A surface veto for the next generation IceCube observatory

DESY Summer Student Programme, 2014

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Abstract

Different kind of scientific tasks could be pursued with a new surface veto for the IceCube observatory. In addition to the improvement of the statistics for diffuse astrophysical ν signal above 100 TeV and of the sensitivity to Galactic point sources, it would be even possible to run cosmic ray composition studies. The purpose of this summer student project is to estimate the efficiency of a surface veto as a function of the muon energy measured in IceCube.

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1. Introduction

1.1. IceCube

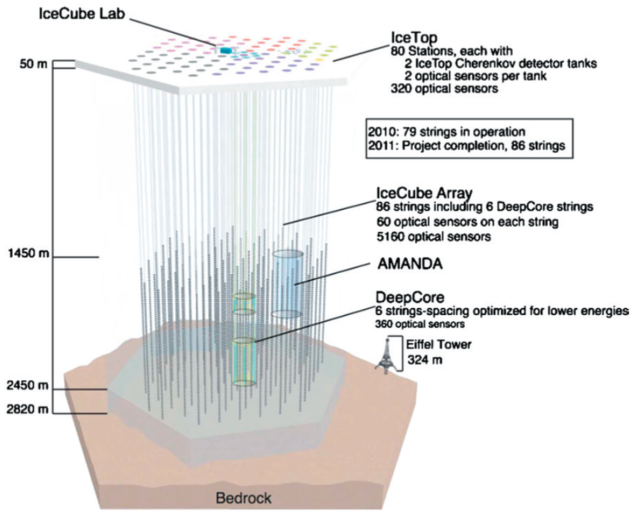


Figure 1: Design of Icecube detector

IceCube is a neutrino telescope consisting of 5160 detectors, embedded inside a km^3 of transparent Antartic ice, sensitive to Cherenkov light emitted by secondary particles produced in the interactions of neutrinos with nuclei in the ice (Figure 1). Each detector, called **DOM** (**D**igital **O**ptical **M**odule), has a complete data acquisition system, that includes a phototube, digitization electronics, control and trigger systems, and light-emitting diodes for calibration. From the Cherenkov light pattern of the secondary particle it is possible to reconstruct the flavor, the energy and the direction of the corresponding neutrino.
The main scientific tasks of IceCube are: the search for point sources of high energy neutrinos, the observation of galactic supernovas, the measurement of the diffuse neutrino flux, indirect dark matter searches and the investigation of ν oscillations.

1.2. Why neutrinos?

High Energy Astrophysics depends on three types of messenger particles: charged particles, photons and neutrinos. Since the charged particles are randomly deflected by the interstellar magnetic fields, they can not provide any kind of directional information. Neutrinos and photons, being neutral, do not undergo this deflection becoming the ideal particles for astronomical studies. Essentially two qualities distinguish the neutrino from the photons:

- Neutrinos actually provide a wider astronomical horizon with respect to the highest energetic photons since gamma rays interact with the photons of the extragalactic and Galactic background light in the process

$$\gamma + \gamma_{EBL} \longrightarrow e^{+} + e^{-} \tag{1}$$

if their center-of-mass energy exceeds the pair production threshold. This makes the universe opaque to gamma-rays emitted from a certain distance.

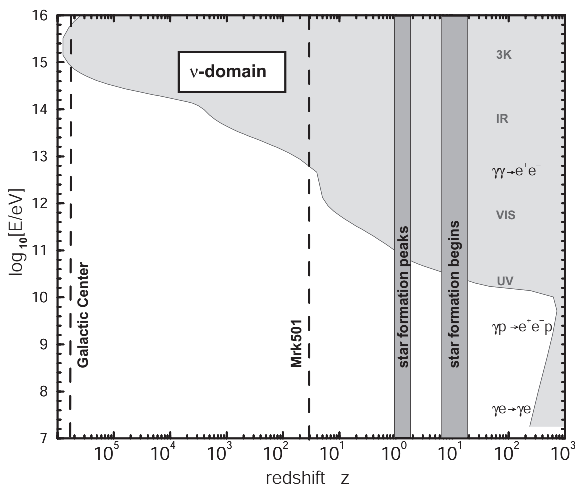


Figure 2: Gamma-ray horizon of the universe. Photons from the gray-shaded region do not reach the Earth. On the right side the responsible absorption process is indicated. Figure adapted from [**?**].

- High-energy neutrinos are the unambiguous sign for hadron acceleration and interaction since they are created in the decay of charged mesons produced in the interactions of accelerated protons and nuclei with target protons or photons via the reactions:

$$\begin{aligned} p + N &\longrightarrow \pi^{\pm} + \pi^{0} + K^{\pm} + K^{0} + ... \\ p + \gamma &\longrightarrow \Delta^{+} \longrightarrow \pi^{+} + n \\ &\qquad\quad\; \longrightarrow \pi^{0} + p \end{aligned} \tag{2}$$

These peculiarities of neutrinos might provide new insights in the search for the sites of production and acceleration of cosmic rays.

2. A surface veto

Due to their long lifetime muons are the neutrino-induced leptons that provide the longest track topology in IceCube ($\sim km$). Their detection however faces an inevitable background: muons generated in the interactions of charged cosmic rays in the Earth atmosphere. If we are looking at the Northern sky we can use the Earth as a "beam dump", stopping all the atmospheric muons. In this case the main signature for a neutrino induced event will be its *up-going* direction. But if we are looking at the southern sky our muon background rate increases as shown in Figure 3. Different strategies are possible to suppress this backgorund, a

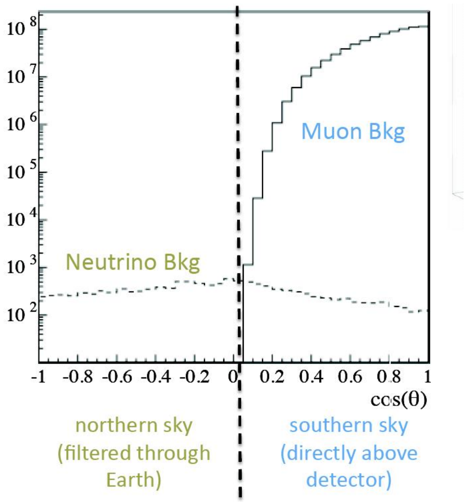


Figure 3: Neutrino and muon background rate for northern and southern sky.

selection of muon tracks that start inside the inside the detector is one option, but it restricts the effective detector volume to about half the instrumented volume. On the other hand the construction of a large array of surface detectors could even allow the detection of events outside the instrumented volume by vetoing atmospheric μ, as it is shown in Figure 4. It would be possible to detect neutrinos with interaction point outside the IceCube volume by demanding that their corresponding reconstructed muon track has no trigger signal in one of the surface detectors.

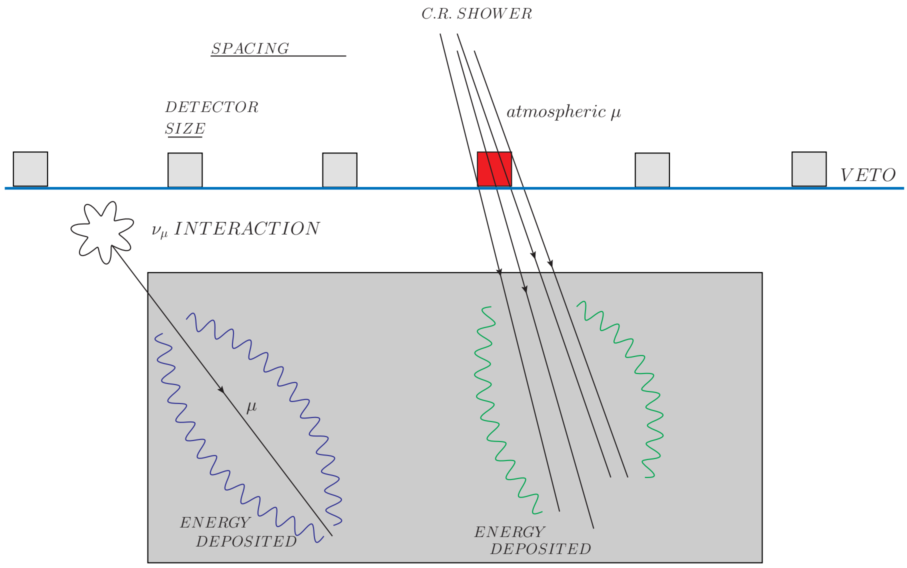


Figure 4: Sketch of the surface veto showing the possibility to distinguish atmospheric and ν-induced muons by searching for a surface trigger

2.1. CORSIKA simulations

The starting point for this work is the simulation of the veto response of an array of surface detectors to an extensive air-shower produced with CORSIKA (COsmic Ray SImulations for KAscade) software [2]. The parameters of the simulated array are:

- type of detector
- size of the single detetctor
- spacing between detectors

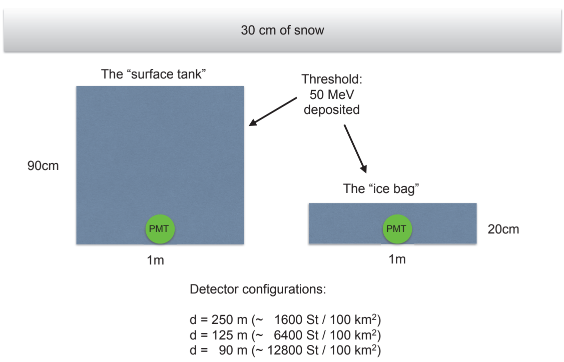


Figure 5: Two different scenarios for the detector of the surface array.

the parameters of the simulated air-shower are:

- the energy of the primary

- the zenith angle of the primary
- the type of primary (H and Fe)

2.1.1. Simulation of the efficiency

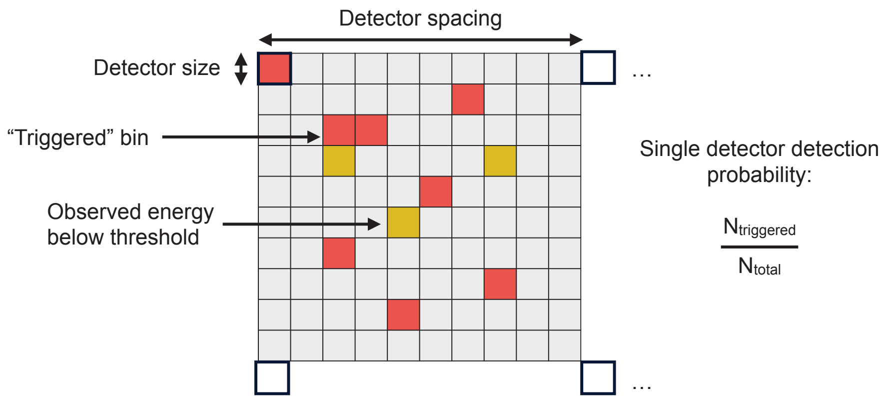


Figure 6: Simple model for the simulation of the detection probability.

The detection probability for each detector is simulated considering a grid of bins defined by the detector size and spacing (Figure 6). If the energy deposited inside a bin (in units of detector size) is over a threshold of 50 MeV, the bin is considered triggered and the detection probability is determined from the fraction of triggered bins

$$\text{detection probability}_{\text{ SINGLE DETECTOR}} = \frac{N_{triggered}}{N_{total}}$$

2.1.2. Approximation for the $\frac{dE}{dX}$ calculation

The first physical quantity that we want to relate to the veto efficiency is the energy deposited by muons inside the detector. We assume that the energy deposited is a linear function of the energy according to the relation

$$\frac{dE}{dx} = -a - bE \tag{3}$$

the constant term $a = 0.00268\ GeV\, g^{-1}\, cm^2$ approximates the energy losses by ionization while the linear term $b = 4.76 * 10^{-6}\ g^{-1}\, cm^2$ sums up the fractional energy loss from other contributions. Since it is not possible to obtain this quantity directly from the data produced by the software the following indirect evaluation is implemented working on the quantity avaible to us from CORSIKA code: zenith angle and initial energy of the muon.
Solving analytically the differential equation (3) one can obtain the expression of the energy

as a function of the position. Using the initial condition $E(x_i) = E_\mu$ one can obtain:

$$E(x) = \left((a + bE_\mu)\, e^{-(x-x_i)} - \frac{a}{b} \right) \tag{4}$$

then, knowing the initial energy E_μ and the path $(x - x_i)$ that the particle travels inside the detector (from the information on its inclination), we evaluate the energy loss over an average path of $1500\,m$ around the center of IceCube (that corresponds to the height of the detector) considering the approximation:

$$\frac{dE}{dx} \approx \frac{E(x_0 - 750\,m) - E(x_0 + 750\,m)}{1500\,m} \tag{5}$$

where x_0 is the center of IceCube. Then we sum this quantity over all muons produced in our simulated air-shower. Figure 5 shows two plot of the veto efficiency for two different configurations of the spacing between the detectors (whith same area and same primary) parameterized with the cosine of the zenith of the incident particle.

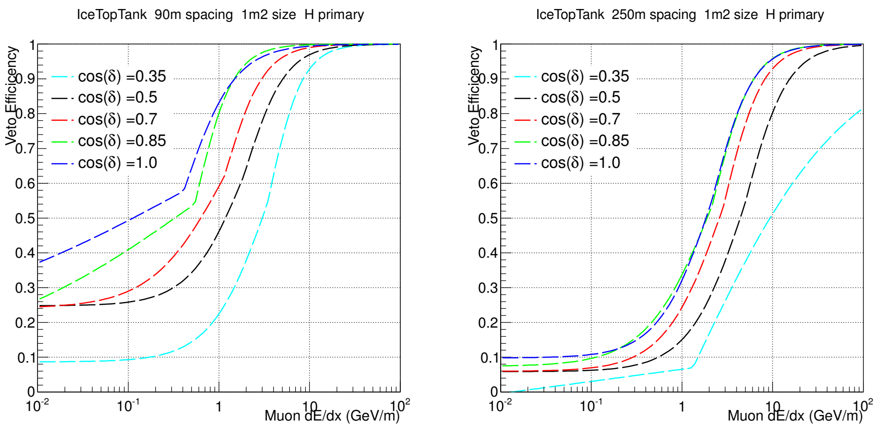


Figure 7: Simulated efficiency response for two different spacing configurations of top tank

3. Angular and energetic dependence

Figure 5 shows the dependence of the efficiency on dE/dx for different zenith angles. In order to interpolate the veto efficiency in the different zenith bands, the dE/dx is parametrized (fixing a value) and then an interpolation with lines is made between the five points we have from the cosine dependence. It is possible to derive the following linear relation:

$$\eta_{dE/dx}(cos(\delta)) = m * cos(\delta) + q \tag{6}$$

for each of the zenith band bounded by the values of the cosine. Figure 8 shows a 2D histogram produced using Equation (6). As expected higher $cos(\delta)$ and dE/dx values result in higher veto efficiency. It is also possible to see that a smaller spacing improves the veto efficiency for smaller energies.

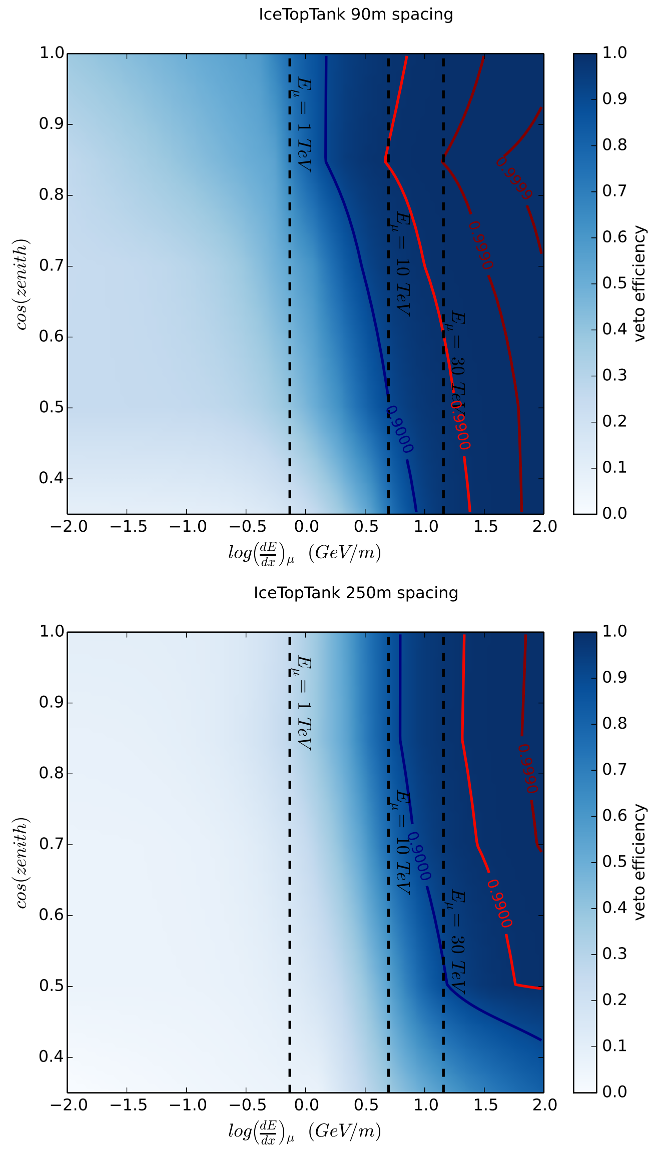
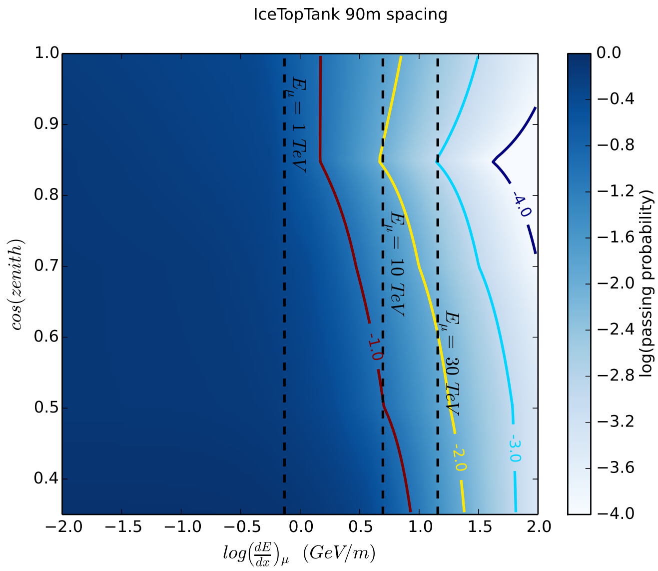


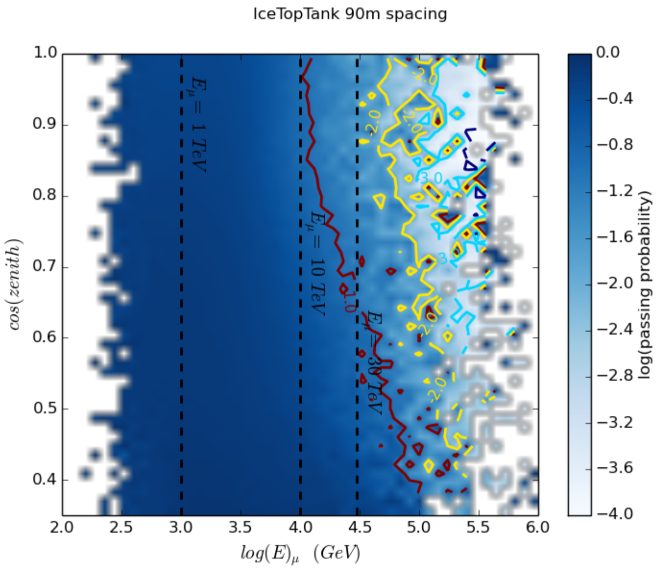
Figure 8: Veto efficiency dependence on the cosine of the zenith of the incident muon and the energy deposited for two different spacing configurations.

4. Zenith and energy reconstruction

For a realistic veto efficiency it is important to take into account how well dE/dx can be reconstructed from the IceCube data. For that the full detector simulation and reconstruction chain of IceCube is used. This simulation provides the detector response and some event reconstruction. Using the same parameters from this corsika simulation(dE/dx and cosine of the zenith of the μ track as in the veto simulation for every event one can relate reconstructed observables (energy and zenith) and veto efficiency (see Figure 9).



(a) 2D plot obtained with the parametrization $\eta_{dE/dx}(cos(\delta))$



(b) 2D histogram with averaged veto efficiency for simulated events inside IceCube detector.

Figure 9: Muon survival probability

5. Conclusions

The surface bag has proven to be, between the two scenarios, the most efficient type of surface detector. With 250 m spacing one can veto muons above $\sim 10\ TeV$ for vertically incident muons with 90%, while for 60 deg inclined muons this veto efficiency is only reached at $\sim 30\,TeV$. For the much denser spacing of 90 m it is possible to have, with vertically incident muons, a veto efficiency of 90% above $\sim 1\ TeV$ and 99% above $\sim 10\ TeV$. It turns out from data analysis that the veto efficiency is worse for reconstructed quantities in comparison to the parametrized dE/dx, a list of possible explanations follows:

- the spread of the energy distribution leads to low energetic events reconstructed as high energetic;
- a bad energy reconstruction of events could shift our data towards lower veto efficiencies;
- the lower energetic events could be high energetic muon with a good veto efficiency that pass slightly outside of the active volume. Their simulated Cherenkov light is detected but they are not reconstructed with the right energy.

Applying some quality cuts on the simulated event could provide a partial confirmation for the previous explanations. Figure 10 shows a 2D histogram with three different types of quality cuts on the data: a quality cut on the reconstructed zenith angle and energy and, to select only events inside the instrumented volume, a quality cut on the closest approach distance to the center of the detector (events with a $c.a.d. > 300\ m$ are removed).

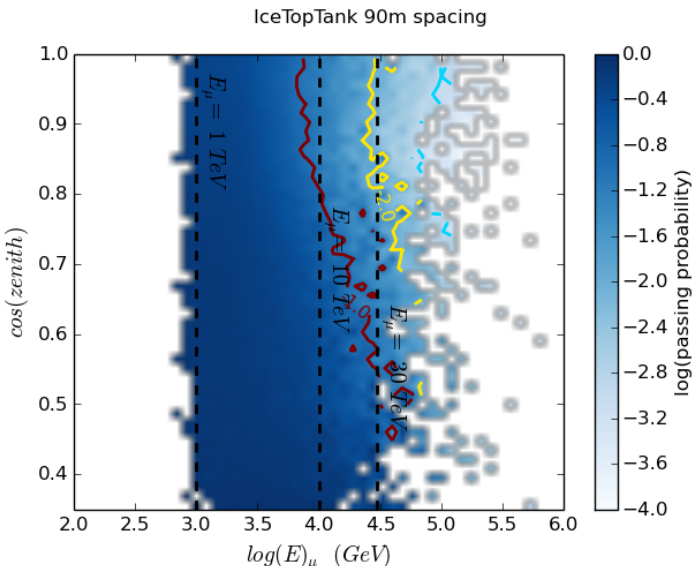


Figure 10: 2D histogram with averaged veto efficiency for simulated events inside IceCube detector whith quality cuts on angular and energetic reconstruction and c.a.d.

The comparison between Figure 10 and Figure 9(b) provides us the information that a significant part of events with energy above $10^5\ TeV$ and with low zenith angles ($cos(\delta) < 60$ deg) are probably misreconstructed. The quality cuts however do not provide any significant improvement in the veto efficiency with reconstructed observables. Indeed we still have for vertically iclined muons a veto efficiency of 0.9 at $\sim 10\ TeV$ while it should be 0.99, according to Figure 8. Further investigations are required to draw some conclusions on the worsening of the veto efficiency with reconstructed quantities in comparison to the parametrized dE/dx.

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