LIP-STUDENTS-20-02

Development of a next generation detector concept to detect astrophysical gamma rays: the possibility of detecting high-energy astrophysical neutrinos

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Abstract. An exploration of the possibility of detection of astrophysical neutrinos with energies ranging from hundreds of GeV to hundreds of GeV, making use of the SWGO detector array, whose main focus is the measurement of astrophysical gamma-rays. This study is performed using CORSIKA to generate extensive air showers, and Geant4 to simulate the detector response. The preliminary results obtained suggest that imposing a cut at signal corresponding to approximately 10^4 optical photons is sufficient to remove the most predominant sources of background and to allow for the possibility of detection of neutrinos with energies in of the order of the TeV.

Keywords: SWGO, Gamma-Rays, Cosmic-Rays, Neutrinos

1 Introduction

1.1 The SWGO collaboration

The SWGO (Southern Wide-field Gamma-ray Observatory) collaboration is a three year research and development project involving 42 research institutions from 11 countries, whose main goal is to design and plan a next generation wide field-of-view gamma-ray detector capable of surveying and monitoring the the southern sky.

As such, the future gamma-ray observatory is based on ground-level particle detection, which is to be achieved via a large compact array of detector units spanning an approximate area of $80,000\ \mathrm{m}^2$ located in South America at a latitude between 10 and 30 degrees south, at an altitude of 4.4 km or higher. This compact array is expected to have a high fill-factor ($\sim 80\%$) associated with an area considerably larger than HAWC resulting in a significantly better sensitivity. In addition to this, it is complemented by an outer array of lower density, thus the setup of the observatory is set to resemble the rendering presented in Fig.1. The stations which constitute the basic unit of this array are to make use of Water Cherenkov Detection (WCD) calorimetric measurement technology, and the most recent concept for their design, as presented by LIP, is depicted in Fig.2. Given this configuration, the main focus of the SWGO is the detection of gamma-rays, covering an energy range from hundreds of GeV to hundreds of TeV. Further information pertaining to the SWGO collaboration can be found in [1].

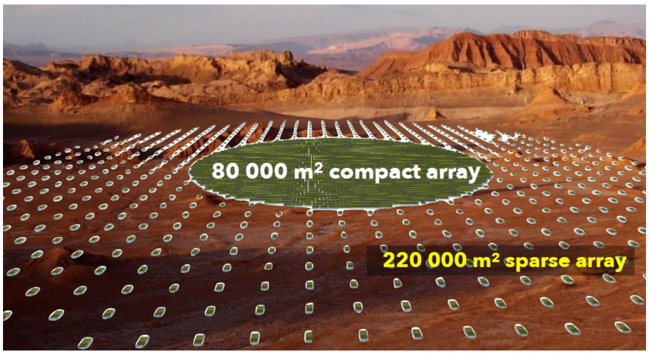

Figure 1: Schematic representation of the proposed structure of the SWGO.

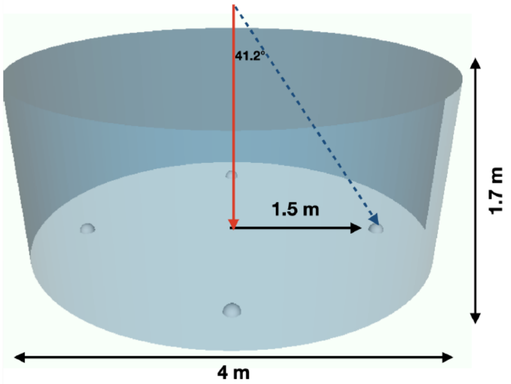

Figure 2: Current LIP station concept. The tank is filled with water, and 4 PMTs (Photo Multiplier Tubes) are placed at the bottom of the structure.

1.2 Viability of neutrino measurements at SWGO

Astrophysical neutrinos constitute a very important object of study, as such particles may carry extremely high energies, of the order of PeV and possibly EeV and, as a consequence of the very small cross section and absence of

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electrical charge associated with neutrinos, are capable of traversing long distances in straight lines. Given this, astrophysical neutrinos point to their respective production sources, which include intense events in the cosmos as is the case with pulsars, remnants of supernovae, gamma-ray bursts and conceivably black hole mergers, all of which are of great scientific interest.

The possibility of neutrino detection has already been confirmed by other experiments including, for instance, the IceCube Observatory which was capable of detecting astrophysical neutrinos with energies of the order of the PeV. Given this, as well the aforementioned characteristics of the SWGO, the possibility of detecting of neutrinos with energies ranging from 10^{11}eV to 10^{15}eV emerges, despite the focus of the SWGO on gamma-rays. This is also the case of the Pierre Auger Observatory, whose main object of study is ultra-high energy cosmic rays yet it also endeavours to measure UHE neutrinos. As the IceCube observatory focus on neutrinos with energies in the range of 10^{15}eV, and the Pierre Auger observatory aims to measure those with energies of the order of 10^{17}eV, the potential measures which the SWGO would perform (10^{11}eV to 10^{15}eV) would provide information on phenomena outside the domain of other current experiments.

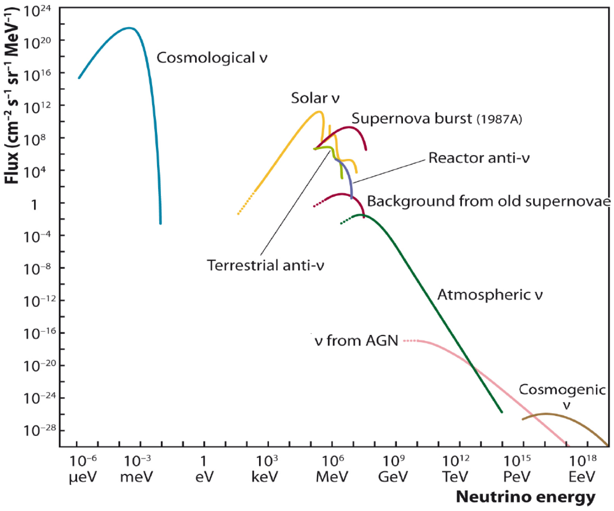

Figure 3: Neutrino energy spectrum. IceCube focuses on the range of energies $10^{13} - 10^{15}$eV, the Pierre Auger Observatory on energies of the order of 10^{18}eV, while the SWGO would work in the $10^{11} - 10^{15}$eV range. **Confirm this**

In order to measure neutrinos, it is crucial to establish the experimental signatures which are expected to be associated with events which containing them. Given the very small cross sections and very large mean free paths of neutrinos, the signature of a neutrino event is likely to be either an event consisting of a single active station with very high signal, or the presence of very inclined showers produced close to the ground.

The large mean free path of neutrinos translates in an overall very small probability of interaction of this particle with the environment it traverses, which similarly allows for the possibility of interaction occurring in close proximity to the detector, which would then give rise to the case of a single active station with very high signal. The major downside of this signature resides in the fact that, while it is highly unlikely for particles other than neutrinos to interact so close the observatory, such an occurrence is still a possibility.

Alternatively, the presence of inclined showers is unambiguously associated with neutrinos, whose small cross section easily allows for the possibility of traversing a large amount of atmosphere (or even the Earth itself) without a single interaction, whereas any other primary particles would interact and give rise to extensive air showers which would then be attenuated to the point where no significant signal would be registered at the detector. For example, at an angle of 80° a particle would have to traverse approximately 4 atmospheres, corresponding to a grammage of around $2000\text{g}/\text{cm}^2$. Seeing as a proton has a mean free path of $60\text{g}/\text{cm}^2$, there is no proton, or subsequent extensive air shower that it gives rise to, that is capable of reaching the detector under such circumstances without being heavily attenuated.

Having established the experimental signatures that would be expected of the relevant events, it is then required to proceed with the estimation of fluxes and neutrino cross-sections, as well as the estimation of background due to extensive air showers induced by gamma-rays and cosmic-rays. The focus of this study is contained predominantly within the latter category. CORSIKA (COsmic Ray SImulations for KAscade) was used in order to generate extensive air showers induced by gamma-rays with energies of 150GeV and 1TeV and by protons of 1, 4, 10 and 40TeV, while the detector response was simulated via Geant4.

2 Simulation Results

2.1 Shower Particles at the ground

The first simulation results are obtained by generating 4000 showers induced by protons with an energy of 4TeV and analysing the particles that reach the ground, as well as their kinetic energy, as is presented in Fig.4. Based on the information presented in this graph, the most numerous particles are photons, followed by electrons and positrons. These particles can be grouped together to form the electromagnetic component, which is the largest constituent of the particles that reach the ground, in accordance with expectations. On the other hand, the remaining particles can be attributed to the hadronic component, that is comprised of muons, protons, and other particles such as pions, all of which may be associated with a considerably large kinetic energy, as evidenced by their respective curves in Fig.4. Overall muons exhibit a peak at higher kinetic energies, when compared to the peak associated with the protons. There are also fewer protons than muons, and thus muons may constitute a relevant source of background.

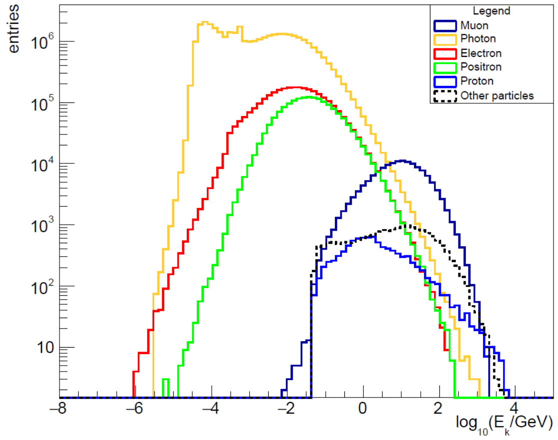

Figure 4: Kinetic energy distribution of shower particles reaching the ground. Particles generated by 4000 showers induced by protons with an energy of 4TeV.

2.2 Energy and Signal in WCD Stations

To more adequately analyse the background associated with an experimental signature of a single isolated station with very high signal, 3 considerations pertaining to the stations are introduced:

- Isolated Stations : stations which register signal, while no other neighbouring stations do. Neighbouring stations are defined as those whose centre is located at distance equals to or lesser than 4.5 m from the centre of a given station.
  - Isolated Stations of Maximum Signal: stations which register the highest amount of signal in a given event, while no other nearby stations register any signal.
- One muon stations: stations that detect only a single muon, and no other particles, in a given event.

Having introduced these considerations, they can now be applied to the cases of extensive air showers induced by photons and protons. For the case of showers generated by photons with an energy of 1TeV, the energy and signal spectra obtained are presented in Fig.5 and Fig.6, respectively.

Firstly, focusing on the energy spectrum depicted in Fig.5, it is evident that the overwhelming majority of isolated stations register smaller amounts of energy, and thus are unlikely to be associated with large amounts of signal which may constitute background. Regarding the one-muon stations, there are a few cases which exhibit more significant energies and as such it is necessary to make use of the signal spectrum to verify if these cases give rise to instances of considerable signal which may constitute background. On a final note, electromagnetic showers are predominantly constituted of phenomena with low transverse momentum (p_T), which leads to most of the particles produced to be focused in a core area, and as a consequence high energy phenomena located away from this central area are very unlikely to occur. This also justifies the spiked profile exhibited by the energy spectrum of Fig.5.

Taking into account that the quantity that would be measured by the detector is the signal, the spectrum presented in Fig.6 is the most relevant one in determining the sources of background. In the case of showers generated by photons with energies of 1TeV, there are no isolated stations or one-muon stations which register a $log_{10}(NOpticalPhotons^1)$ above 4,and thus by imposing a cut at this value would remove gamma-rays of this energy as source of background. This observation also assuages any concerns regarding muons as potential background sources, as would be expected, seeing as muons lose energy predominantly via the production of Cherenkov light and as a consequence these particles are unlikely to generate large signals, in comparison to the signal that would be generated by an electromagnetic shower. Given that the aforementioned cut also holds for the case of photons with an energy of 150GeV (graphs presented in Fig.11 and Fig.12, in the appendix), it is confirmed that gamma-rays are not a source of background.

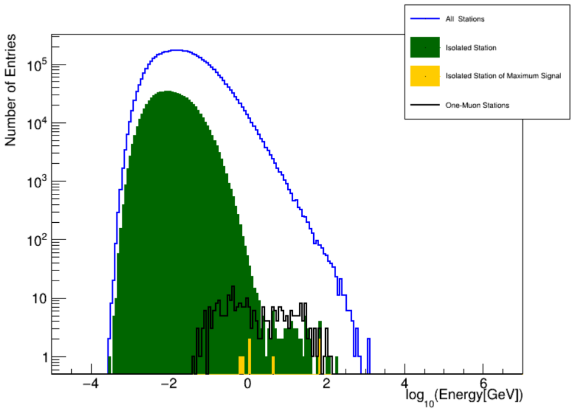

Figure 5: Energy spectrum of showers generated by a 1TeV photon. 3613 showers simulated.

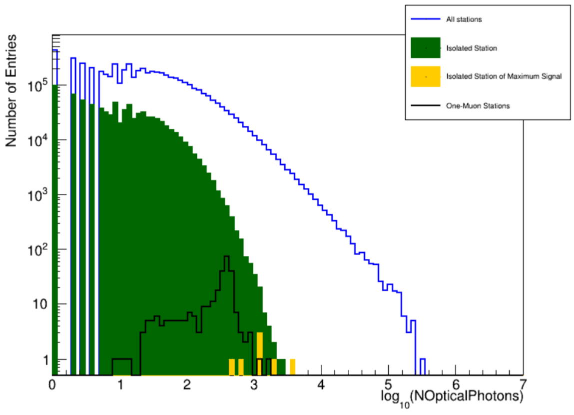

Figure 6: Signal spectrum of showers generated by a 1TeV photon. 3613 showers simulated.

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[1] $NOpticalPhotons$, otherwise known as the signal, is the number of optical photons registered by a given station

Concerning showers induced by protons, in particular the case of a proton with an energy of 4TeV, the energy and signal spectra obtained are presented in Fig.7 and Fig.8, respectively.

Firstly, the energy spectrum depicted in Fig.7 exhibits a very distinct profile than that associated with showers generated by gamma-rays, which can be attributed to the higher transverse momentum of proton generated showers. As a consequence of this, higher energy phenomena can be detected at greater distances from the shower axis resulting in a higher likelihood of isolated stations registering higher values of energy and potentially signal. In particular, there are two cases of isolated stations of maximum signal which register an energy close to 10^4GeV, and could possibly be related to events of considerable signal and thus, also related to relevant sources of background. Of these two events, one consists of a lone proton reaching a single station, which confirms that while it is unlikely for such a particle to reach the ground without interacting, such an occurrence can still be observed. Similarly to the energy spectrum of showers generated by gamma rays, in Fig.7 one-muon stations are associated with substantial values of energy, which need to be examined in the signal spectrum to determine if these cases contribute to the background.

Secondly, focusing on the signal spectrum for the case of showers induced by protons with an energy of 4TeV (Fig.8), it can be observed that all instances of isolated stations and one-muon stations register $NOpticalPhotons$ lower than 10^4, and as such the aforementioned cut at $log_{10}(NOpticalPhotons) = 4$ still holds, and allows for the removal of this source of background. In particular, neither the two previously mentioned cases of high energy isolated stations of maximum signal nor the one-muon stations are associated with signals large enough to compromise this cut. Additional cases of protons with energies of 1TeV, 10TeV and 40TeV were tested as well (graphs presented in Fig.15 and Fig.16 as well as Fig.19 -22, in the appendix), for which the cut at $log_{10}(NOpticalPhotons) = 4$ remains valid.

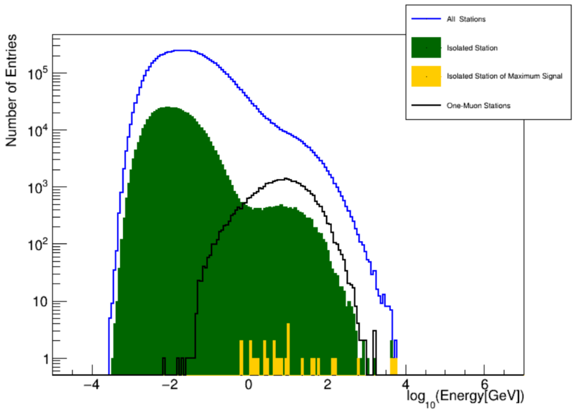


Figure 7: Energy spectrum of showers generated by a 4TeV proton. 3694 showers simulated.

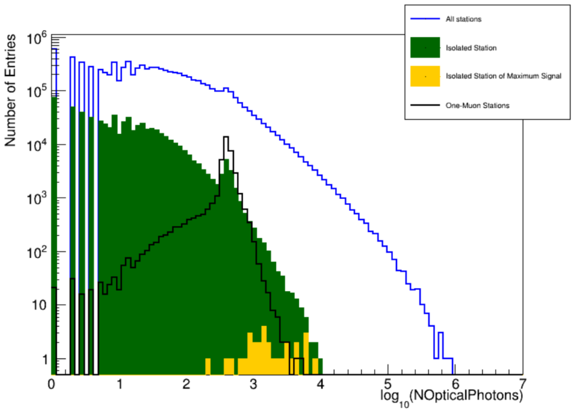
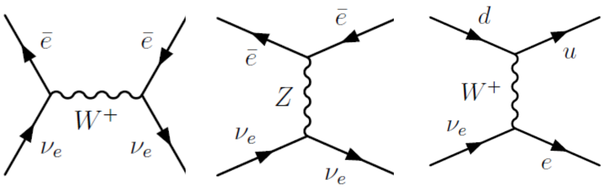


Figure 8: Signal spectrum of showers generated by a 4TeV proton. 3694 showers simulated.

2.3 WCD Signal from neutrino shower

An astrophysical neutrino can interact with particles of Earth's atmosphere, namely neutrons, protons, electrons or positrons, to produce a high energy electron, as is the case with the processes whose Feynman diagrams are depicted in Fig.9.



(a) (b) (c)

Figure 9: Feynman diagrams representing neutrino interactions which produce electrons (or positrons).

Given this, single electrons of 7 distinct energies were injected into a WCD : 10MeV, 100MeV, 1GeV, 10GeV, 100GeV, 1TeV, and 10TeV, all of which were composed of 1000 entries each. Gathering the mean signal and standard deviation associated with each case into a single depiction results in the signal-energy graph which is presented in Fig.10.

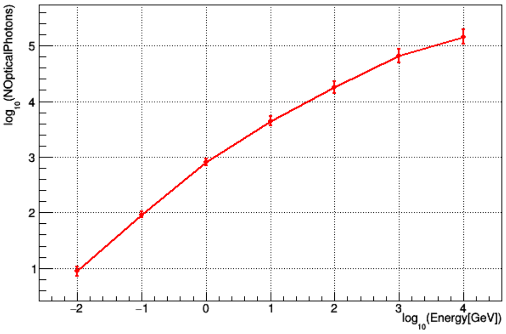


Figure 10: Mean Signal-Energy relation for 7 one- electron scenarios, of different energies between 10MeV and 10TeV.

Based on the data presented, it can be stated that saturation begins to be observed, at around 10TeV ($log_{10}(Energy/\mathrm{GeV}) = 4$, yet signal still grows. Furthermore, the proposed cut at $Log_{10}(Signal) = 4$ corresponds to an energy of the order of 100GeV,and thus requiring $Log_{10}(Signal) > 4$ in isolated stations seems to allow the observation of neutrinos with energies of the order of TeV.

3 Results and Conclusions

With the data obtained, it was determined that gamma-rays do not constitute a source of background, and that the simulated sources of background can be removed by imposing a cut at $log_{10}(Signal) = 4$. It was also observed that protons with an energy of the order of a few TeV can, in fact, reach the ground, although this is a very rare occurrence. Finally, requiring that $log_{10}(Signal) > 4$ in isolated stations seems to allow the observation of neutrinos with energies of the order of TeV. On the whole, these are very promising results, but it is very important to emphasise that this project is still a work in progress, and thus is very exploratory in nature.

Acknowledgements

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Thanks to Mário Pimenta as well, for his assistance in expanding my knowledge and comprehension of the topic at hand.

References

[1] *The Southern Wide-field Gamma-ray Observatory (SWGO)*, https://www.swgo.org/SWGOWiki/doku.php?id=start, [Online]

4 Appendix

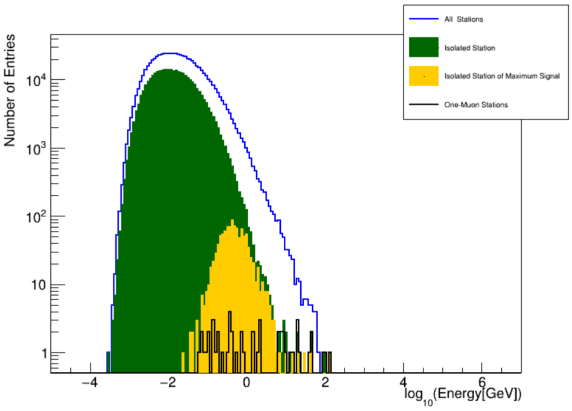

Figure 11: Energy spectrum of showers generated by a 150GeV photon. 3600 showers simulated.

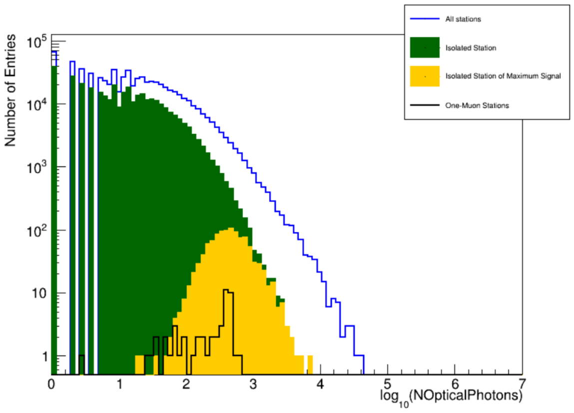

Figure 12: Signal spectrum of showers generated by a 150GeV photon. 3600 showers simulated.

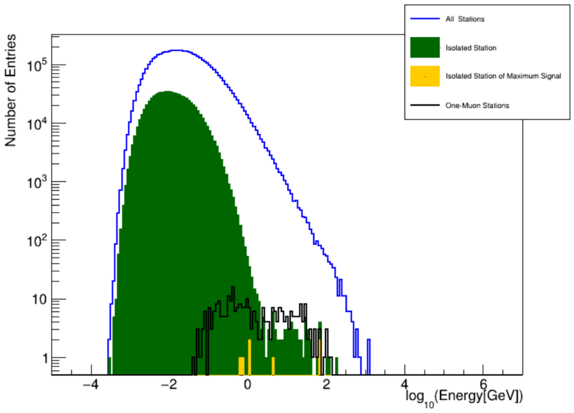

Figure 13: Energy spectrum of showers generated by a 1TeV photon. 3613 showers simulated.

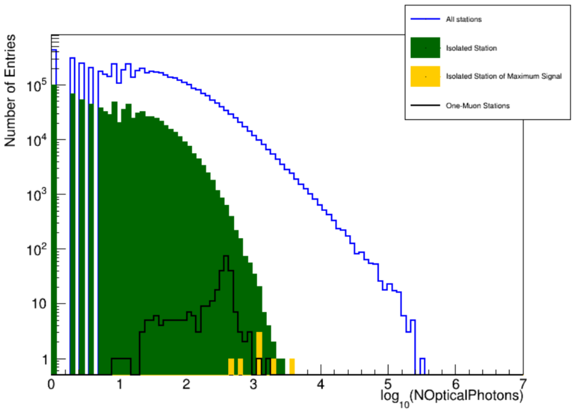

Figure 14: Signal spectrum of showers generated by a 1TeV photon. 3613 showers simulated.

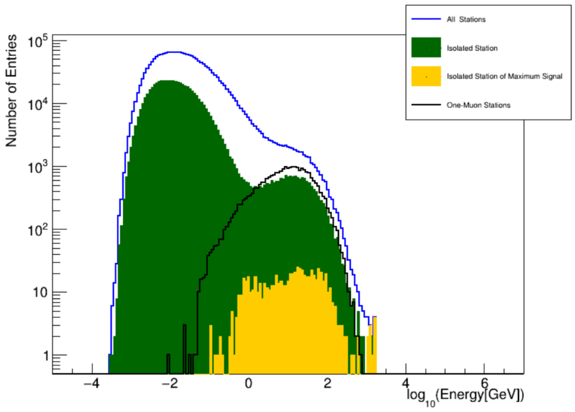

Figure 15: Energy spectrum of showers generated by a 1TeV proton. 3575 showers simulated.

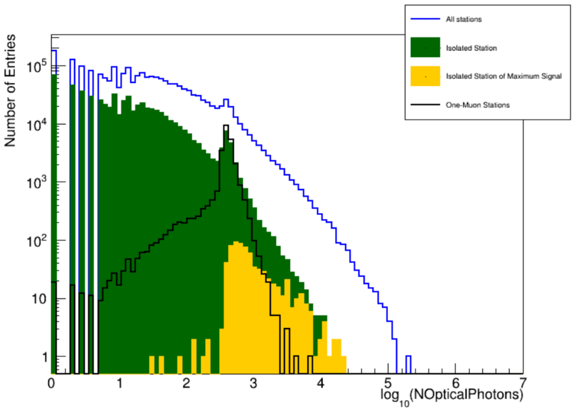

Figure 16: Signal spectrum of showers generated by a 1TeV proton. 3575 showers simulated.

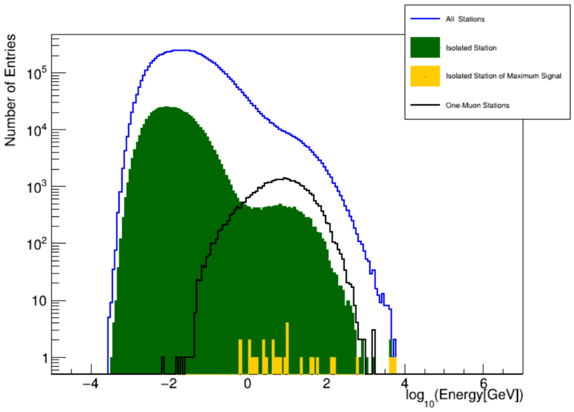

Figure 17: Energy spectrum of showers generated by a 4TeV proton. 3694 showers simulated.

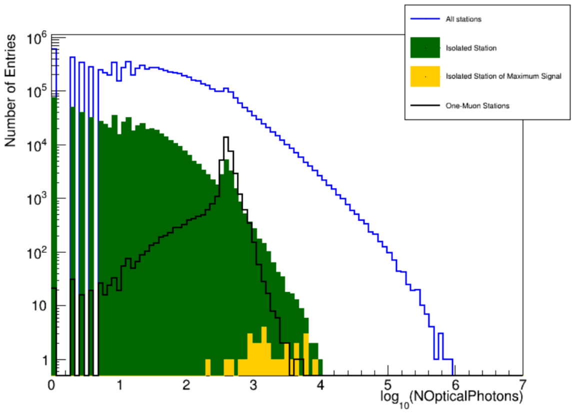

Figure 18: Signal spectrum of showers generated by a 4TeV proton. 3694 showers simulated.

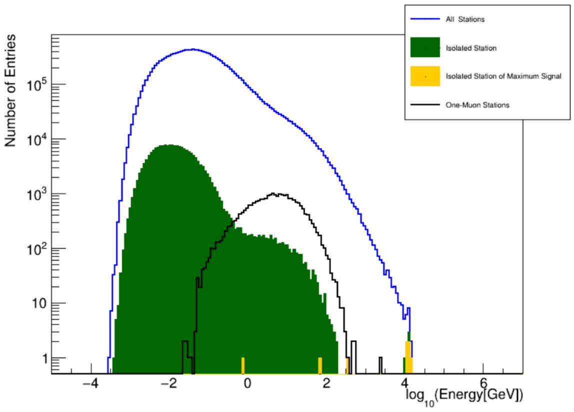

Figure 19: Energy spectrum of showers generated by a 10TeV proton. 3679 showers simulated.

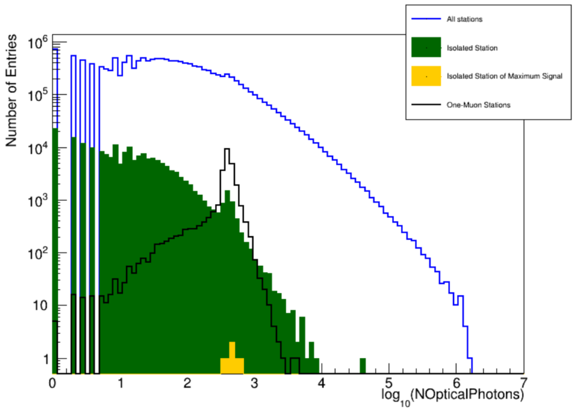

Figure 20: Signal spectrum of showers generated by a 10TeV proton. 3679 showers simulated.

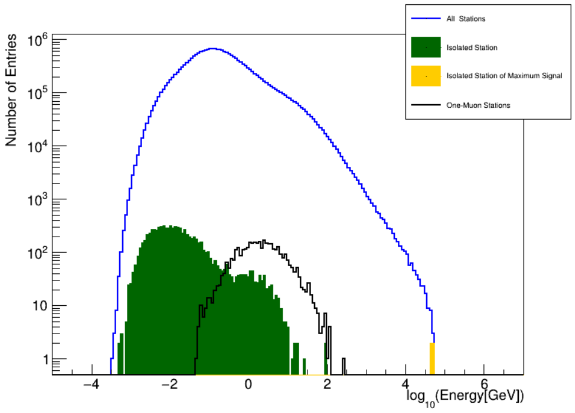

Figure 21: Energy spectrum of showers generated by a 40TeV proton. 3686 showers simulated.

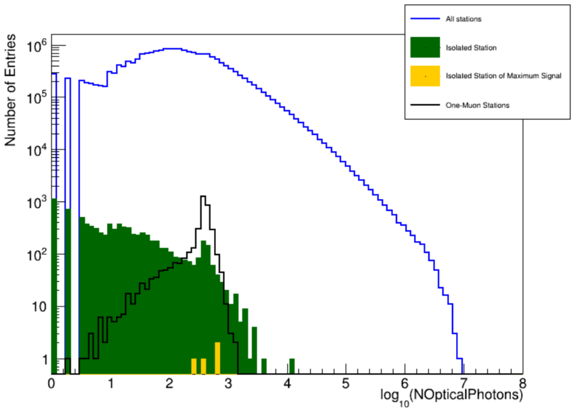

Figure 22: Signal spectrum of showers generated by a 40TeV proton. 3686 showers simulated.