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Ultra-High-Energy Transient Source Search using IceCube Neutrinos and Pierre Auger Photon Candidates

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The origins of ultra-high-energy particles remain one of the most profound mysteries in astrophysics. If nearby transient sources of ultra-high-energy particles exist, we might expect correlated emission of neutrinos and photons, arriving in close temporal and spatial coincidence. The IceCube Neutrino Observatory, located at the South Pole, is sensitive to neutrinos from TeV to EeV energies, while the Pierre Auger Observatory, in Argentina, detects cosmic rays and has the capability of observing ultra-high-energy photons using surface and fluorescence detectors. The ultra-high-energy photon candidates reported by the Auger Collaboration, though consistent with cosmic ray backgrounds, provide a compelling opportunity to search for correlated neutrino-photon events. In this contribution, we present the framework to search for ultra-high-energy transients by combining multi-flavour neutrino data from IceCube with photon candidates from the Auger Detector from 2011 to 2017. We will report the sensitivities that we expect to achieve from the search and the astrophysical implications of the possible outcomes.

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1. Introduction

An enduring question in astrophysics is the origin of ultra-high-energy particles. One method for finding these sources is through multi-messenger astronomy. Proton-proton (pp) or proton-gamma ($p\gamma$) interactions in a nearby source could yield photons and neutrinos with energies greater than one EeV. We will search for ultra-high-energy sources using spatial and timing coincidences between two messengers. For a similarly sized detector to the Pierre Auger Observatory, accounting for photon interactions while propagating in the cosmic microwave background (CMB), we would expect to detect photons with energies greater than 10 EeV from a source similar to a low-luminosity gamma-ray burst (LLGRB) within 10 Mpc, after which the detection probability decreases [1]. Coincident photons and neutrinos from nearby astrophysical sources should be detectable. Figure 1 illustrates the diffuse landscape at energies above 10 TeV for neutrinos, UHE photons, and cosmic rays. Assuming neutrinos and photons are produced by the same hadronic interactions at the source, we would expect that the neutrino flux and UHE photon flux to be comparable. This is illustrated by the comparison of the upper limits on the diffuse UHE photon flux set by the Auger Detector [2–4] to the extrapolated diffuse neutrino flux measured by the Medium Energy Starting Events (MESE) selection in IceCube [5]. In this analysis, we will be looking for photons and neutrinos produced by a transient flare from the same astrophysical source.

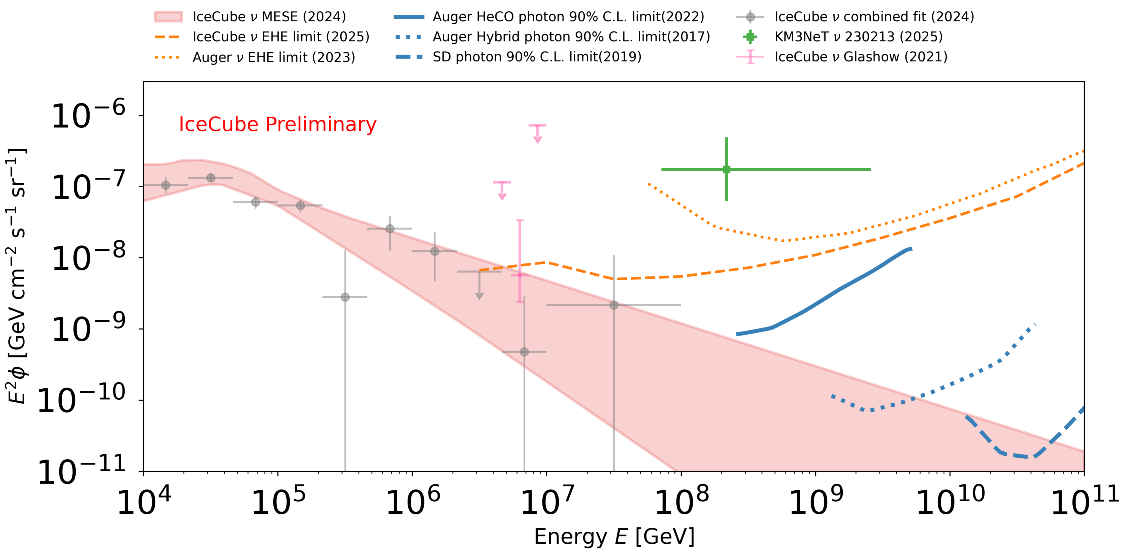


Figure 1: Multi-messenger diffuse flux measurements for neutrinos [6, 7]. Upper limits for the ultra-high energy photons is included [2–4]. Upper limits are compared to the projection of the diffuse neutrino flux using measurements from the Medium Energy Starting Events (MESE) selection [5]. Differential limits are shown for the high-energy neutrino flux set by IceCube and Auger Detector [8, 9]. The measurement from the KM3-230213A neutrino is also shown [10].

1.1 IceCube Neutrino Observatory

IceCube is a cubic kilometer neutrino observatory located at the geographic South Pole. It provides full-sky coverage with a greater than 99% uptime [11]. IceCube has performed many prior searches for transient sources. These searches have resulted in upper limits on the neutrino emission from high luminosity Gamma Ray Bursts (GRBs), such as GRB 221009A [12]. Searches for coincident neutrinos from gravitational wave (GW) emission, such as during the O3 run, have not found significant emission [13]. IceCube has found evidence for neutrino emission from the flaring blazar TXS 0506+056, which has coincident gamma-ray emission [14].

1.2 Pierre Auger Observatory

The Pierre Auger Observatory is a cosmic ray detector composed of a surface detector (SD) and florescent detector (FD). The SD comprises of 1660 water-Cherenkov detectors distributed over an area of 3000 km^2. The FD is composed of 27 telescopes operated at 4 different sites to measure the longitudinal development of the air shower [15]. In addition to detecting cosmic rays, the Pierre Auger Observatory is also capable of observing EeV photon showers. Using events detected by the FD in combination with the SD, photon candidates are selected using differences in muon fraction and the depth of the shower maximum compared to cosmic ray showers [16].

2. Analysis Method

In this proposed analysis, we are searching for neutrinos from the direction of photon candidates. These candidates will have a similar treatment to previous IceCube searches of neutrinos from the same direction and time as gravitational waves [17]. To accomplish this, we seek a significant neutrino detection in spatial and timing coincidence with the photon candidate while accounting for the uncertainty in photon reconstruction. This section details how photon candidates and IceCube neutrino event selections are incorporated into the analysis. Additionally, we outline the unbinned maximum likelihood method that will be employed in the analysis.

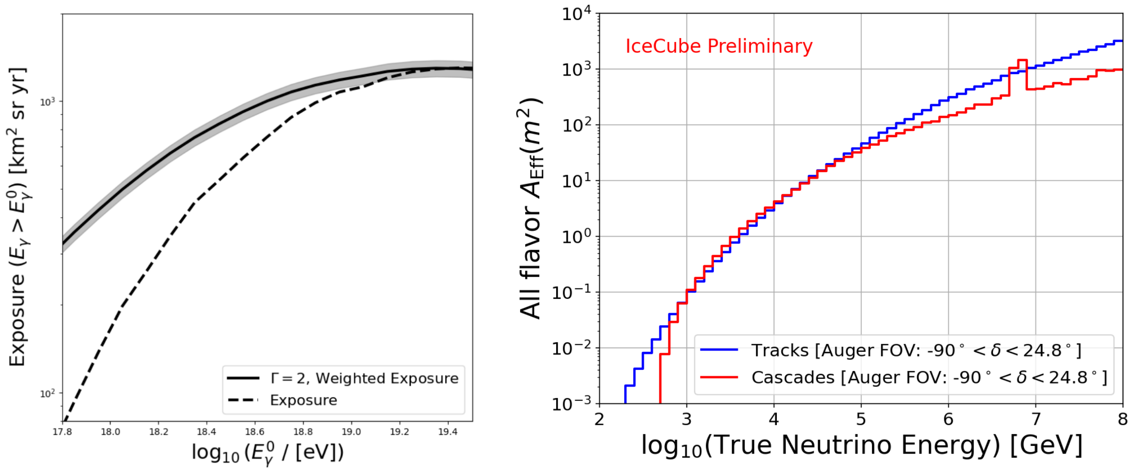
2.1 Photon Candidates

To perform this analysis, we utilize UHE photon candidates with energies greater than one EeV from the Auger Observatory as a prior for a source location, where the uncertainty in the directional reconstruction map is accounted for by a spatial probability density function (PDF). For hybrid events, the uncertainty in reconstructed direction is approximately one degree. While we sample these photons from the hybrid photon analysis [16], the Auger Collaboration has performed additional searches for UHE photons [2–4, 18]. Figure 2a shows the exposure for the hybrid photon selection, i.e. events detected by the FD in combination with the SD.

2.2 Neutrino Selections

The field of view of the Auger Observatory for photons ranges from declinations of -90° to 24.8°. To increase our sensitivity to transients in those directions, we use a multi-flavor neutrino sample. The sample consists of two IceCube event selections. The first is an all-sky throughgoing tracks selection [19], which is predominately composed of muon neutrinos with well-reconstructed directions. These events are characterized by long "tracks" through the detector. The second selection is the cascades selection, which is primarily composed of neutral-current, ν_e^{CC} (charged-current), and ν_τ^{CC} neutrino interactions that leave compact, spherical energy deposits in the detector.

These events have less precise angular reconstruction. The cascades selection was previously utilized to detect the emission of high-energy neutrinos from the galactic plane at 4.5σ [20]. We remove overlapping events between these selections in data, choosing to leave the overlapping events in the cascade selection and removing them from the track selection (less than .1% of tracks selection). Figure 2b shows the effective area of the tracks and cascade selections for neutrinos in the field of view of the Auger Detector.



(a) **(b)**

Figure 2: (a) The exposure for the photons analysis from [16]. The weighted exposure (solid line) assumes a power-law spectrum of $\gamma = 2$. The raw exposure (dashed line) is also shown for comparison. **(b)** The IceCube tracks [19] and cascades [20] selection effective areas in the field of view of Auger Detector.

2.3 Likelihood Construction

To perform this analysis, we construct an unbinned likelihood for a combined sample

$$\mathcal{L}(\gamma, n_s) = \prod_{j}^{M} \frac{(n_s^j + n_b^j)^{N^j} e^{-(n_s^j + n_b^j)}}{N^j!} \prod_{i \in j}^{N^j} \left[\frac{n_s^j}{n_s^j + n_b^j} \mathcal{S}_i^j(\delta_i^j, \sigma_i^j, \gamma = 2) + \frac{n_b^j}{n_s^j + n_b^j} \mathcal{B}_i^j(\delta_i^j) \right], \quad (1)$$

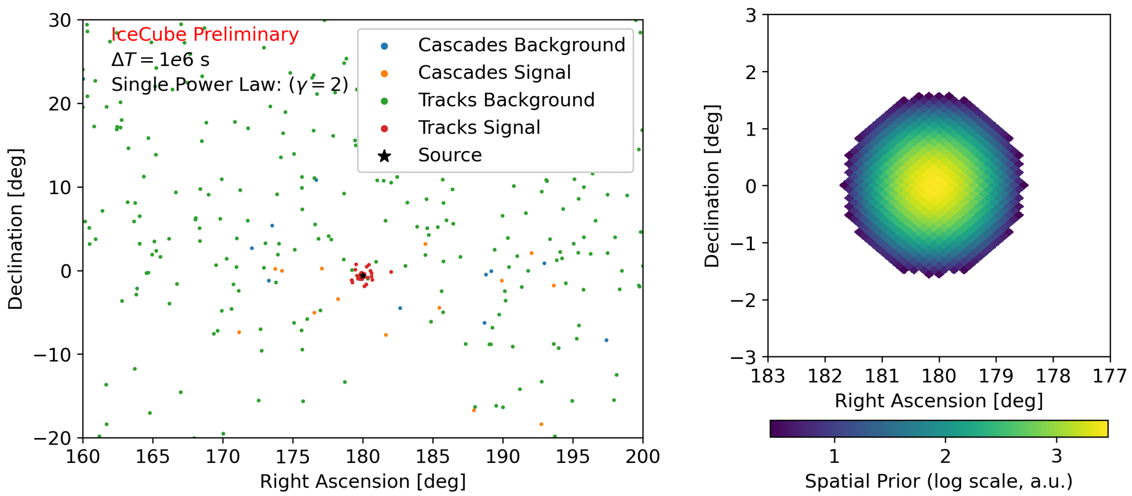
where M is the number of samples and j iterates over the samples, while N^j is the total number of events in each sample occurring during the transient time window and i iterates over those events. Additionally, n_s is the fit number of signal events, and n_b is the expected number of background events. $\mathcal{S}$ and $\mathcal{B}$ are the signal and background PDFs respectively, which are composed of energy, spatial, and time PDFs

$$\mathcal{S}_i^j(\delta_i^j, \sigma_i^j, \gamma = 2) = \mathcal{S}_{\rm space} \times \mathcal{S}_{\rm energy} \times \mathcal{S}_{\rm time} \quad (2)$$

as described in [21] and the background PDFs is constructed from

$$\mathcal{B}_i^j(\delta_i^j) = \mathcal{B}_{\rm space} \times \mathcal{B}_{\rm energy} \times \mathcal{B}_{\rm time}. \quad (3)$$

where σ_i is a per-event description of the point spread function (PSF) and δ_i is the declination. The signal energy PDF is generated assuming a $\gamma = 2$ power law spectrum at the source and the background energy PDF is generated from data. The energy PDF describes the relative count of events at different energies for each declination. For example, a harder signal spectrum than background spectrum will result in a ratio above one at high energies when comparing the signal to background PDF. The signal spatial PDF is a circularized PSF described by a Kent distribution with a spread σ_i. When the spread is less than 7 degrees, the PSF is approximated by a Gaussian. The background spatial PDF is constructed using the data rate as a function of declination. Tracks have greater precision in reconstructed direction compared to cascades, so signal events will be clustered closer to the source, as depicted in Figure 3a. The background spatial distribution is also



(a) (b)

Figure 3: **(a)** A single power law injection for a flare of a million seconds from an arbitrary direction in the Auger Detector's photon field of view. The longer flare is to increase the number of background events for visualization. Each point shows the reconstructed direction of a neutrino event. 50 total signal events where injected, and are split between tracks and cascades by the effective area of each selection. The spread in signal events comes from the precision with which events can be reconstructed. Cascades have a larger point spread function than tracks, so they have more spread. Background scrambled events from tracks and cascades are also shown, where the tracks selection has a higher event rate than cascades. **(b)** An example spatial prior map representing the uncertainty of a point source position with a gaussian σ of 1 degree made by smoothing a HEALPix map using healpy [22]. The spatial prior is masked for 99.9% containment of the cumulative density function starting with the most probable position. The position on the sky is arbitrary.

depicted. The timing PDF is a boxed timing window centered on the photon candidate time with a total width of 20,000 seconds. Longer-time window estimates for LLGRBs and Long-GRBs have durations of up to 10,000 seconds [23]. The timing window is then extended to 10,000 seconds before the photon arrival time to allow for the case that the photon is emitted late in the flare. We construct a test statistic (TS) by maximizing the log-likelihood ratio

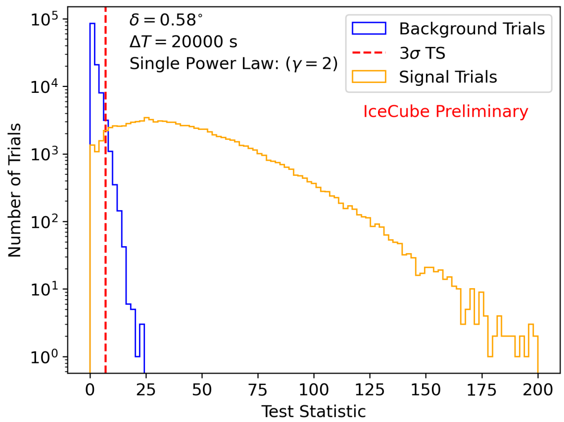
$$\mathrm{TS} = \max\left(-2\ln\left[\frac{\mathcal{L}(n_s=0)}{\mathcal{L}(\hat{n_s})}\right] - 2\ln\left[\frac{1}{w(\Omega)}\right]\right), \tag{4}$$

where a penalty is applied to the TS based on the location in the spatial prior map. The penalty term makes up the second component of the equation, where w is probability that the source is at the location Ω on the sky over the best fit location of the photon candidate. We normalize the penalty factor w so that it equals 1 at the most probable location. We compute the TS at each pixel in the spatial prior and pick the highest resulting TS. Figure 3b depicts a spatial PDF that is a Gaussian with a spread (σ) of 1 degree. The location of the spatial PDF is arbitrarily chosen within the field of view of Auger Observatory. The size of the spatial prior was chosen to be similar to the size of the angular resolution of the hybrid photon candidates. The spatial prior is masked for 99.9% containment of the cumulative PDF starting from the most significant pixel to the least. The significance of our results are computed from the TS.

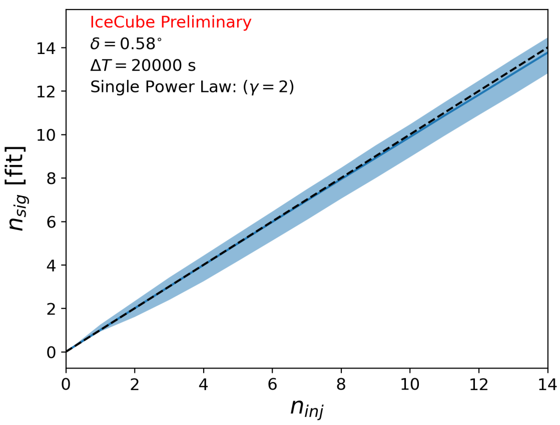
3. Sensitivities

3.1 Defining Sensitvities

To construct our sensitivities, we perform background trials by randomly scrambling the neutrino data. For the scrambling procedure, we inject data events with Poisson fluctuations at the background rate from outside of the active flare time window. The arrival time of neutrino data is randomized within the flare timing window. We then evaluate the TS of each background trial using the unbinned maximum likelihood method. Over many trials, we produce the background TS distribution represented by the blue line in Figure 4a, which is an example picked at an arbitrary declination. To find our sensitivity, we perform injection trials with Poisson fluctuations around a



(a)



(b)

Figure 4: (a) The background test statistic distribution is depicted in blue and the TS value corresponding to the 3σ sensitivity in red for a declination of $\delta = 0.58$. The orange line shows the test statistic distribution when injecting a mean of 3.42 signal events, which corresponds to the 3σ sensitivity. The fit is fixed at a spectral index of 2 and uses a boxed timing window. **(b)** An injection and recovery test at a declination of $\delta = 0.58$. In blue, the median and 1 sigma error bands for the fit n_{sig} are shown for different n_{inj}. The dashed black line is the diagonal showing a ratio of 1 for fit n_{sig} to n_{inj}. The fit is fixed at a spectral index of 2 and uses a boxed timing window.

mean n_s corresponding to a flux from a given source model increasing the strength until 90% of the TS values are greater than the 3σ TS value for the background TS distribution. The lowest fluence that meets the 90% criteria is the 3σ sensitivity. Figure 4a shows in orange the TS distribution for the number of signal events injected at the 3σ sensitivity. In addition, we demonstrate that the fit recovers the number of injected neutrinos over a wide range of injection strengths. The result of this process for a single point source is shown in Figure 4b.

3.2 Transient Sensitivities

With the multi-flavor neutrino sample and the EeV photon candidates, we will perform a search for UHE transient sources by performing the coincidence search described above. To evaluate the sensitivity of IceCube to transient neutrino sources, we evaluate tracks and cascades: both combined and individually, for a flare duration of 20,000 seconds centered on the photon candidate time at all declinations, as depicted in Figure 5. The effect of the choice of timing window for the sensitivities are depicted in Figure 6. The 90% sensitivity does not shift much with a larger timing window, but the 3σ sensitivity worsens for flare durations larger than 100 seconds.

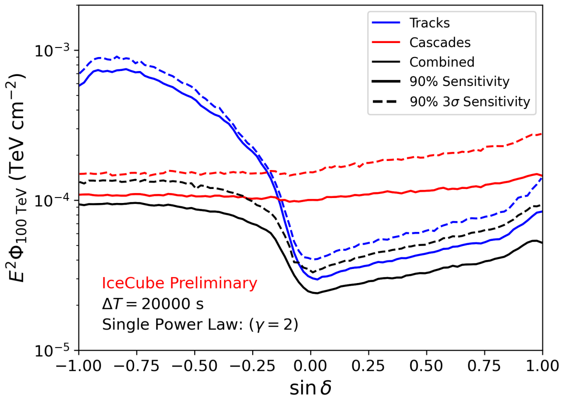


Figure 5: The transient sensitivities of the IceCube tracks and cascades sample are calculated using a point source likelihood for a source model with a single power law energy spectrum with a spectral index of 2, a flare duration of 20,000 seconds. The timing PDF uses a boxed timing window. In the northern sky and at the horizon, the sensitivity of the combined sample comes from tracks, whereas in the southern sky, where an extensive atmospheric muon background is present, the sensitivity of the combined sample is dominated by the cascades selection.

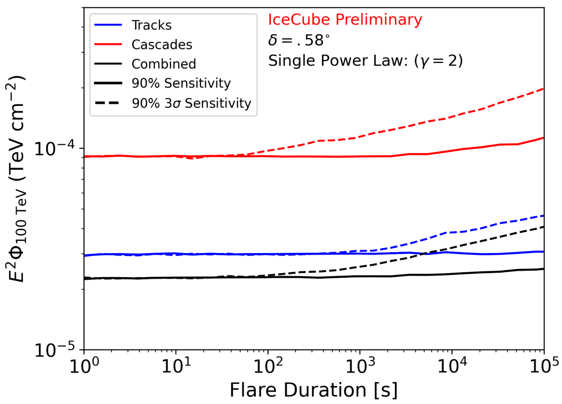


Figure 6: The sensitivities at different flare durations range from 1 to 100,000 seconds at a declination of $\delta = 0.58°$. The injected source spectrum is a single power law with a spectral index of 2. The fit is fixed at a spectral index of 2 and uses a boxed timing window. The timing PDF uses a boxed timing window.

4. Conclusion

We will conduct the first search for multi-messenger coincidences between EeV photon candidates and neutrinos to identify ultra-high-energy transient sources. We describe the unbinned likelihood maximization methodology used in the analysis, which involves searching for a significant detection of neutrinos in spatial, energy, and temporal coincidence with UHE photon candidates. A significant detection would provide new information, including the identification of photon candidates as true EeV photon showers rather than cosmic ray background, and also serve to identify astrophysical sources of ultra-high energy particles.

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