IceCube/ARA Coincidence Analysis - Technical Note

Alan Salcedo G, Alex Machtay

Contents

Abstract

This document provides a summary and a quick tutorial on how we do IceCube/ARA coincidence simulations.

1 Introduction

Since IceCube has measured neutrinos up to a few PeV, ARA can also search for radio emission from some of the same neutrino interactions. A detection by ARA coincident with an event reported by IceCube would be the first definitive detection of a neutrino with the radio technique and it would come with a confirmation that it came from a neutrino interaction. That's why we do this coincidence analysis. Easy! Let's dive into details.

2 Files Location

All the required files to run simulations for IceCube/ARA coincidence are located in Connolly's group project space in the Ohio Supercomputer Center (OSC). The path to the corresponding directory is: /fs/project/PAS0654/IceCube_ARA_Coincident_Search.

There, you will find several files and directories. The relevant files for this document are AraRead_corrected_MultStat.py and AraRun_MultStat.sh, as well as directories AraSim and setup_files. These files and directories contain the latest version of IceCube/ARA coincidence analysis which allows the user to find coincidences between IceCube and ARA stations 1, 2, or 3.

2.1 Files Explained

Here, I will provide (1) a general overview of each file, (2) a quick tutorial on how to use each file, and (3) a detailed description of the file tasks.

2.1.1 AraRun_MultStat.sh

General overview: This batch script runs AraSim in an array of jobs using setup_MultStat.txt as an input file. The location of this setup file is /fs/project/PAS0654/IceCube_ARA_Coincident_Search/setup_files/MultStat.

How to use it: This batch script must be run in the directory where it is located using the following command: sbatch --array=1-<max>%<concurrent number> --export=ALL AraRun_MultStat.sh <ARA station number> where <max> stands for the total number of jobs to be submitted as an array, <concurrent number> stands for how many jobs should be running at a given time, and ARA station number is (of course) the station number of ARA that you want to run IceCube/ARA coincidence analysis on. For example, if you want to run 10 jobs at a time out of 20 total jobs simulating ARA station A2, you would submit sbatch --array=1-20%10 --export=ALL AraRun_MultStat.sh 2 through the command line.

Detailed overview: Once you submit this batch script as just mentioned, the script will setup all necessary directories for data storage and will look for the setup_MultStat.txt file. In the file, the station number contains the placeholder string NOS which will be replaced by the station number specified in the submission. In the example given above, NOS is replaced by 2. Then, AraSim will run with the configurations specified in the setup file. **Important: Avoid running the script again with a different station number if the maximum number of jobs have not been submitted. Otherwise, the station number will be modified.** For example, if 10 out of 20 jobs are running with station number 2 and you run the batch file again with station number 3. The last 10 jobs from the previous run (meant to simulate station 2) will run for station 3 instead. **I haven't taken the time to figure out a way around this problem. Ideas are welcome here :)**

Then, the batch script runs AraRead_corrected_MultStat.py on the output ROOT files from AraSim for some data extraction. The extracted data is stores in Coincident_Events.txt. The contents of this file are found in /fs/project/PAS0654/IceCube_ARA_Coincident_Search/AraSim/outputs/Coincident_Search_Runs/$SLURM_ARRAY_JOB_ID/$SLURM_ARRAY_TASK_ID/ where $SLURM_ARRAY_JOB_ID and $SLURM_ARRAY_TASK_ID/ are the job ID and the job number in the job array. **Go through the directories for this to make more sense.**

2.1.2 AraRead_corrected_MultStat.py

General Overview: This file is a python code that determines if each of the events simulated with AraSim would cross through the surface of IceCube. It takes in two arguments (1) path to the ROOT file to read data from and (2) number of ARA station being analyzed.

How to use it: The batch script already gives the corresponding arguments to this code, so you don't need to use it independently. i.e. running the batch script takes care of using this code accordingly.

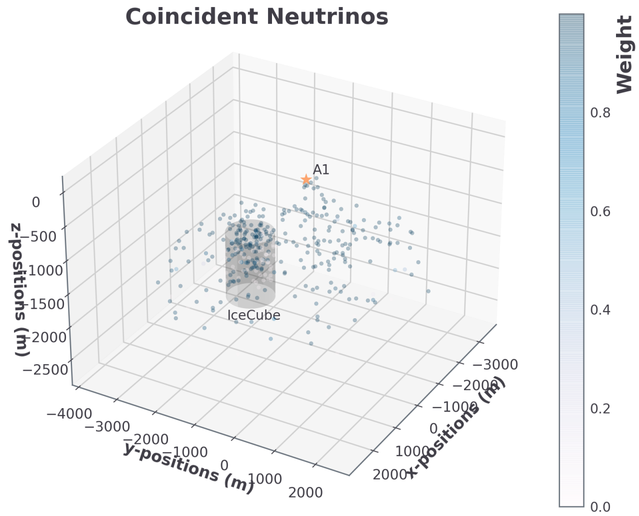
Detailed overview: The details of the code are a bit complicated. In general, it determines of the simulated events cross IceCube by solving the geometry provided in Slide 3 of this document. Then, relevant data is stored in a file called Data.csv found in the same directory as Coincident_Events.txt. The stored data contains: Event Number, Detected by ARA, Through IC, Coincident, Energy (log10) (eV), Inelasticity, Radius (m), Azimuth (rad), Zenith (rad), Theta (rad), Phi (rad), x-position (m), y-position (m), z-position (m), weight, and flavor.

2.2 Data Analysis

Once we got the data from AraRun_MultS tat.sh, we are ready for a coincidence analysis. For this, we use the jupyter notebook ICARA_Analysis_Template.ipynb (found here) to process the data and create relevant plots. The jupyter notebook is properly commented and has relevant links to references where more detailed information may be needed. You can refer to the notebook for details on the data analysis. Here, I will just show the plots that we generate.

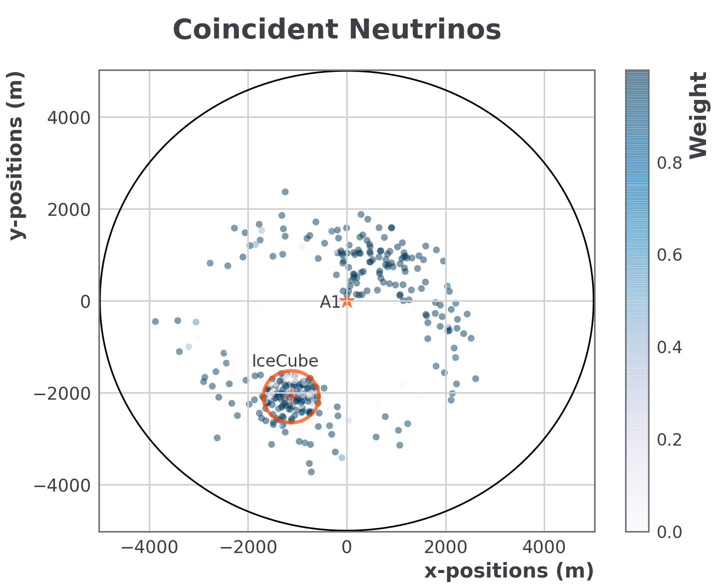
2.2.1 3D Positions of Coincident Neutrinos

This plot shows the (x,y,z) positions of the coincident events. The ARA station is located at the origin and marked with a star and IceCube's volume is depicted by a shaded cylinder. The color bar or weight represents the probability of the interaction to happens. This takes into account that the neutrinos may go through the earth, reducing the probability of the interacting at the shown position.



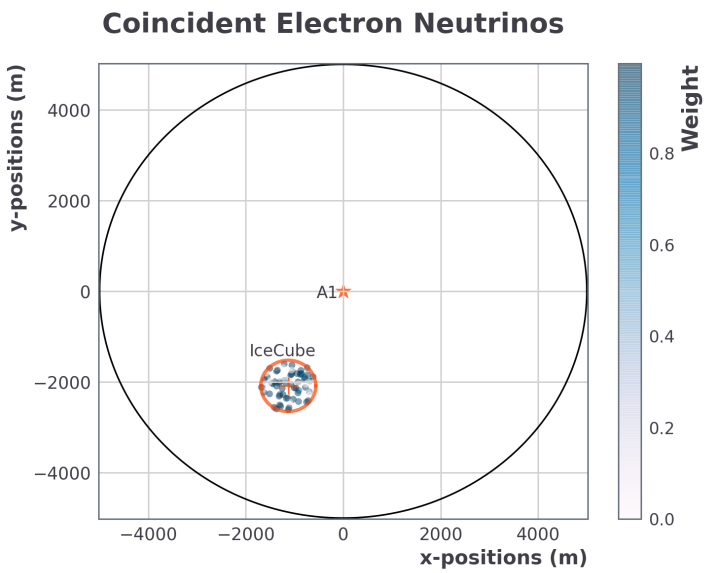
2.2.2 XY Positions of Coincident Neutrinos

Similar to the previous, this just shows the positions of the coincident events but only as seen from above projected on the XY plane. The black circunference represents the area on which neutrinos were injected for simulations (5 km around ARA's station in this case).



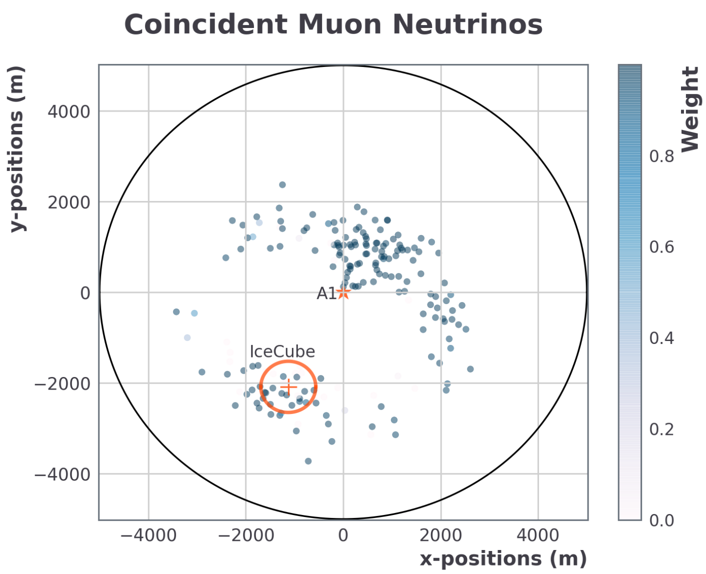
2.2.3 XY Positions of Coincident Electron Neutrinos

Here, we are only plotting the positions on the XY plane for coincident electron neutrinos.



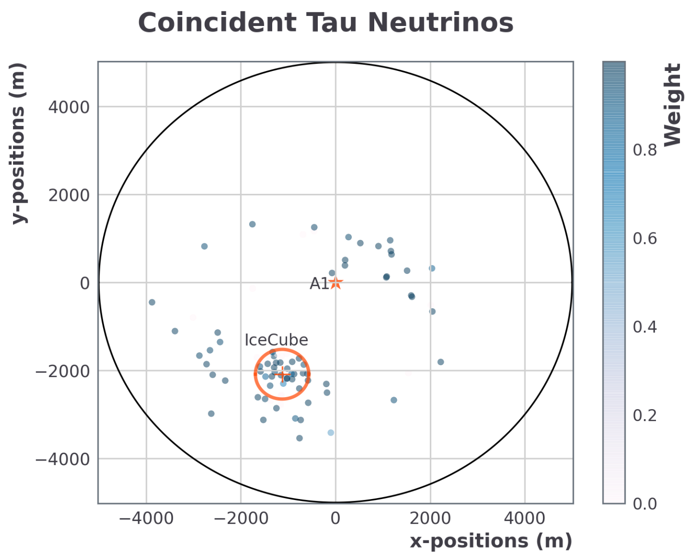
2.2.4 XY Positions of Coincident Muon Neutrinos

Here, we are only plotting the positions on the XY plane for coincident muon neutrinos.



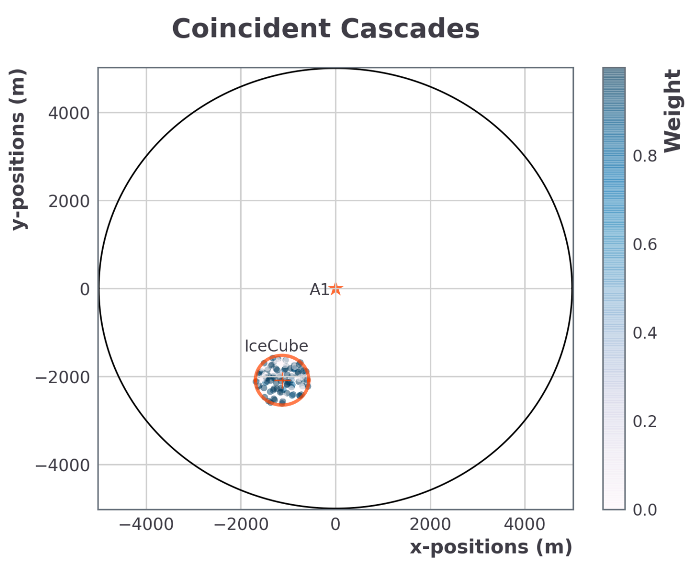
2.2.5 XY Positions of Coincident Tau Neutrinos

Here, we are only plotting the positions on the XY plane for coincident tau neutrinos.



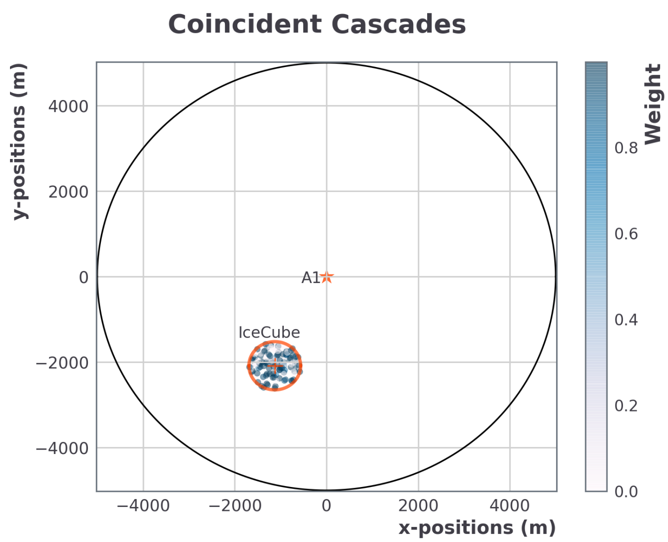
2.2.6 XY Positions of Coincident Cascades

Here, we are only plotting the positions on the XY plane for coincident cascades. The word cascades refers to neutrinos whose interaction positions are within IceCube's volume.



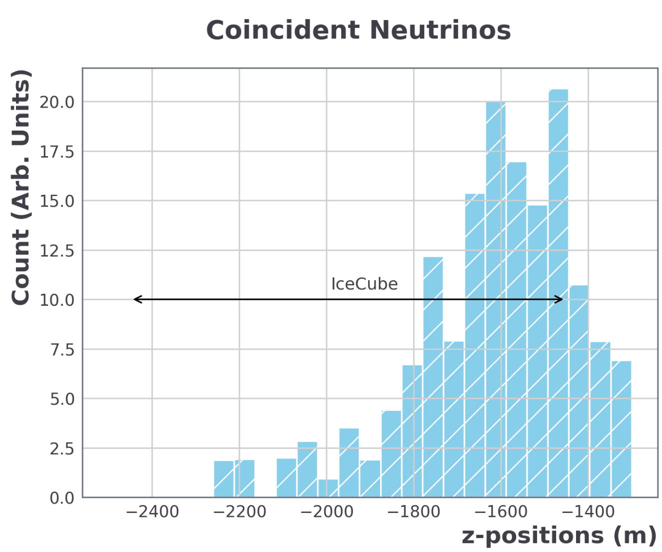
2.2.7 XY Positions of Coincident Tracks

Here, we are only plotting the positions on the XY plane for coincident tracks. The word tracks refers to neutrinos whose interaction positions are outside of IceCube's volume.



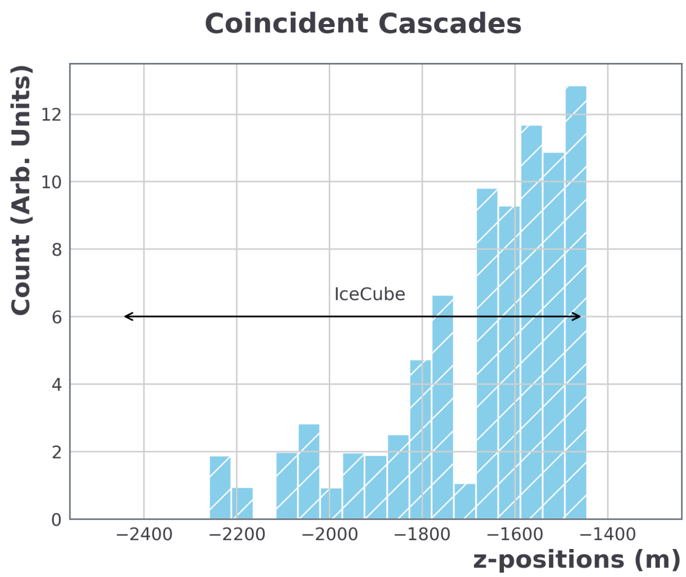
2.2.8 Z Positions of Coincident Neutrinos

This is a histogram for the z-positions of interaction vertices of coincident neutrinos. The black double-headed arrow represents the vertical range that IceCube occupies.



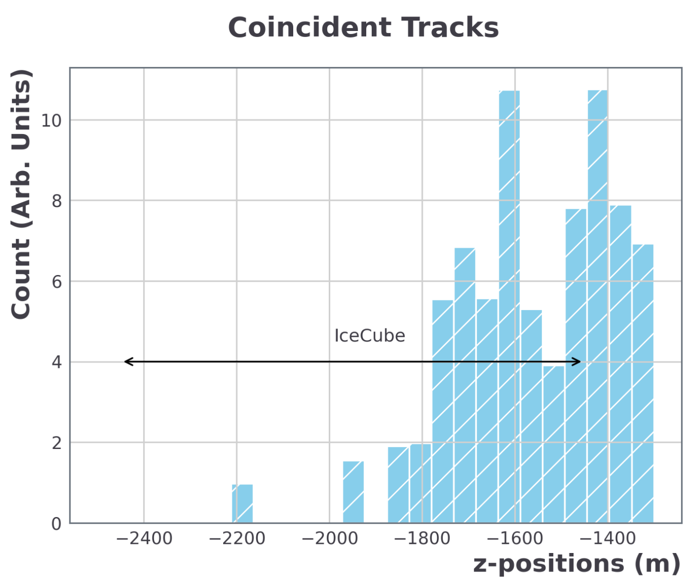
2.2.9 Z Positions of Coincident Cascades

Here, we only histogram the z-positions for cascades.



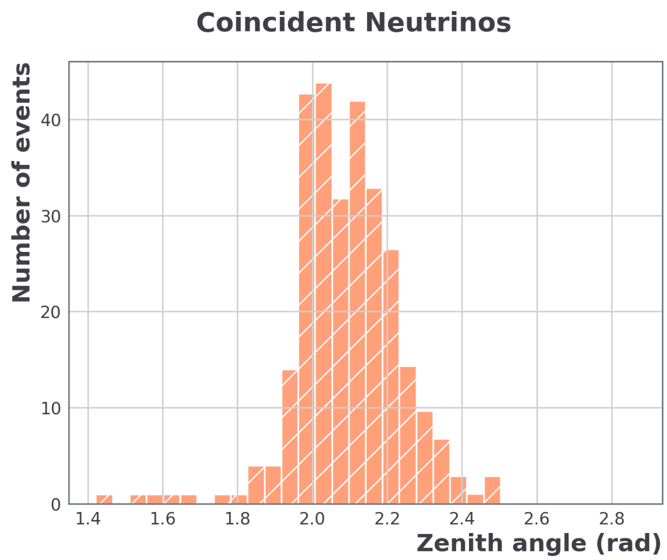
2.2.10 Z Positions of Coincident Tracks

Here, we only histogram the z-positions for cascades.



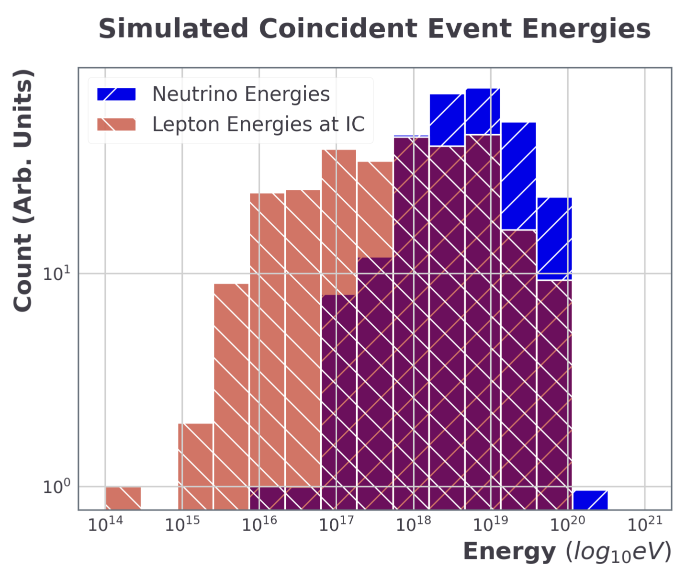
2.2.11 Zenith Angles of Coincident Neutrinos

This is a histogram for the zenith angles of coincident neutrinos.



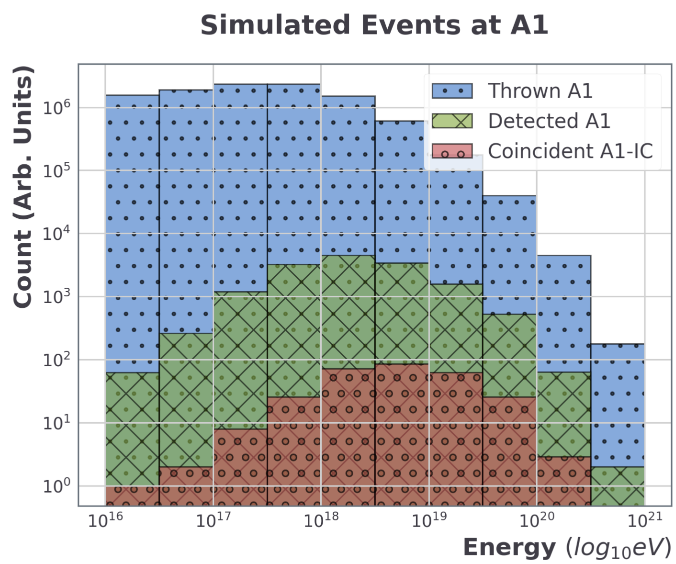
2.2.12 Energy Distributions for Coincident Neutrinos and Leptons

This plot shows the energy distribution histogramed every half decade in energy for the coincident neutrinos and produced leptons when they reach IceCube.



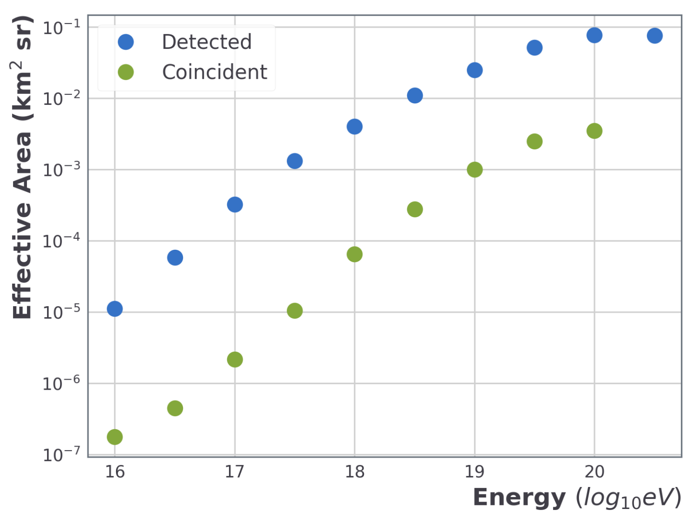
2.2.13 Energy Distributions for Thrown, Detected, and Coincident Neutrinos

This plot shows the energy distribution histogramed every half decade in energy for the thrown neutrinos, neutrinos detected by ARA, and coincident neutrinos.



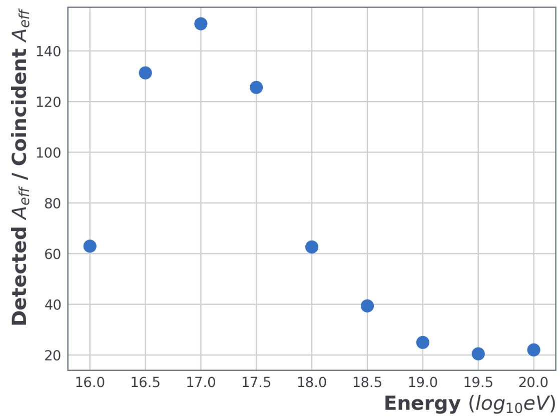
2.2.14 Detected and Coincident Effective Areas

This plot shows the detected and coincident effective areas every half decade in energy.



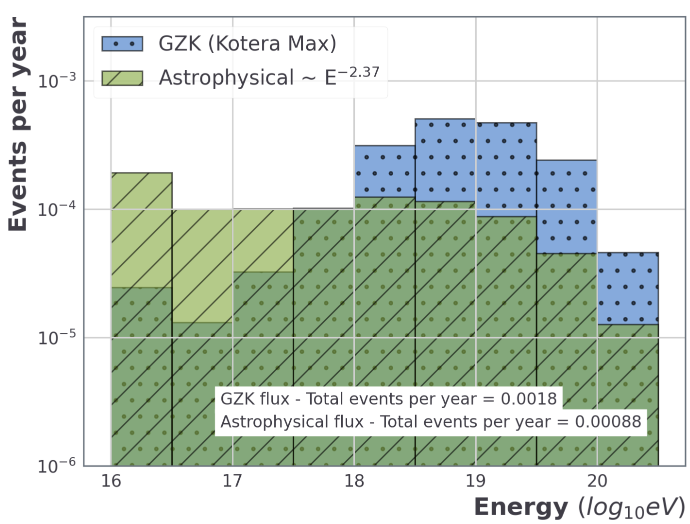
2.2.15 Detected/Coincident Effective Area Ratios

This plot shows the ratio of detected/coincident effective areas every half decade in energy.



2.2.16 Expected Coincident Events Count

This plot shows count of expected coincident events to be detected in a year assuming a GZK and an Astrophysical flux with spectral index of $\gamma = 2.37$. To get an absolute count of events in a year, the counts can be added across all energies. This number shown in the plot in the text box.



3 Conclusion

In this technical note, we (1) motivated the reasons for doing an IceCube/ARA coincidence analysis, (2) mentioned the location of our files used for simulations, (3) explained the tasks managed by each of the files generally and in detail, as well as how to use them, (4) briefly mentioned how the coincidence data analysis is done and what plots are generated.

We have identified the following areas of opportunity for the project: (1) The count of expected coincident events does not decrease with decreasing energy (see green histogram in 2.2.16). It may be relevant to expand this analysis to even lower energies until coincident events become negligible, (2) add secondary showers to simulations in AraSim which have been ignores until now, (3) maybe add a software to simulate IceCube's detection which has only done geometrically in this analysis.