Cosmic-ray background for beam neutrinos at the surface

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Abstract

The second round of simulations using GEANT4 toolkit has been carried out to characterize and quantify the background from cosmic rays in a liquid argon detector located close to the Earth surface. This report complements and extends the first report of the Cosmogenics group published in August 2012 [1]. The background can be divided in two different categories: 1) background caused by muons and their secondaries; 2) background caused by neutrons from atmospheric showers.

In this report we have focused on specific cuts on various parameters, such as point of closest approach to the muon track, event angle with respect to the beam and fiducial volume cut, in rejecting muon-induced events. When considering muon-induced background we have been primarily concerned about photons producing electron-positron pairs far from the muon tracks which can be mis-identified as ν_e interactions. We have found that the most significant contribution to this background may come from photons from π^0 decays. After applying the most efficient point-of-closest-approach cut and assuming a 98% efficient $e-\gamma$ separation, we still have a significant rate of events which need to be further suppressed by more sophisticated analysis, including event topology, for instance hadron activity at the vertex of ν interactions. An efficient photon detector will reduce the rate of background events down to a few events per year.

In addition to the photon-induced cascades, we have studied electron-induced cascades from knock-on electron production by muons. This type of event can easily be rejected using a number of simple cuts on the point of closest approach to the muon track and fiducial volume.

Background caused by neutrons from atmospheric showers can be suppressed by putting the detector below ground or cover it with shielding that should be at least 13 m w. e. thick.

The results show that more detailed investigation is required as part of the overall project. Some of the existing problems, such as the dependence of the results on the physics list in

GEANT4, inaccuracies in track and energy reconstruction etc, need to be studied and the uncertainties need to be reduced. Proper detector geometry and surface profile should be taken into account. The work on this has been started but require time and efforts to be completed.

1 Introduction

The current goal of the LBNE Working group 'Cosmic Rays and Cosmogenics' is to assess the background due to cosmic rays in the liquid argon TPC (about 10 kt fiducial mass) located at the surface at Homestake. With a detector located at the surface, it is unlikely that the LBNE experiment will be able to carry out any physics tasks beyond neutrino oscillation study using beam neutrinos from Fermilab. (Supernova neutrino bursts are still under investigation but will require a sophisticated trigger to not miss a neutrino burst while limiting the amount of data recorded. In addition, spallation backgrounds may be prohibitive). With a relatively slow argon TPC as a target it was not obvious that the detection of beam neutrinos would be unaffected by a large backgrounds generated by cosmic-ray muons and neutrons from atmospheric showers. The main problem arises from the long drift time of electrons in the TPC (≈ 1.4 ms), which is much bigger than the duration of the beam spill (≈ 10 μs). This is to be compared with other neutrino detectors at the surface, which typically have event readout times of less than a μsec. This note summarizes our preliminary evaluation of background produced by cosmic rays in an LBNE detector based on liquid argon at the surface of the Earth. More details and progress on simulations can be found in our regular LBNE notes (see, for instance, [2, 3, 4] and other notes on LBNE docDB).

2 Beam parameters and muon fluxes

To sample muon energy and zenith angle on the surface we have used the parameterisation proposed by Gaisser [5], modified to include large zenith angles, fraction of prompt muons and muon decay in the atmosphere:

$$\begin{aligned}\frac{dI_\mu}{dE_\mu d\Omega}(E_\mu,\theta) &= 0.14\times(E_\mu+\Delta)^{-2.70}\times p_d \\ &\times \left(\frac{1}{1+\frac{1.1E_\mu\cos\theta^\star}{115GeV}}+\frac{0.054}{1+\frac{1.1E_\mu\cos\theta^\star}{850GeV}}+R_c\right), \qquad (1)\end{aligned}$$

where $\frac{dI_\mu}{dE_\mu d\Omega}(E_\mu,\theta)$ is the differential muon intensity at sea level in units cm^{-2} s^{-1} sr^{-1} GeV^{-1}, E_μ is the muon energy at the surface in GeV, θ is the muon zenith angle at the surface, $\theta^\star$ is the muon zenith angle at the height of muon production, Δ is the muon energy loss in the atmosphere (important for low-energy muons only), $R_c = 10^{-4}$ is the ratio of prompt (e.g. charm decay) muons to pion generated muons, p_d is the probability for a muon to not decay in the atmosphere. There are several parameterisations for the $\cos\theta^\star$ as a function of θ which take into account the curvature of the Earth atmosphere. In some parameterizations correction factor for muon decay is included in the term Δ and then $p_d = 1$ (see [6, 7, 8, 9] and references therein for more details). The total muon flux on the surface of the Earth through a sphere is equal to 170 $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$, whereas a flux through a horizontal plane is 130 $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ [10]. Positioning the detector at a depth of 10-11 m w. e. underground will reduce the flux on the detector by approximately a factor of 2 down to about $\sim 100\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}$.

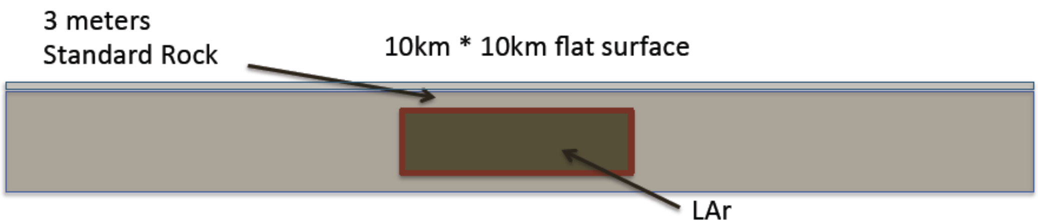

Figure 1: Schemtic view of the detector and surrounding rock.

In further evaluation we assume that the beam spill has a duration of 10 μs whereas the maximum drift time within a cell is 1.4 ms. We assume that a 10 kt detector with a size of 30 m (length along the beam) $\times$ 15 m (width) $\times$ 16 m (height) is located at the surface of the Earth at Homestake and is shielded by 3 m of rock with a density of 2.71-2.82 g/cm^3 (the type of shielding is not crucial here as long as the column density does not change). 3-4 metres of rock is expected to suppress the hadronic component of cosmic rays by more than an order of magnitude. It is generally assumed that the fast neutron attenuation length is about 1.6 m w. e. (see, for instance, [11] and references therein). With the muon flux at the detector location of about 100 $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$ through a sphere, the muon event rate in the detector is about 70 for 1.4 ms event record. Assuming 1.33 s spill repetition time and 2×10^7 s of beam running per calendar year, the total duration of the data collection (with 1.4 ms time window per spill) per year is 21053 s. We expect then about 10^9 muons passing through the detector in a calendar year. If an independent trigger for a beam neutrino induced event can be provided (for instance, by the light detector – arrays of PMTs), then the time window for beam data collection can be reduced to 10 μs and the total data collection time and hence, the number of muons, per calendar year can be 140 times less: 150 s and about 7.1×10^7 muons, respectively. The schematic of the detector and surrounding rock is shown in Figure 1.

The detector model in our simulations is slightly different from the current detector design and has a total mass of 10 ktonnes and a fiducial mass of 9.1 ktonnes if a volume within 30 cm from the walls is excluded from the analysis.

The beam is assumed to be pointing 6° upwards along the long side of the detector and the Earth surface is assumed to be flat. There is now a plan to position the LBNE detector beyond the hill to suppress the flux of atmospheric muons coming from directions close to the beam. Detailed simulations for this design will be completed later.

3 Background induced by cosmic rays

Detailed discussions about potential problems with high rate of muons at the surface can be found in our first report [1] and other LBNE notes. We believe that the main problem caused by cosmic rays is mimicking the ν_e interaction events. We expect to detect a few tens of ν_e interactions per calendar year in a 10 kt detector and need the cosmogenic background to be much smaller than this event rate. We assume that the signal events of interest will be in the energy range of 0.5-5 GeV. Note that this corresponds to a neutrino energy. Since in charge-current neutrino interactions not all neutrino/antineutrino energy is transferred to an electron/positron, the energy of electron-induced cascade can be smaller than the minimum neutrino energy of 0.5 GeV, with part of neutrino energy being transferred to hadrons. Further on we assume the electron energy to be greater than either 0.1 or 0.25 GeV. Detection and reconstruction of a hadronic component from a ν_e interaction will help substantially in identifying signal events.

Below is the list of some potential sources of background, possible ways to mitigate them and potential loss of effective volume:

- *Electron tracks, e^+e^- pairs or tracks of any other charged particle produced by a muon or any other charged particle in a cascade.* The vast majority of these events will be associated with knock-on electron and e^+e^- pair production by muons. Rejecting this background is relatively easy as will be shown below: all events that start within a few cm from the muon track or have a point of closest approach (PoCA) to the muon track within a few cm will be rejected. This will remove all charged tracks associated with a muon and other charged particles with a negligible loss of fiducial volume. Some of the tracks may start in, end in or pass through the dead regions. This will require removing volumes (a few cm thick) close to dead regions. This will be done anyway since ν_e interactions in dead regions may not provide enough information about the energy of the event. Similar cuts should be applied to the surface of the detector (charged tracks entering the detector should not be considered as candidate ν_e interactions). In total the fiducial volume due to this cut could be as much as 90% of the total volume. The fiducial volume cut will also help to avoid track confusion. It is worth noting that the current design includes 30 cm cut around dead regions and detector surfaces. (More stringent cuts may be required to reject other types of event.)

- *Bremsstrahlung from muons.* Most photons will travel close to the initial muon and have PoCA close to 0. Photons/electrons (and induced electromagnetic cascades) travelling close to the original muon (small angle and/or PoCA) can be rejected in the same way as charged tracks.

- *Neutral hadrons.* Among these hadrons, the most dangerous are π^0 giving two photons, K^0_S decaying into two neutral pions and then 4 photons, and neutrons giving neutral pions and again photons. In all these cases we will have two or more photons in the final stage.

- *K^0_L decay.* This is in fact a special case of neutral hadron production and decay which can mimic ν_e interactions. The signature of the decay can be exactly the same as the signature of the signal event. K_L^0 can decay into $\pi^{\pm}$, $e^{\mp}$ and $\bar{\nu}_e/\nu_e$. In most cases K_L^0 will decay at rest (losing energy in hadronic interactions before it decays) and the kinetic energy of the electron will be below the minimum energy of interest – 0.25 GeV. However, above the threshold the K_L^0 decay will be indistinguishable from a neutrino event.

- *Cascades without a muon in the detector.* In this case a neutral particle (e.g. a photon) enters the detector and produces a cascade. These events can only be rejected by reducing fiducial volume of the detector.
- *Events initiated by neutrons from atmospheric showers.* These events are not linked to muons in space although may occur at the same time if a neutron and a muon are produced in the same atmospheric shower. Removing these events completely is critical to the detector performance.

We present here the status of our investigations of all these types of background. We have split them in 3 different types:

1. Background events from muons which cross the detector.
2. Background events from muons which do not cross the detector.
3. Background events caused by neutrons from atmospheric showers.

4 Background events caused by muons passing through the detector

The performance of the LBNE LAr detector and analysis in rejecting background events depends crucially on the accuracy of the neutrino energy and angle reconstruction. Figure 2 [12] shows the simulated distribution of electron angle w.r.t. the beam as a function of the electron energy for events induced by neutrinos. Above 0.5 GeV most events lie within a 40° angle w.r.t. the beam (θ_b). Hence rejecting events with θ_b greater than 40° would remove most of the background, at the same time keeping most of the signal events. A significant fraction of background events "near parallel" to the beam is produced by muons moving close to the horizon. Hence, placing the detector beyond the hill, as currently planned, will help reducing this background.

At energies below 0.5 GeV, a non-negligible number of signal events have θ_b greater than 40° and rejecting background events based on this cut by itself is not efficient. Hence for low-energy events, positioning the detector beyond the hill will not be an efficient way of removing background events.

In our first studies reported in August 2012 [1] we concentrated primarily on studying photons as the prime source of background, namely: photon angle with respect to the beam and the incoming muon and the distance from the photon conversion point to the muon. We have also reported initial studies of PoCA of electron tracks (in photon-initiated cascades) to muons.

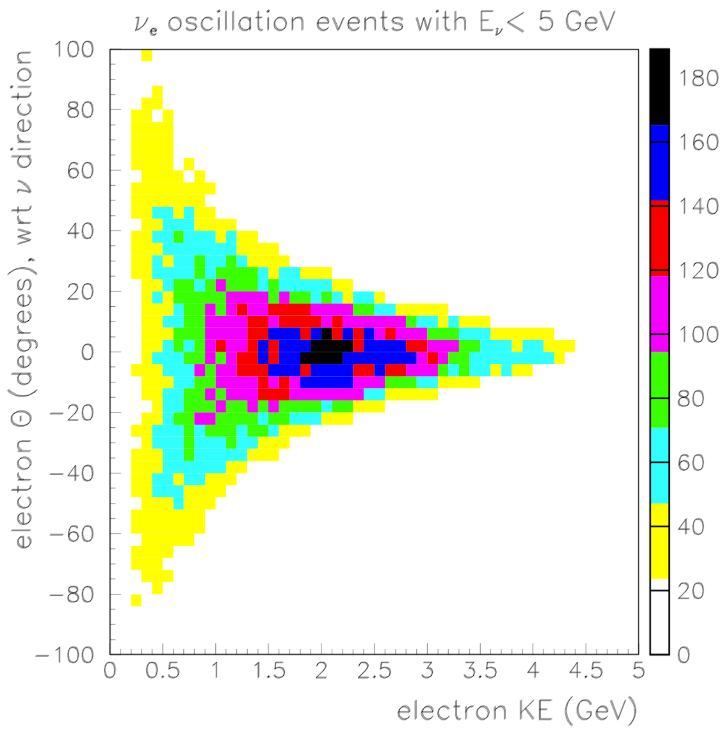

Figure 2: Projected electron emission angle as a function of electron energy in electron neutrino induced events [12].

Here we extend these studies to all electron tracks produced by muons including knock-on electron production and investigate all sources of photons.

For each electron we calculated its point of closest approach (PoCA) to the original muon track. The variables are shown in Figure 3.

The PoCA technique is well known and should give reliable results, but the low-energy muons (which produce low-energy electrons) are deflected by multiple scattering and stochastic processes (in our case this is bremsstrahlung, for instance, leading to the production of an electron with energy greater than 0.1 GeV) inside the liquid argon. Thus the muon track is not simply a straight line. Figure 4 shows five example muon tracks which produced at least 1 electron with energy above 0.1 GeV. Assuming that the reconstruction software will be able to accurately reconstruct the muon track we have calculated the PoCA by tracking back the electron and comparing it to every point along the muon track (as recorded by G4Step).

Table 1 shows electrons (or positrons) with energy greater 0.1 GeV produced in different interactions before and after specific selection cuts. The simulated statistics corresponds to 990 s of continuous beam running time or 0.047 of the calendar year. The event rate in the table has been evaluated per calendar year of running. Muons with energy greater than 1 GeV were sampled on a flat surface of the Earth above the detector and transport to and through the detector using GEANT4.9.5 (physics list: Shielding).

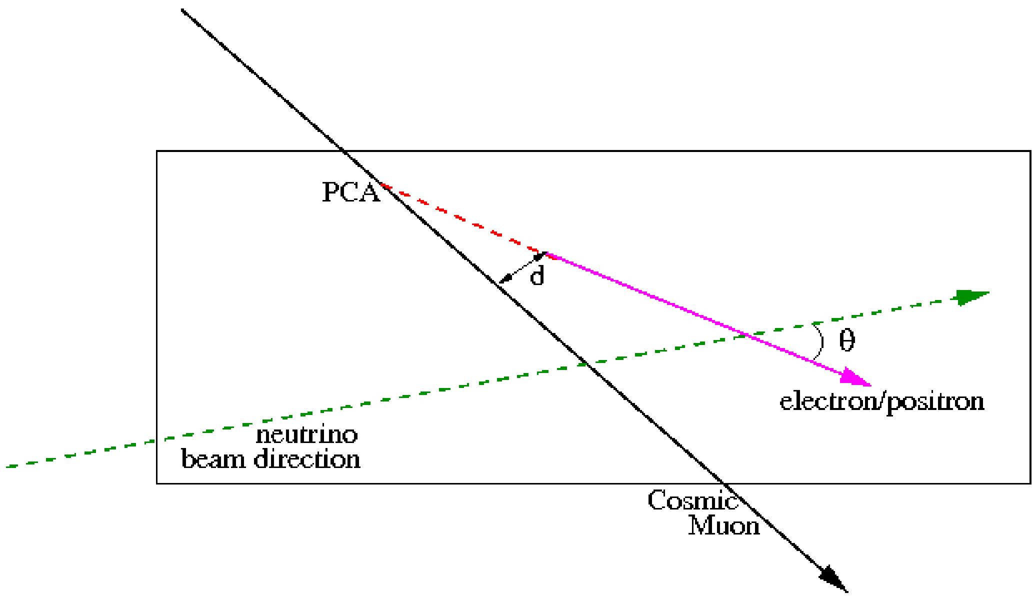

Figure 3: The vertex location and original momentum is used to determine how close the back-traced path of the electron gets to the muon track (PoCA). The distance variable shows how far the vertex is away from the muon track.

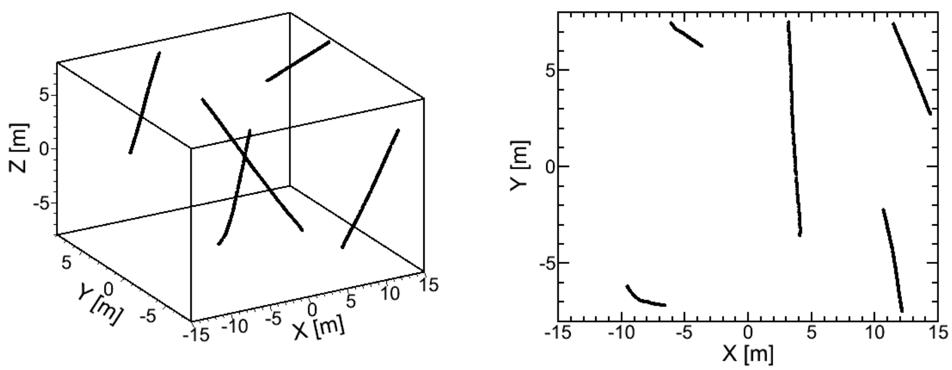

Figure 4: Five example muon tracks which have produced at least 1 electron with energy above 0.1 GeV. The left hand figure plots the 3-D track. The right figure plots the same tracks as viewed from the top of the detector. The effects of scattering are clearly visible.

The first row with event rates in Table 1 shows the contribution from knock-on electron and $e^{\pm}$-pair production by muons. The rejection of these events is quite straightforward since the electron track begins at the muon track. The estimated PoCA value depends in this case on the steps along the muon and electron tracks used in the PoCA calculation: the smaller these steps are, the more accurate PoCA value and the more efficient the rejection of background events will be. Also, for $e^{\pm}$-pairs more accurate estimate would be provided by the total momentum of the pair rather than individual particles. In a real experiment, the accuracy will be determined

Table 1: Rate of electrons with energy above 0.1 GeV per calendar year from different sources before and after cuts on PoCA (d) and energy. Columns from 2 to 6 shows event rates after specific cuts on PoCA and electron energy: column 2 – electron energy $E > 0.1$ GeV; column 3 – $E > 0.1$ GeV, PoCA $d > 10$ cm; column 4 – $E > 0.25$ GeV, PoCA $d > 10$ cm; column 5 – $E > 0.25$ GeV, PoCA $d > 30$ cm (this column gives an estimate for the expected rate of events since PoCA evaluation has been done for γ's, not electrons). The last column shows additional cut on fiducial volume: events starting within 30 cm from the walls are rejected. The simulated statistics corresponds to 0.047 of the calendar year. The figures in this Table do not account for an efficient (≈98%) $e - \gamma$ separation factor [13] or for a reduction of the time window due to the efficient photon detection system.

	Rate per year				
Source of electrons	$E > 0.1$ GeV	$E > 0.1$ GeV $d > 10$ cm	$E > 0.25$ GeV, $d > 10$ cm	$d > 30$ cm (estimate)	30 cm from the walls
Knock-on electrons and e^+e^- pairs, $\mu \to e^\pm$	1.25×10^8	< 1000	< 100	~ 0	~ 0
Charged particles (not muons) or from outside	3.04×10^6	1.33×10^4	2.68×10^3	~ 0	~ 0
$\pi^0 \to e^\pm$	2.47×10^3	447	170	~ 70	~ 70
$K_L^0 \to e^\pm$	~ 100	< 100	~ 0	~ 0	~ 0
$\mu \to \gamma \to e^\pm$	1.28×10^6	< 100	< 100	~ 0	~ 0
$\pi^0 \to \gamma \to e^\pm$	3.02×10^5	4.47×10^4	2.01×10^4	8.4×10^3	$\sim 8 \times 10^3$
outside $\gamma \to e^\pm$	1.61×10^6	1.93×10^4	4.55×10^3	1.8×10^3	~ 200

by the spatial resolution which is expected to be of the order of a few mm. The large number of background events in this category (before cuts) implies that the rejection must be very efficient. The simulations show that this is indeed the case and we expect a negligible background from these events after cuts. Note that the collected statistics does not allow us to determine the annual background rate with high precision and much more statistics is required to a proper evaluation of the background rate. This is true for all background sources.

The 2nd row in Table 1 shows electrons produced by other charged particles but not muons, or coming from outside the detector. The initial muon is still required to pass through or stop in the detector. Although quite a large number of these events survive initial cuts, the electron tracks and hence cascades will be directly linked to the original charged particles and will be rejected if PoCA is calculated with respect to their parents rather than the initial muon. Proper evaluation of this can be done when our initially simple Monte Carlo will be developed to a stage when all particles in cascades will be recorded and analysed. This requires a large computing infrastructure: millions of CPU-hours and many terabytes of disk space, and significant manpower.

The 3rd row in Table 1 shows events coming from a direct decay of π^0 into a photon and an $e^\pm$-pair. The rate of these events is small and they can be rejected with PoCA and other cuts.

Events shown in the 4th row are coming from K_L^0 decay $K_L^0 \to \pi^\pm + e^\mp + \bar{\nu}_e/\nu_e$. Potentially these events are dangerous since they may give a signal indistinguishable from the ν_e interactions: an electron-induced cascade accompanied by a hadron. Initial simulations show that the rate of these events is small partly because of the energy threshold of 0.1 GeV or above. K_L^0 most likely will lose a significant part of its energy in interactions before it decays and so the products of its decay will have relatively small energies.

The last three rows show events produced by photons. Muon bremsstrahlung events are given in the 5th row. They are present in large numbers but the high-energy photon direction is almost parallel to the muon direction, so a PoCA cut will remove this background.

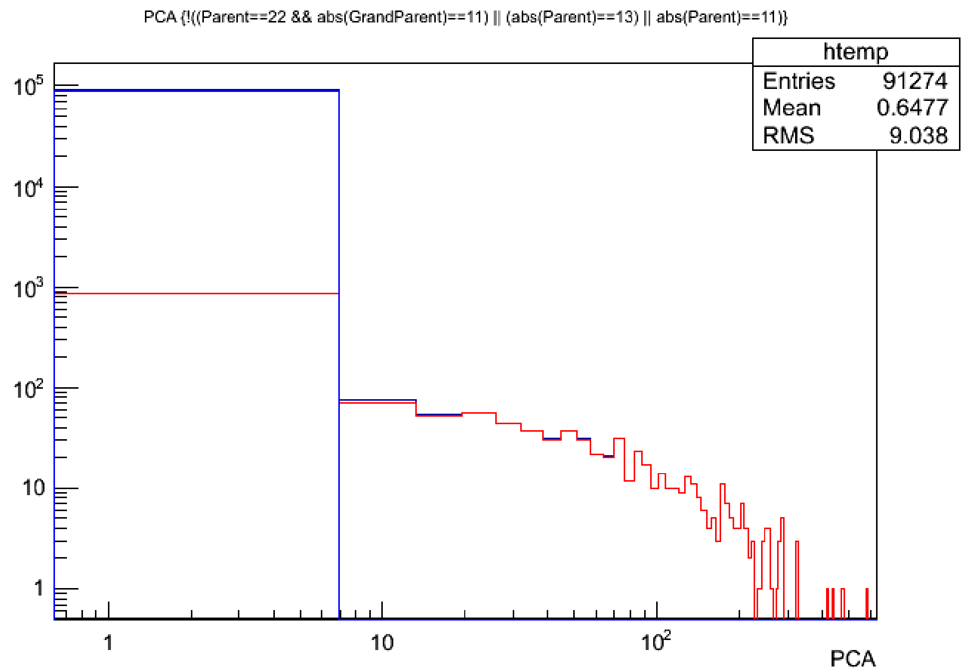

Figure 5: Distribution of PoCA values for events originated from gammas. Red histogram shows events from π^0 decays. Blue histogram is for events from bremsstrahlung photons which can be rejected by a PoCA cut. This and other figures are based on limited statistics and are shown for illustration purpose only. Yearly rates are given in Table 1 and in the text.

The most dangerous background is presented in the 6th row. These events are coming from π^0 decays. The π^0 parents are in many cases high-energy neutrons produced in muon-induced cascades. These neutrons can travel far from the muon track and the direction of the electrons may not be correlated with the muon direction so it is difficult to reject these events using PoCA or other cuts. Figure 5 shows the PoCA distribution for background events originated from gammas. Events from π^0 decays (red histogram has a wide distribution of PoCA values). Energy spectrum of events is presented in Figure 6. Most events from π^0 decays are below 1 GeV. A scatter plot of PoCA vs energy is displayed in Figure 7. Note that all figures in this note contain limited statistics (a fraction of a year) and are shown for illustration purpose only. Yearly rates are given in Table 1 and in the text. Below we suggest several methods which may help to reduce the background from π^0 decays.

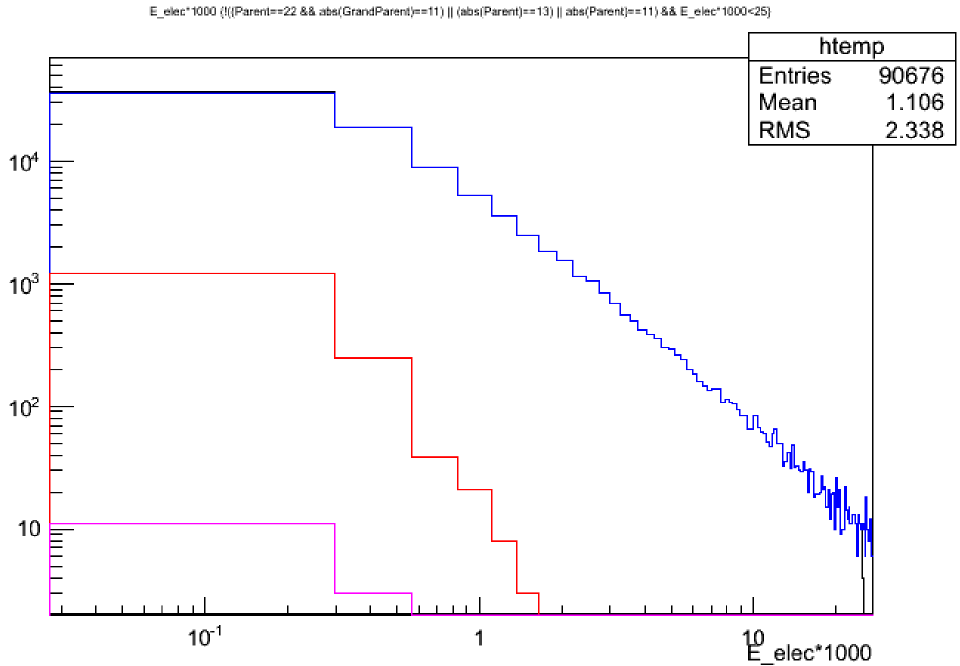

Figure 6: Energy spectra of events originated from gammas. Red histogram shows events from π^0 decays. Blue histogram is for events from bremsstrahlung photons. Magenta histograms is for $\pi^0 \rightarrow \gamma + e^+ + e^-$.

1. High-energy neutron events, including π^0 production and associate electromagnetic cascade are usually associated with a large muon-induced cascade. So far we recorded only electrons or photons and, on some occasions, their immediate predecessors without recording all particles in a muon-induced cascade. Future full simulations (requiring a lot of CPUs and disk space) should identify additional features associated with these events which would help us to reject them.

2. Liquid argon TPC will be able to pick up differences between ν_e interactions and neutron interactions with π^0 production. ν_e interactions will give an electron and, possibly, one or more hadrons. All tracks will start from the same point. Neutron interaction may also give several particles in the final state one of which could be π^0, some others being charged hadrons. Here the tracks of electrons/positrons will start from a different point in space compared to charged hadrons enabling the rejection of these events with a certain efficiency.

3. π^0's produced by charged hadrons can be rejected if PoCA is calculated with respect to the parent charged hadron track.

4. $\approx$98% efficient $e - \gamma$ separation factor will be applied to further reduce the background. This is true for all entries in Table 1.

5. Additional information about angle with respect to the muon or parent track and with

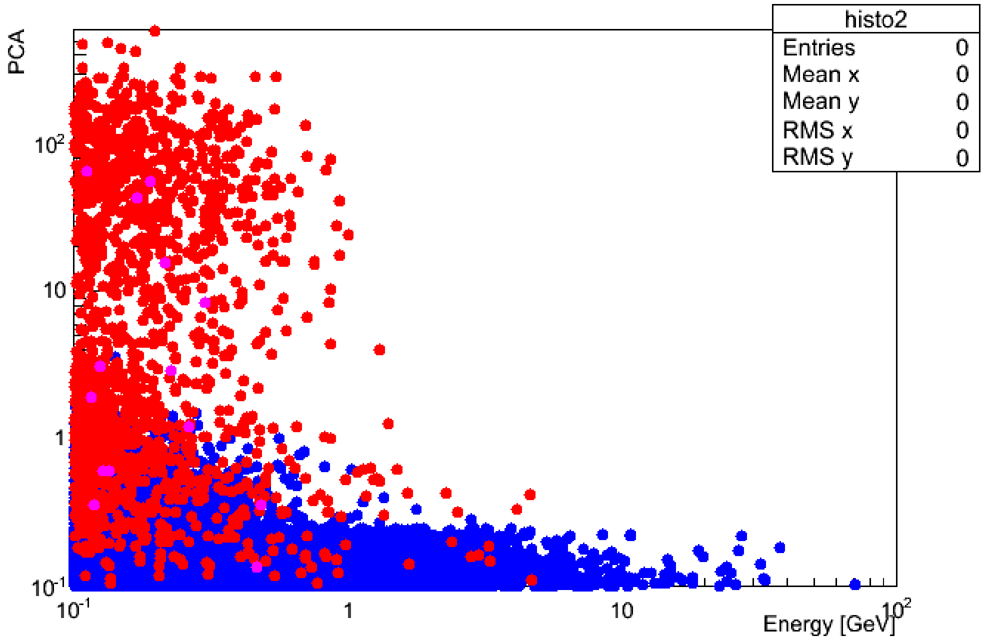

Figure 7: A scatter plot of PoCA vs energy. Red dots shows events from π^0 decays. Blue dots are for events from bremsstrahlung photons. A few magenta are for $\pi^0 \to \gamma + e^+ + e^-$.

respect to the beam will also be collected and analysed.

The last row in Table 1 shows events where gammas are coming from outside the detector. The rejection capability for these events requires extrapolating muon and electron tracks backwards to outside the detector and calculating PoCA for extrapolated tracks. This is currently under study so further improvements in the rejection power of these events are expected.

Choosing the angle with respect to the beam as being within the curves shown in Figure 2, will remove almost 2/3 of the background events bringing the expected number from about 8000 down to about 3200 per year before other possible cuts are applied (see Figure 8 for an angular distribution of background events with respect to the beam direction).

Further reduction by about a factor of 50 can be achieved by applying $e - \gamma$ separation cut [13] leaving about 64 background events per year in total, most of which must be rejected using additional features described above, for a successful operation of the detector.

Applying stronger cuts on PoCA, on the angles with respect to the muon track and with respect to the beam direction, helps to reduce the background further. The spectrum of selected events with PoCA > 50 cm, angle with respect to the muon $> 10°$ and angle with respect to the beam $< 40°$ is shown in Figure 9. Again almost all events are below 1 GeV. The cut on the angle with respect to the beam $< 40°$, however, reduces the efficiency of the ν_e detection below 0.5 GeV by about 40%.

Finally, a light detector will help in separating events by time within an accuracy of tens of

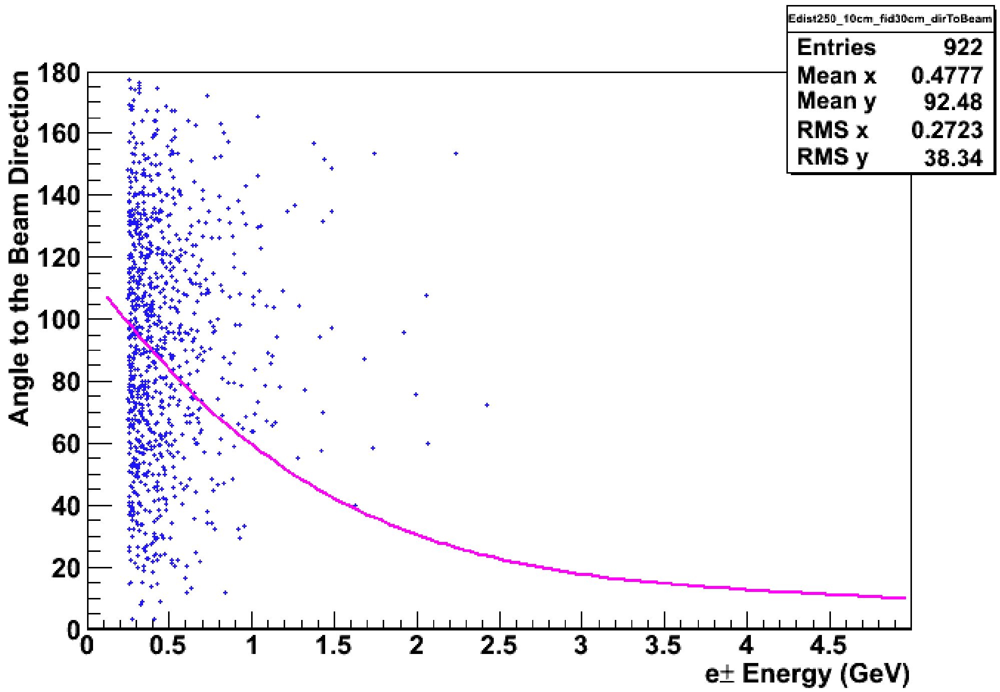

Figure 8: Scatter plot of angle with respect to the beam vs electron energy for background events (muons are detected).

nanoseconds.

Different simulations revealed that the results may depend on the physics list used in GEANT4. The new physics list 'Shielding' currently recommended for underground rare event searches and shielding calculations is supposed to provide the most accurate results. The majority of our simulations including those reported in Table 1 have been carried out with this physics list. Another physics list 'QGSP-BERT' gives a very similar total number of events but possibly smaller number of events passing selection cuts making the expected background rate lower. The results on PoCA cuts using 'QGSP-BERT', as well as the efficiency of cuts on the distance from the muon track, angles with respect to the muon and the beam have been included in the previous report [1]. We are currently investigating possible differences but included here a conservative estimate of the background rate obtained with the 'Shielding' physics list.

5 Background events without muon track in the detector

For muons that do not pass through the active detector, associated background events cannot be vetoed by connecting them to parent muons. These background events in the LAr detector are primarily induced by secondary neutral particles, such as neutrons, gamma-rays, π^0, etc. These neutral particles can produce charged particles in the detector with tracks that cannot be traced back to muons. While these background events have smaller rate compared to those produced by muons passing through the detector, they are much more difficult to reject by

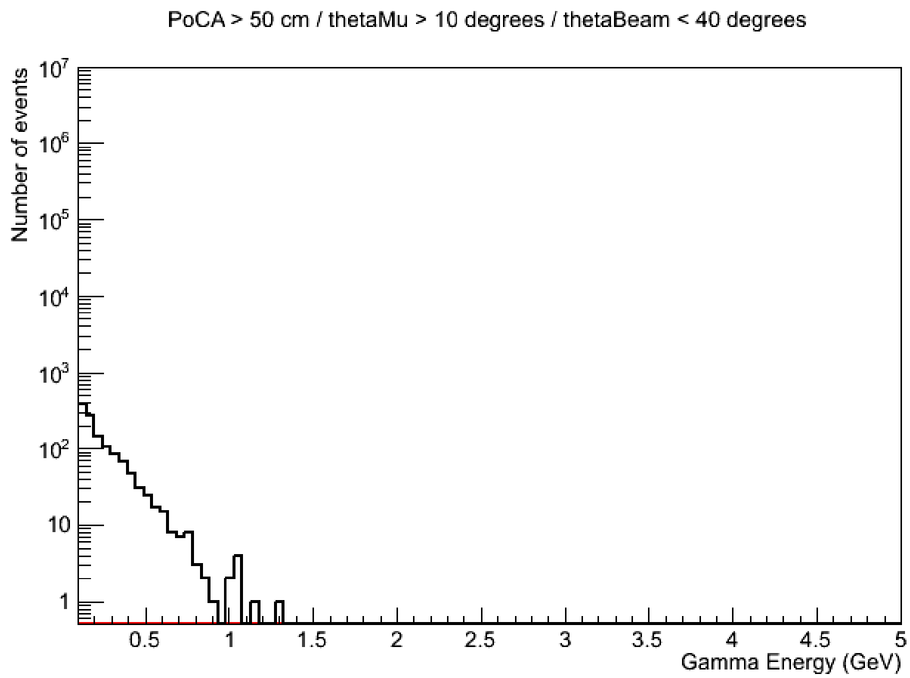

Figure 9: Energy spectrum of remaining events after selection: PoCA $>$ 50 cm, angle with respect to the muon $> 10^\circ$ and angle with respect to the beam $< 40^\circ$. (Muons are detected.)

kinematic cuts.

This background can be reduced by applying a fiducial volume cut. It is currently foreseen that at least 30 cm active argon volume close to the walls will not be used for analysing neutrino events.

First estimate of this background have been made in our report published in August 2012 [1]. At that time we concentrated on high-energy muons ($E_\mu > 10$ GeV and events with $E > 0.5$ GeV. Reducing the energy threshold for electrons down to 0.1-0.25 GeV increases significantly the number of background events as shown below.

We expect about 2.06×10^4 electrons with $E > 0.1$ GeV per calendar year giving a signal in the detector without an associated muon. About a half of these events can easily be rejected by the 30 cm fiducial volume cut since they are caused by electrons entering the detector volume from outside. The remaining 1.06×10^4 events per year are caused by gammas and are more difficult to reject. 1260 of them will survive the 30 cm cut and 360 will have energies $E > 0.25$ GeV. About 200 per year will have energies $E > 0.25$ GeV and survive a 50 cm fiducial volume cut. With an additional rejection of 98% of events originating from photons rather than neutrinos [13], the number of background events will drop to about 4 per year with a 50 cm fiducial volume cut, or to about 7 per year with a 30 cm cut. A further decrease by about a factor of 2 is achieved by selecting events within a cone around the beam direction as specified by the curve in Figure 2. The angular distribution of events with respect to the beam direction is shown in Figure 10. This leaves in total about 3 events per year with a 30 cm fiducial volume cut or 2 events with 50 cm cut.

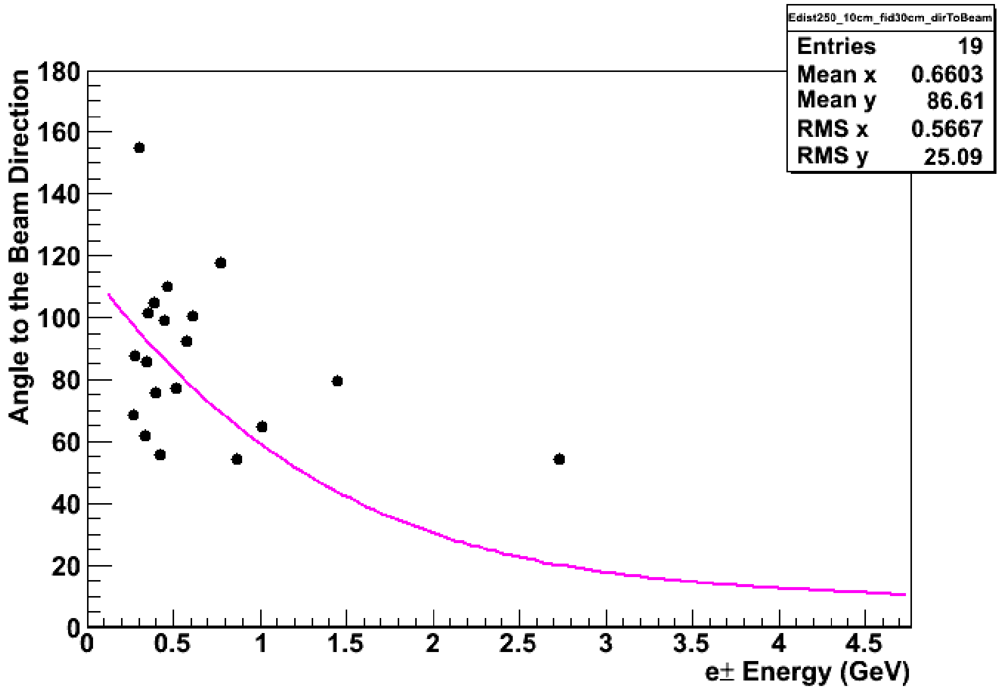

Figure 10: Scatter plot of angle with respect to the beam vs electron energy for background events (muons are not detected).

Figure 10 shows that practically all these events can be removed if we select the angle with respect to beam to be within 40°. However, the statistics is quite small and further simulations are needed.

The rate of these events can be further reduced by identifying other possible particles entering the detector and associated with this event (using, for instance, PoCA with respect to any other nearby track). The most efficient way would be to install a simple and efficient active veto system around the detector to track all muons.

Additional background will come from muons which cross dead regions of the detector and hence will be missed. Due to a small aperture for these muons (small volume of dead regions) their rate should not be high and the current design includes a 30 cm fiducial volume cut around the inner dead spaces.

6 Background caused by neutrons from atmospheric showers

It is currently assumed that the detector will be positioned at a depth of about 3 metres of rock or be protected by a (concrete) shielding equivalent to 3 m of rock coverage. Additional protection from the beam direction will be provided by placing the detector beyond the hill.

The goal of the studies described in this section is to identify which minimum depth is required to get rid of background events associated with hadronic component (neutrons) of atmospheric air showers. This is the first study of this kind which has not been reported previously.

In our simulations the detector has been positioned under a flat surface (accurate surface profile will be implemented later) with a vertical depth of 3 m and rock density of 2.71 g/cm^3, giving a vertical overburden of 8.13 g/cm^2. Neutrons have been sampled according to the energy spectrum generated by CRY [14]. Since CRY uses the database for atmospheric shower particles generated by primary protons only, the results may underestimate the actual rate by 50-70%. All events in the detector are due to high-energy neutrons so the results reported below were obtained with neutrons with energies above 0.1 GeV to achieve higher statistics. The statistics corresponds to 0.057 calendar years.

About 10^4 electrons with energy $E > 0.1$ GeV per calendar year are either coming from outside the detector or are produced by charged particles originated outside. They are rejected easily by the fiducial volume cut. About 1.05×10^4 electrons per year are originated by photons either coming from outside of the detector or produced in π^0 decays. In all cases neutrons were the prime source of these events. A fiducial volume cut of 30 cm (rejecting all cascades which start within 30 cm from the walls) reduces the number of background events to 5.67×10^3. Increasing the energy threshold to 0.25 GeV will decrease the rate further down to 2.84×10^3 per year. An efficient 98% $e - \gamma$ cascade separation [13] will get us to about 57 events per calendar year. Rejecting all events outside the chosen cone around the beam direction removes about 2/3 of the background leaving 20 events per year (see Figure 11 for angular distribution of events with respect to the beam).

This background can be reduced to a negligible level by increasing the depth (shielding) for the detector. The depth used in these simulations corresponded to 8.13 hg/cm^2 or m w. e. of overburden. Since only neutrons and muons can penetrate through this thickness of matter (ignoring neutrinos), removing this particular background component will require reducing the neutron flux. Neutron flux attenuation length [11] is about 1.6 m w. e. Reducing the calculated background of 20 events per year down to a safe value of < 1 event per year will require a factor of 20 reduction in neutron flux and an additional vertical overburden of about 5 m w. e. (13 m w. e. altogether). This is equivalent to about 4.8 metres of rock altogether (additional 1.8 metres relative to the originally assumed 3 m) or 5.9 m of concrete (density of 2.2 g/cm^3). Because of the uncertainty in neutron flux normalisation (see above) this is the minimum additional protection required in these circumstances.

Simulations for 4 m of rock deep location show that the neutron flux is attenuated by about an order of magnitude, meaning that the neutron attenuation is higher than reported in [11] and the attenuation length is probably about 1.2 m w. e. If this is the case, then the required vertical overburden may be slightly smaller.

7 Conclusions

We have presented an update of the simulations of cosmic-ray background for a LAr TPC at the surface looking for beam neutrino interactions. The main improvements from the previous

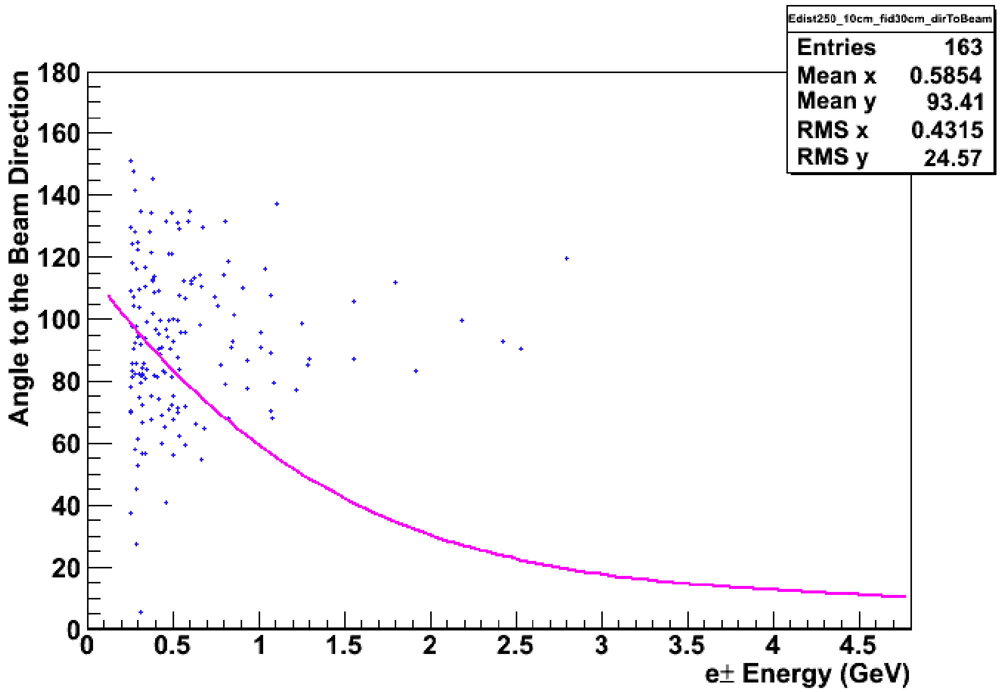

Figure 11: Scatter plot of angle with respect to the beam vs electron energy for background events due to atmospheric neutrons.

version of the report include: 1) reducing the energy threshold for electrons down to 0.1 GeV and 0.25 GeV; 2) studying PoCA with two different physics lists; 3) calculating background from neutrons from atmospheric showers and determining the required depth for the detector operation.

The simulations have shown that the most dangerous background is connected with photon-induced cascades where photons are produced by π^0 having neutron parents. These events are very difficult to reject using PoCA cuts. We expect to have 60 (150) events of this kind above 0.25 GeV in a 10 kT detector per calendar year after 30 (10) cm PoCA, fiducial volume and $e-\gamma$ separation (98% efficiency) cuts are applied. Different GEANT4 models may give results different by a significant factor. Here we have followed a conservative approach. We have identified a number of additional cuts which may help to reduce this background, such as angular information and calculation of PoCa with respect to all tracks in a muon event. This will be a subject of further studies.

The background from K_L^0 decay may give a signal indistinguishable from a ν_e interaction. Although we have not found this background to be critical at the moment, more studies are planned to ensure id does not affect the detector sensitivity.

Events not accompanied by a muon, may give a non-negligible background. Again, angular information helps with rejecting a large fraction of these events reducing this background down to a few events per year after applying the $e-\gamma$ separation cut.

Cascades linked to neutrons from atmospheric showers may compromise the detector sensitivity if the detector is positioned at a distance less than 13 m w. e. from the surface.

Current studies have revealed the need for more detailed simulations to identify the most promising selection criteria to remove background events from a sample of neutrino interactions. Although the calculated background is definitely non-negligible, we hope that further investigations as part of this project will allow us to reduce the background event rate down to the level where it will not compromise the detector sensitivity to the beam neutrino interactions.

The studies presented in this report do not include consideration of the photon detection system which performance is under investigation. Efficient photon detection system will allow to reduce the time of data collection to the duration of the beam spill (rather than the maximum drift time) and hence the overall background can be reduced by at least a factor of 140.

The uncertainties of our results are quite large due to: 1) relatively small statistics for some processes (only a fraction of a year has been simulated); 2) more thorough investigation required for some processes, such as K_L^0 decay; 3) possible dependence of the results on the model (physics list); 4) simplified energy reconstruction and event selection. Even with this large uncertainty the detector operation with an efficient photon detection system looks feasible at the surface.

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