

Shower angular resolution in IceCube-Gen2 and implications on diffuse science

The IceCube-Gen2 Collaboration

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Over the past decade, the IceCube Neutrino Observatory has discovered a diffuse astrophysical flux and evidence for the first astrophysical neutrino sources, thus highlighting the utility of neutrinos as a new messenger in astronomy. IceCube-Gen2, proposed to be eight times larger than the current detector, will be able to accelerate new discoveries. In order to reach the target volume necessary, the detector is designed with a sparser string spacing. With twice the inter-string distance of IceCube, the angular reconstruction of particle showers in IceCube-Gen2 will benefit from new multi-PMT optical modules, accurate modeling of ice properties and a precise understanding of all available sensor data. In this contribution, we show the achievable angular and energy resolutions for shower events observed in IceCube-Gen2 and their dependencies on sensor efficiencies. Implications on diffuse measurements will also be discussed.

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1. Introduction

High-energy neutrinos, originating from cosmological distances, play a crucial role in advancing our understanding of fundamental particle physics and exploring the extreme realms of the Universe. To detect and study these elusive particles, the IceCube Neutrino Observatory was constructed at the geographic South Pole over a decade ago [1]. With its state-of-the-art instrumentation and data collection capabilities, IceCube has provided invaluable insights into the cosmic neutrino landscape. Notably, the IceCube collaboration reported neutrinos emitted from astrophysical sources in close proximity to supermassive black holes, such as NGC 1068 [2], TXS 0506+056 [3, 4], as well as neutrinos originating from within our own galaxy, the Milky Way [5].

In order to improve the detection efficiency for high-energy neutrinos, it is essential to increase the size of the detection volume. As a result, the spacing between strings in the detector has been expanded from 120 m to 240 m [6]. A larger detector also allows better pointing with high-energy muon and tau tracks thanks to a longer lever arm and therefore support point source identifications and multimessenger follow ups [7]. However, the impact of the expanded detector on cascades from charged current electron neutrino interactions and all-flavour neutral current interactions is less certain.

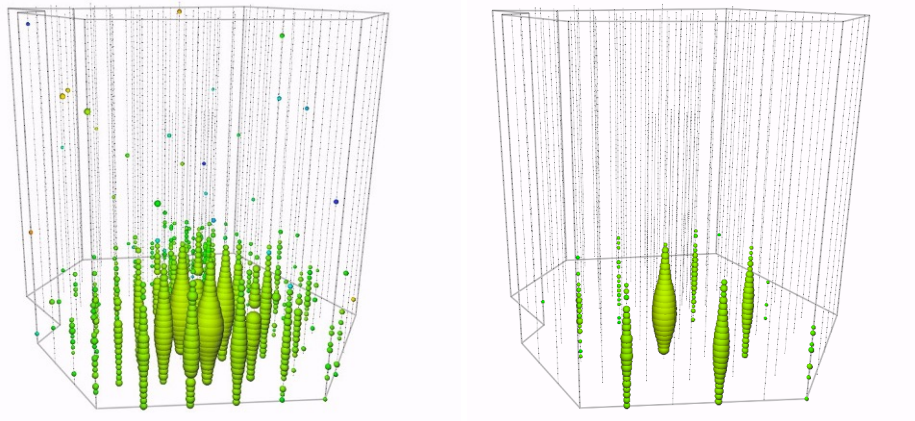


Figure 1: An example 100 TeV electron neutrino induced charged current event seen in IceCube (left) and in Gen2 (right)

Cascades play a critical role in detecting extragalactic and galactic diffuse neutrino emissions. Compared to tracks from muon neutrinos, cascades originating from electron and tau neutrinos possess a distinct advantage due to their reduced probability to the atmospheric neutrino background [8]. Typically, photons produced by a 100 TeV cascade resulting from an electron neutrino-induced shower can travel to strings within a range of ~ 300 m, depending on the optical properties of the ice layer where the interaction takes place [9]. Figure 1 (left) illustrates an event simulation of such a cascade in IceCube, while Fig. 1 (right) shows the corresponding detector response in the context of Gen2.

Accurate angular resolution of cascades is crucial for diffuse analyses. It helps to distinguish the signal from the atmospheric prompt neutrino flux by leveraging the self-veto mechanism [8, 10, 11], which considers the presence of accompanying muons within the same cosmic-ray shower.

Additionally, precise pointing capabilities with cascades are essential for measuring the diffuse flux originating from the Galactic plane and for searching for extended point sources in that region.

In this proceeding, we focus on the idealized angular resolution of cascades in IceCube and IceCube-Gen2, assuming perfect knowledge of the ice and detector properties. Our study is based on the use of single-pixel light sensors. Additionally, we provide a brief discussion on the potential reconstruction improvements that can be achieved by introducing segmented sensors in the ice.

2. Cascade reconstruction

There is a trade-off between speed and accuracy in photon yield models used in reconstruction. For the purposes of this proceeding, we focus on event reconstruction with relatively fast evaluation times at the expense of additional approximations.

Due to sparse instrumentation and complexity inherent in the natural detection medium, several challenges arise in the reconstruction of particle showers. These include ice modeling [12], shower longitudinal extension [13], and randomness introduced by the response of the detector itself [1]. The essence of event reconstruction routines used in IceCube relies on recovering the underlying physics parameters that yield photon arrival time expectations most closely matching the observed data, which can be simulated or real [14]. Likelihood-based metrics to define closeness are widely employed. With such approaches, it is obvious that accurate modeling is important and necessary in order to reduce systematic bias [15, 16]. In this section, we discuss approaches taken to evaluate ideal directional resolution for cascades and potential room for future improvement by incorporating multi-PMT sensors [17, 18].

2.1 Ideal cascade resolution

In order to illustrate the potential of ice as a natural neutrino detector and directly compare shower reconstruction with IceCube-Gen2 to that in IceCube, we use simplified model where contained cascades in IceCube are in addition reconstructed with a Gen2-like string spacing. An example of such an event in both geometries is shown in Fig. 1, and a simulated sample of contained cascades is used for performance evaluation. Furthermore, several assumptions are made in the simulation used for the benchmark. First, we require the ice model used in simulation to exactly match that used in reconstruction. Second, we assume that the cascade longitudinal extension is negligible. Third, we assume a detector response function that does not introduce additional smearing in the conversion of photons incident at the PMT photocathode to the actual digitized data stored as a timeseries of representations of photoelectrons [1]. That is, we assume an idealized version of cascade and detector. These assumptions allow us to set a limit on what is achievable for cascade reconstruction due to only photon statistical fluctuations.

The left panel of Fig. 2 shows the IceCube median angular resolution for a sample of simulated, contained electron (anti)neutrino interactions as a function of the true, deposited energy and obtained under the idealized scenario described above. The blue (orange) solid line shows the median 50% quantile over the distribution in angular spread between true and reconstructed directions when including (excluding) the nearest, “bright”, DOMs. The respective color bands correspond to the 25% and 75% quantiles for the angular distance distribution. At an energy of 1 PeV the resolution is below one degree when including bright DOMs. A visual comparison to the event views shown

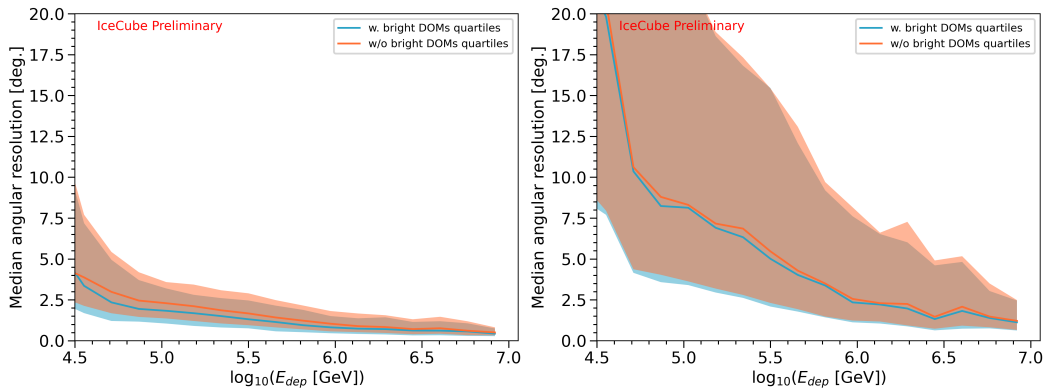


Figure 2: The left panel shows the median angular resolution (solid lines) for an idealized sample of IceCube-contained cascades as a function of the deposited energy. The blue (orange) line shows the resolution with (without) the nearest DOMs, typically referred to as “bright” DOMs. Color bands corresponds to the 25% and 75% quantiles for the angular distance distribution. The right panel shows the same reconstruction with bright DOMs, but for an approximate IceCube Gen2 string spacing. A toy Gen2 geometry is obtained by masking out IceCube strings such that the approximate inter-string distance is doubled compared to IceCube’s. The additional photocathode coverage expected for Gen2 DOMs is approximated by a global increased efficiency that is three times the detection efficiency of IceCube DOMs. Thus, this does not incorporate directionality information from multi-PMT sensors, which are under construction for IceCube-Gen2.

in Fig. 1 illustrates the challenge in cascade reconstruction while highlighting the impressiveness of a less than 1° resolution, even if only currently under the idealized scenario.

IceCube-Gen2 is envisioned as a detector approximately eight times larger than IceCube. To stay within resource constraints, Gen2 strings will be spaced approximately 240 m apart. Thus, with roughly double the string spacing of IceCube, the instrumentation in IceCube Gen2 is effectively four times sparser. New sensors planned for Gen2 will have increased photocathode coverage, increasing light detection efficiency by up to a factor of four. However, the light yield falls off exponentially with distance and this limits the absolute photon statistics detectable by Gen2 for cascade-like morphologies [14]. The resolution obtained under the idealized scenario for a toy Gen2 geometry with a global OM efficiency scaling of $3\times$ IceCube-DOM equivalent is shown in Fig. 2 (right panel) and, while there is clear degradation compared to the left panel, it is worth highlighting that at 1 PeV the median resolution is approximately 2.5° . Considering that this is for the reconstruction of particle showers that appear nearly spherical, the potential to utilize cascade directionality in IceCube Gen2 is high if sensor information can be accurately and efficiently unlocked.

2.2 Potential improvements with future multi-pixel sensors

The Long Optical Module (LOM) is a sensor currently being developed for IceCube-Gen2. It combines the elongated shape of the D-Egg (Dual optical sensors in an Ellipsoid Glass for Gen2) with the 4π pixelation of the mDOM (Multi-PMT Digital Optical Module), both of which will be deployed for the IceCube Upgrade [19]. The LOM is the reference optical sensor design for IceCube-Gen2 [20], equipped with either 16 or 18 PMTs per sensor. The LOM design offers a

sensitivity gain of approximately four times the current IceCube DOM and provides additional timing-dependent directional information.

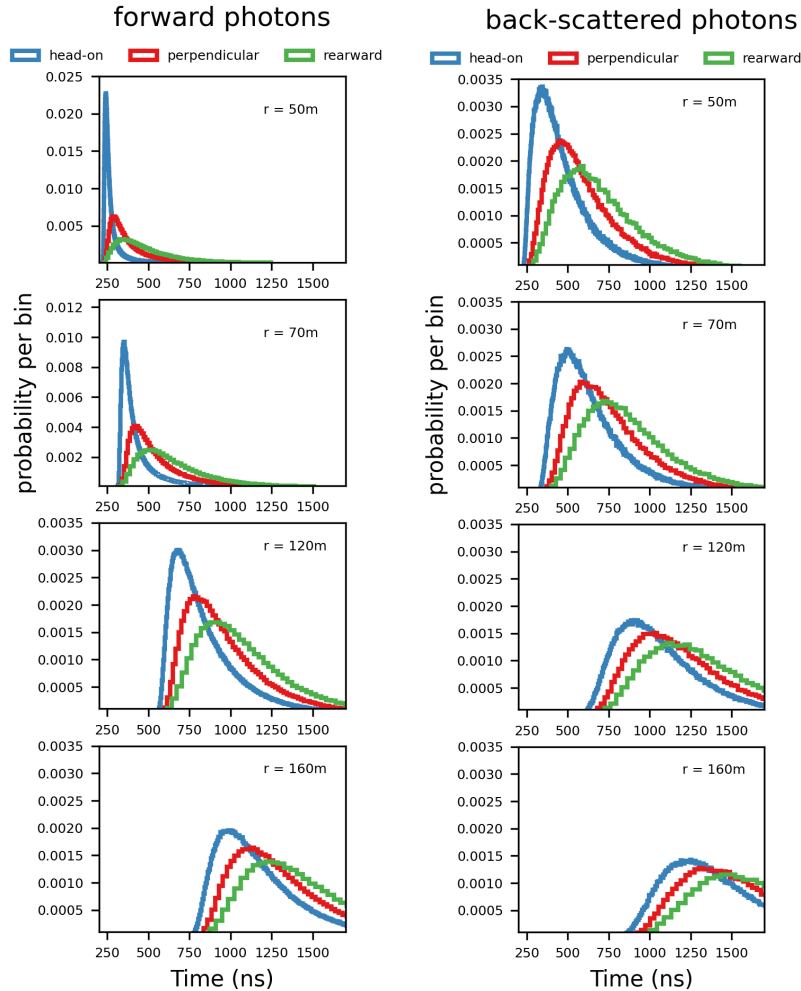


Figure 3: Timing Distributions for Forward (left) and Back-Scattered (right) for Photons emitted in a single direction in homogeneous ice. The forward scattered photons are arriving from the direction of the source. The backwards scattered photons are arriving from the direction away from the source. Head-on photons are when the photons are emitted in the direction of the sensor, perpendicular are when photons are emitted in a direction perpendicular to the sensor, and rearward are when photons are emitted away from the sensor.

The directional reconstruction method for the LOM relies on a maximum likelihood fit, which involves six free parameters: the interaction time, vertex position and the direction angles. When the emission direction of the initial photon changes, the timing distributions at a given sensor location in the ice undergo variations in shape and relative flux. These changes are influenced by factors such as the distance from the source and the arrival direction of the photons.

To illustrate the reconstruction improvement achieved with pixelation, we conducted simulations using an up-going photon emitter [21]. In the simulation, we injected photons with wavelengths sampled from the Cherenkov radiation spectrum, taking into account the wavelength acceptance of the photon sensors [1]. The effective scattering length and the absorption length of the photons

were set to 19.9 m and 63.8 m, respectively. During the simulation, the positions and directions of photons are traced and recorded.

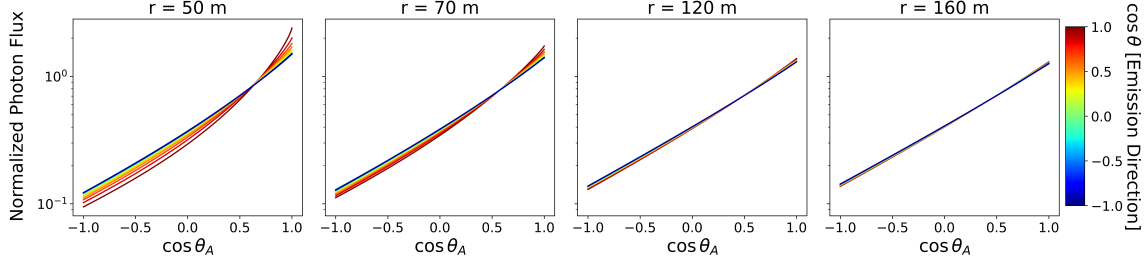


Figure 4: The four panels depict the normalized photon flux as a function of the arrival zenith of the photon ($\cos \theta_A$) depending on the emission direction of the light source ($\cos \theta$). The light source is emitting head-on when $\cos \theta$ is 1 and rearward when $\cos \theta$ is -1. The photons are forward scattered when $\cos \theta_A$ is 1 and back-scattered when $\cos \theta_A$ is -1. As distance increases, the shape of the photon arrival flux distribution loses its dependence on emission direction, while the dependence of photon flux on arrival direction remains.

Figure 3 shows directional information of photons emitted in a single direction in homogeneous ice. The forward scattered photons are arriving from the direction of the source. The backwards scattered photons are arriving from the direction away from the source. Head-on photons are when the photons are emitted in the direction of the sensor, perpendicular are when photons are emitted in a direction perpendicular to the sensor, and rearward are when photons are emitted away from the sensor. The risetime of photon arrivals is influenced by various by the position of the receiver relative to the source and the direction of the photons after scatterings [22]. When photons undergo fewer scatterings, the waveform rises more quickly. Figure 4 illustrates the relative photon flux as a function of the photon arrival direction at various distances for different photon emission angles. The figures show that head-on/rearward asymmetries at close distances, which are crucial for providing multi-pixel information for directional reconstruction. Additionally, the forward/backward asymmetry contributes to improved reconstruction of the vertex position, even at a distance of 160 m.

Cascade reconstructions harvesting pixellation information is under development. One notable difference from existing reconstruction algorithms is the inclusion of both the position and directional information of the arrival photons relative to the receiver. Traditionally, only the photon directions are considered, while the positions are marginalized as long as the photons reach the sensor. We expect a further improvement of angular resolution with pixellation taking into account.

3. Implications on diffuse science

The ability to accurately reconstruct the directions of cascades despite the larger detector spacing will substantially improve IceCube-Gen2’s ability to observe extended neutrino emission, such as that recently reported from our own galaxy [5]. To illustrate this, we use `toise` [23] to model IceCube-Gen2’s sensitivity to Galactic neutrino emission. To estimate the detector acceptance, we compare the effective area of the selection presented in [24] to a similar selection for IceCube-Gen2, and find that the latter is a factor ~ 8 larger. We take this as a generic scaling factor from IceCube to IceCube-Gen2 for selections of cascade-like events, and apply it to the effective area from [5] to obtain an approximate effective area for a high-acceptance event selection in IceCube-Gen2.

To treat angular resolution, we fit a Fisher-von Mises distribution to the distribution of opening angles for an idealized (but single-pixel) reconstruction in Gen2 (cf. Fig. 2 right panel), and smooth a Galactic emission template in an energy-dependent way using the resulting concentration parameter. Fig. 5 shows examples of this smoothing. In order to be able to compare to existing results in the same framework, we also approximate the response of IceCube using the angular resolution and (unscaled) effective area from [5]. With these approximations, we expect to obtain a median significance of the Galactic emission, assuming that the true flux is $0.55 \times \text{KRA}_\gamma^5$ (the best fit from [5]), of approximately 11.1σ with 10 years of IceCube-Gen2 data alone, versus approximately 4.7σ for 10 years of IceCube data. In order to demonstrate the high-energy reach of Gen2 for galactic emission, we construct the artificial scenario shown in Fig. 5 (right), where the galactic flux continues with a spectral index of 2.4 beyond the cutoff predicted in the KRA_γ^5 model. In this scenario, IceCube would be able to exclude the predicted cutoff with a median significance of only 2.5σ after 10 years of observations, while Gen2 would be able to exclude it with 7.4σ .

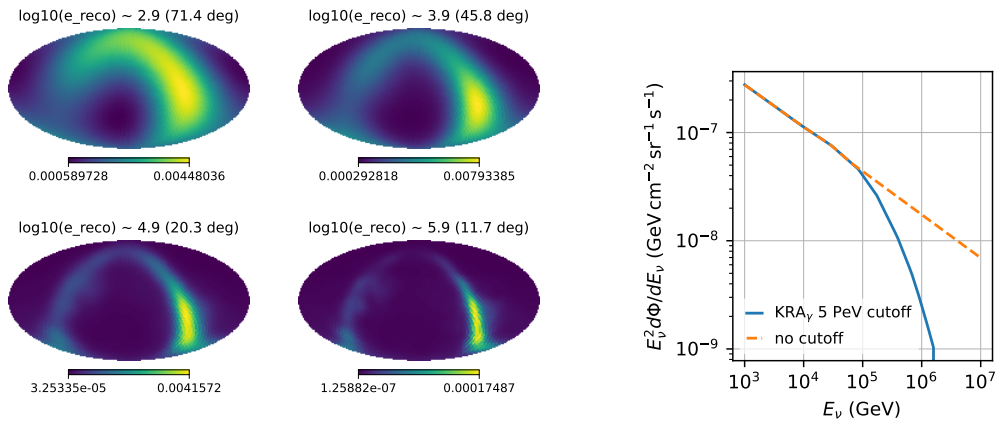


Figure 5: Left: expected distributions of reconstructed galactic neutrino events in Gen2 in four energy bands, assuming the baseline angular resolution shown in Fig. 2 (right panel). The maps are presented in equatorial coordinates with right ascension running left to right from $+180^\circ$ to -180° , putting the Galactic center in the lower right of each map. Right: toy flux model to illustrate IceCube-Gen2's ability to distinguish between galactic neutrino emission scenarios. The solid line shows the KRA_γ flux from [25], scaled to the best-fit normalization found in [5]. The dashed line shows a flux with the same shape at low energies, but that continues beyond the cutoff with a spectral index of 2.4.

4. Conclusion

We presented a simulation study to showcase the idealized angular resolution for cascade events measured in IceCube-Gen2, relying on a sparser version of the IceCube geometry with double the string spacing compared to IceCube. Using a single-pixel sensor with a photon detection efficiency three times that of the IceCube DOM, we achieved a median angular resolution of approximately 8° at 100 TeV and 2.5° at 1 PeV. With such angular resolution and effectively a factor of eight gain of detector volume we expect a rejection of the hypothesis of no cutoff in the diffuse galactic emission at 7.4σ after 10 years of data taking with IceCube-Gen2. Further improvements are expected after taking into account the LOM pixellation information.

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