity function for both Compton-thin and Compton-thick AGNs with $10^{42}\,\mathrm{erg\,s^{-1}} \leq L_X \leq 10^{46}\,\mathrm{erg\,s^{-1}}$ presented in [18] as inputs and neglect any uncertainties. We restrict the simulation to sources that have an intrinsic X-ray flux $F_X \geq 10^{-16}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ because fainter sources will not make a significant contribution to the diffuse neutrino flux at Earth. Moreover, we set an upper limit on the X-ray flux equal to the flux from CGCG 420-015, the faintest of the eight individual sources in Table 1, to avoid an overlap between the source population and the separately included nearby sources. Placing those cuts on the intrinsic X-ray flux, we end up with a population of $\sim$ 19 million sources with given redshift, declination, and X-ray luminosity. Each source can then be transformed into a neutrino source using $L_\nu \propto L_X$ and the spectral model discussed in Section 2.

4. Results

For each source in the source population and the separately included point sources, we calculate the expected number of neutrino events in 10 years of IceCube using `icecube_tools`[2], a python package that provides tools for working with public IceCube data. Here, we use the effective area from the 10-year IceCube data set of track-like events for point-source searches [21].

The expected number of neutrino events for each considered nearby source is given in Table 1. In agreement with observations, we find that NGC 1068 is by far the brightest neutrino source, with around 40 neutrino events. All other sources, including the second brightest source CGCG 164-019, are only expected to produce $\sim 1-3$ events within an observation time of 10 years. In addition, the source population is expected to produce $\sim$ 230 events that cannot be attributed to individual sources in the sky. A sky map of the expected number of neutrino events from the individual nearby sources and the population is shown in Fig. 2. In addition to the individual nearby sources, one can identify a few other dark spots in the sky. These correspond to sources in the population that produce $\sim$ 0.1 events. The diffuse neutrino emission from the entirety of all sources in the source population is visible as a light blue background.

The total diffuse neutrino flux from the source population and the point sources is shown in Fig. 3 together with the diffuse astrophysical neutrino flux measured by IceCube. Compared to the flux from the individual point sources, the diffuse flux from the population dominates up to $\sim$ 20 TeV. In the lowest energy bin, the flux from the source population constitutes around 10% of the total diffuse flux measured by IceCube. At higher energies, the flux from NGC 1068 and the population are approximately equal but small compared to the observed flux. We conclude that the entire population of Seyfert galaxies consisting of many very faint neutrino sources is more important for the diffuse flux than the contribution of single nearby sources.

In addition to the diffuse flux, we also investigate the detectability of the nearby individual sources with IceCube using similar methods to [23]. For each source, we compute the expected number of signal events in 10 energy bins between 1 and 100 TeV and do the same for the expected number of background events around the position of the source. Here, the background consists

[2]https://github.com/cescalara/icecube_tools

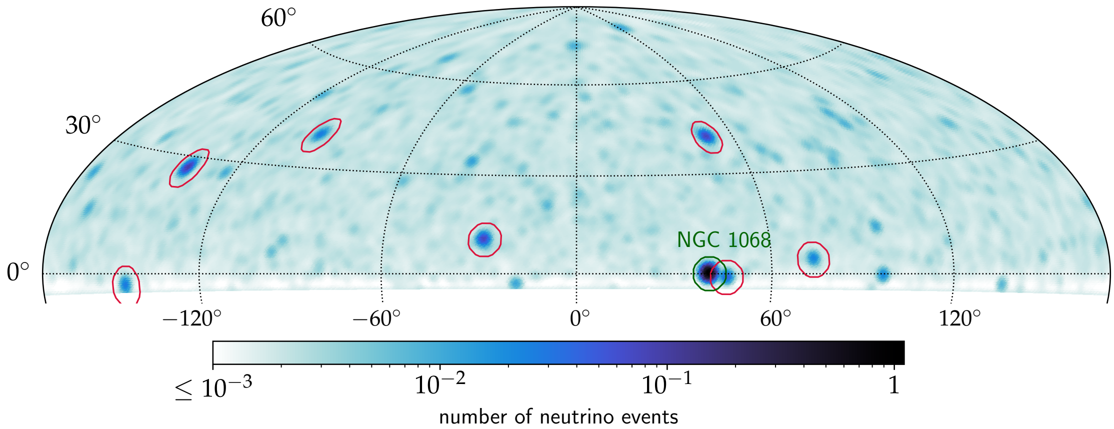

Figure 2: Sky map of the expected number of neutrino events in 10 years of IceCube from the source population and the separately included sources listed in Table 1. The latter are marked with red circles, and the colour scale indicates the number of neutrino events per pixel. The map shows the Northern hemisphere in equatorial coordinates using a Hammer-Aitoff projection and is smoothed with a symmetric Gaussian with $\sigma = 1.0°$. No atmospheric or diffuse astrophysical neutrino background is included in this plot.

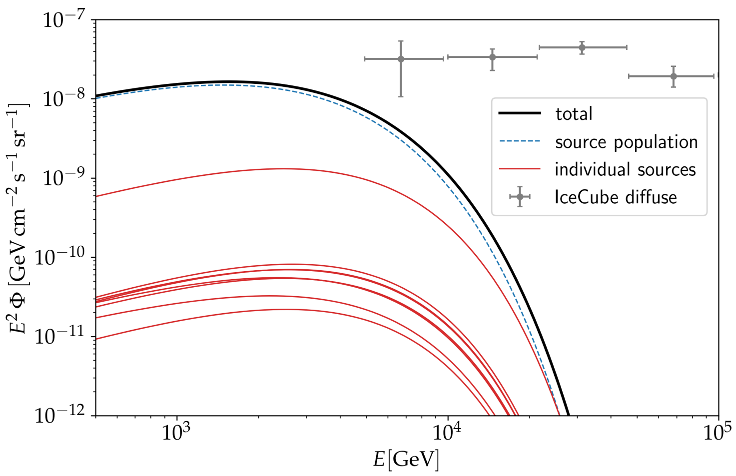

Figure 3: Diffuse per-flavour flux from the source population (blue dashed line) and the nearby sources (red lines). The black line corresponds to the sum of the two components. The diffuse neutrino flux from IceCube cascade data (grey data points) is shown for comparison [22].

of an atmospheric component originating from interactions of high energy cosmic rays with the Earth's atmosphere and an additional astrophysical component. For the astrophysical component, we approximate the diffuse IceCube flux shown in Fig. 3 as $\Phi \propto E^{-2}$. This approximation should be resonable as below $\sim$ 10 TeV, where most of the signal events are produced, the atmospheric background dominates over the astrophysical component. The angular resolution of IceCube at TeV energies is set to $\sigma = 1.0°$ [24] and, for each source, all signal and background events contained within an angular bin with radius 1.58σ around the source position are considered. This choice of the bin size is discussed in more detail in [25]. The expected p-values for each of the sources after 10 years of IceCube observations are shown in Table 1. With a local p-value of 7×10^{-5}, corresponding to a significance of 3.7σ, NGC 1068 is by far the brightest source in IceCube. At the moment, all other sources are very unlikely to be observed.

This could change once next-generation neutrino telescopes such as IceCube-Gen2 or KM3NeT start operating. IceCube-Gen2 is a planned expansion of the instrumented volume of IceCube from $1\,\mathrm{km}^3$ to $10\,\mathrm{km}^3$ [26]. Thanks to the fact that longer muon tracks can be contained within a larger detector volume, the effective area of IceCube-Gen2 will be a factor of ~ 5 larger than that of IceCube, and the angular resolution will increase by a factor of ~ 2 [27]. However, performing a calculation similar to the one described above, we find that for an observation time of 10 years, the prospects for detecting individual nearby sources besides NGC 1068 in IceCube-Gen2 are not very promising. Even for CGCG 164-019, the second brightest source after NGC 1068, we only obtain a p-value of 0.09 corresponding to a statistical significance of 1.3σ.

Nevertheless, a stacking analysis could help to uncover the cumulative neutrino emission from nearby bright Seyfert galaxies. Here, we approximate a full stacking analysis by simply adding the log-likelihood ratios (cf. Eq. (A2) in [23]) of the individual sources assuming that the events in the spatial bins associated with the different sources are independent. In our case, this assumption is reasonable since the considered sources are all far enough apart in the sky. Including all sources in Table 1 except for NGC 1068, we find that after 16 years of operation, IceCube-Gen2 is expected to identify neutrino emission from these sources at a level of 3σ.

KM3NeT is a neutrino telescope currently under construction in the Mediterranean Sea. Due to the increased scattering length of Cherenkov photons in water, it has an excellent angular resolution of $\sim 0.3^\circ$ at neutrino energies of $\sim 5\,\mathrm{TeV}$ [28]. Because of the large atmospheric neutrino background that decreases with the square of the angular resolution of the detector, KM3NeT is expected to have a significantly higher sensitivity to point sources emitting TeV neutrinos than IceCube. In addition, KM3NeT will be able to observe the Southern hemisphere. This is particularly interesting as several Seyfert galaxies located in the Southern Sky, such as the Circinus galaxy or NGC 7582, have a very high intrinsic X-ray flux and could thus be promising targets for KM3NeT.

5. Conclusions and outlook

We present a simple spectral model that connects the X-ray properties of a Seyfert galaxy to its neutrino emission and use this model to investigate the diffuse emission from a population of Seyfert galaxies and the detectability of a selection of individual nearby sources. So far, our results are consistent with observations: NGC 1068 is the brightest neutrino source, while all other nearby Seyfert galaxies are much fainter. Moreover, we find that the entire population of Seyfert galaxies could contribute a significant fraction to the observed diffuse neutrino flux at TeV energies. Based on our assumptions, analyses considering the combined emission of multiple sources are the most sensitive to uncovering further NGC 1068-like objects in neutrino observations, and we plan to explore this possibility further in future.

References

[1] M. Aartsen et al., *Phys. Rev. Lett.* **111** (2013) 021103 [1304.5356].

[2] M. Aartsen et al., *Science* **342** (2013) 1242856 [1311.5238].

[3] K. Murase et al., *Phys. Rev. Lett.* **116** (2016) 071101 [1509.00805].

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

[5] N. Tikhonov and O. Galazutdinova, *Astrophys. Bull.* **76** (2021) 255.

[6] P. Padovani, *A multi-wavelength overview of NGC 1068*, Talk at Topical Workshop: NGC 1068 as cosmic laboratory, Garching, Germany, March 6-10, 2023.

[7] A. Marinucci et al., *MNRAS* **456** (2016) L94 [1511.03503].

[8] V. Acciari et al., *Astrophys. J.* **883** (2019) 135 [1906.10954].

[9] Y. Inoue et al., *Astrophys. J. Lett.* **891** (2020) L33 [1909.02239].

[10] B. Eichmann et al., *Astrophys. J.* **939** (2022) 43 [2207.00102].

[11] K. Murase, *Astrophys. J. Lett.* **941** (2022) L17 [2211.04460].

[12] A. Lamastra et al., *A&A* **596** (2016) A68 [1609.09664].

[13] E. Peretti et al., *arXiv* (2023) [2301.13689].

[14] S. Abdollahi et al., *ApJS* **247** (2020) 33 [1902.10045].

[15] F. Oikonomou, *Proceedings 37th ICRC* (2021) 030 [2201.05623].

[16] C. Dermer and G. Menon, *High Energy Radiation from Black Holes: Gamma Rays, Cosmic Rays, and Neutrinos*, Princeton University Press, Princeton (2010), 10.1515/9781400831494.

[17] C. Ricci et al., *ApJS* **233** (2017) 17 [1709.03989].

[18] Y. Ueda et al., *Astrophys. J.* **786** (2014) 104 [1402.1836].

[19] J. Buchner et al., *Astrophys. J.* **802** (2015) 89 [1501.02805].

[20] J. Burgess and F. Capel, *JOSS* **6** (2021) 3257 [2107.08407].

[21] IceCube Collaboration, *All-sky point-source IceCube data: years 2008-2018*, Dataset (2021), 10.21234/sxvs-mt83.

[22] M. Aartsen et al., *Phys. Rev. Lett.* **125** (2020) 121104 [2001.09520].

[23] A. Kheirandish et al., *Astrophys. J.* **922** (2021) 45 [2102.04475].

[24] R. Abbasi et al., *arXiv* (2021) [2101.09836].

[25] D. Alexandreas et al., *NIMPA* **328** (1993) 570.

[26] M. Aartsen et al., *arXiv* (2014) [1412.5106].

[27] B. Clark, *J. Instrum.* **16** (2021) C10007 [2108.05292].

[28] S. Adrián-Martínez et al., *JPhysG* **43** (2016) 084001 [1601.07459].