Cosmic ray rates on a surface Liquid Argon TPC

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Introduction

This note gives some calculations on the rates of cosmic muons and cosmic photons entering a Liquid Argon detector of mass 50 ktons situated on the surface of the earth at the altitude of the Soudan Mine (400 meters). The context is an accelerator-beam based experiment.
Cosmic rays could affect the experiment in (at least) four ways;

- they could generate so much data that the data-acquisition is overwhelmed.
- they might obscure such a large fraction of the volume of the detector that they overlap the events of interest to the point where the events cannot be reconstructed accurately.
- they might overwhelm the reconstruction and analysis such that the computing time required simply to remove the cosmic rays from the analysis is prohibitive.
- they could generate interactions in the argon which mimic the neutrino events of interest.

Detector Parameters
The detector is characterized by the volume of argon, the anode to cathode distance (drift-distance) and the wire spacing. The present discussion considers a detector based on a liquefied natural gas tank, a cylinder with its axis vertical and with diameter the same as its height, $\approx$ 35.5m. The drift-distance is 3 meters giving a maximum drift-time of 2 milliseconds at a drift field of 500 V/cm. The wire-spacing is set at 5 mm with 3 readout co-ordinates (vertical and $\pm 30°$) resulting in $\approx 250,000$ wires. Each wire is equipped with a continuous wave-form digitizer running at 2 MHz and the detector therefore generates numbers at a rate of 5E11/second. A scheme of recording the differences between successive digitizations [1] allows these numbers to be encoded into 3E11 bytes/second. The design of the readout system [2] allows for a total transfer rate of 5E9 bytes/second or about 16 milliseconds of the raw history of the entire detector per second.

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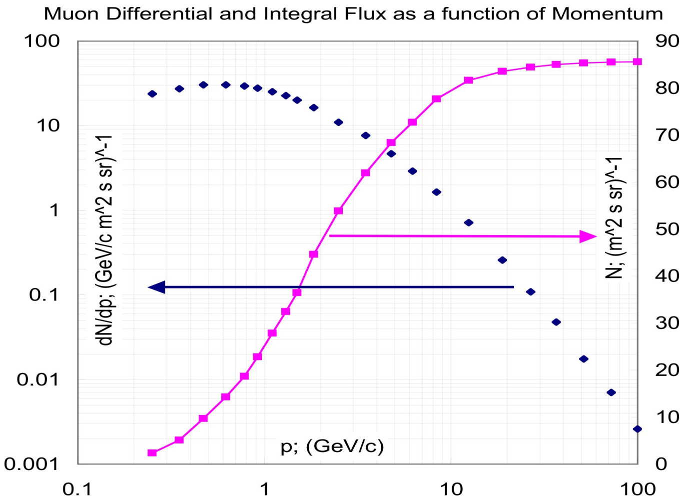
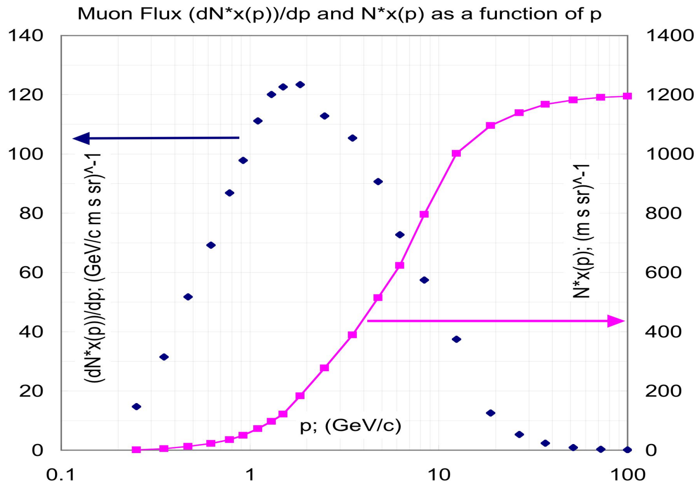
Data Acquisition Challenge
We assume there is no fast signal that defines the time of a cosmic ray entering the detector. If we wish to ensure that the *full* trajectory within the detector of any cosmic ray which generates signals in the detector live-time is reconstructed, the readout interval needs to cover from the maximum drift-time before the beam-spill to twice the maximum drift-time after the beam spill, a total of 6 milliseconds. (The 10 microseconds of actual spill is ignored.) If we simply want to tag a track as out of time, (as distinct from reconstructing the full trajectory inside the detector) it is not necessary to record for the full drift-times on both sides of the valid drift-time; recording before and after the nominal drift-time interval for 0.1 millisecond which is large compared to the few microsecond spill-timing uncertainties is sufficient[3].
The data acquisition is capable of transferring 16 milliseconds of raw history allowing for a beam-spill rate of $16/6 = 2.6$ Hz(full reconstruction) or $16/2.2 =$ 7Hz (tagging). This is faster than any accelerator cycle time proposed in the long baseline study [4].

Obscuring real events
The issue of background particles obscuring (confusing the reconstruction of) the events of interest, unlike the data acquisition issue, *does* depend on the background rates. The data source for these rates (both muons and photons) is the compendium by P. K. F. Grieder [5]. The rate of cosmic ray muons into our 35.5 meter height/diameter cylinder is 250 kHz. This number is calculated using a $\cos^2(\theta)$ distribution independent of momentum and includes particles entering from the top and from the sides (1/2 of the total).
The muon spectra for the calculations are shown in the first two figures.





The first figure shows the momentum spectrum at the zenith and its integral. The spectrum of the total path length of muons (the product of the flux at a given momentum and the path length in liquid argon of a muon of that momentum) and the integral thereof is given in the second figure. (For a muon with sufficient energy to traverse the full detector, the path length contribution is set to 50 meters.)

In the two millisecond live time, some 500 cosmic muons enter the detector; the muons have a typical energy of 3 GeV and travel about 15 meters given the dE/dx of 2.1 MeV per cm. Consider that each ray obscures a square tube of side 1 cm along its path, and traverses the whole detector (a conservative assumption given the 15 meter average path) and consider that the vertex of a genuine event occupies a region 2 cms long and 1 cm transverse. (This is the region of the event sensitive to spurious particles since it is important to identify a single ionizing electron before it showers.) The fraction of the volume of the detector obscured is then $\approx 500 \times 36 \times 3 \times 2 \times 10^{-4}/36,000 = 3 \times 10^{-4}$. This is an acceptably small inefficiency. The number of cosmic *photons* entering the detector is less than 1% of the muon rate (see below) and their impact on 'seeing' the true events is negligible.

Burden on reconstruction

Identifying and removing/ignoring the extraneous data from the muon tracks is also a requirement for successful operation of the experiment. The number of wires (in one co-ordinate) that a ray passes is ≈ 1000 and we may expect some 500,000 signals on the wires in one co-ordinate (7 tracks/wire) and about 1.5E6 signals total. An obvious scheme for identifying cosmic muons involves first finding lines in each co-ordinate separately. This is convenient logistically because one can present the data from sets of consecutive wires to a number of independent computers. Since the computers process their data in parallel, the number of computers (or equivalently, the number of wires per computer) can be set to achieve the analysis rate required.

Cosmic Rays as a source of Background events

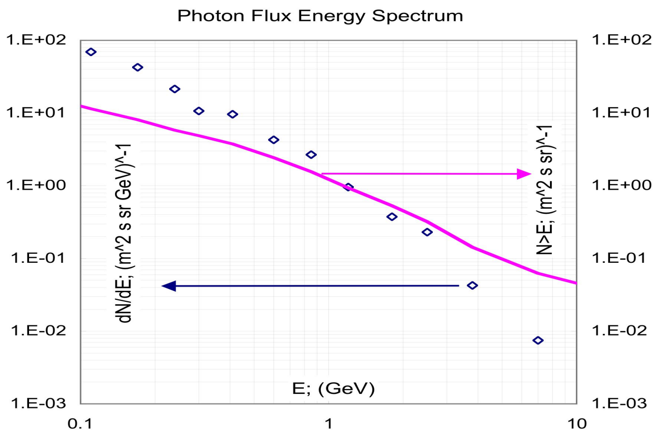
The last issue considered is background events from cosmic ray interactions in the detector. All that is done here is to establish the rejection rates required; the rejection we may expect still needs to be calculated.

Muons

The required rejection depends inversely on the number of protons-on-target (POT) per spill. A run of 15×10^{20} POT at 3×10^{13} POT per spill is 5×10^{7} spills, and some 2.5×10^{10} cosmic muons would cross the detector. If one considers a total number of 100 signal events, a rejection of order 2.5×10^{8} is required against these muons. It is indeed highly unlikely that any muon with sufficient energy to produce a background event be missed. The rejection, however, requires understanding the rate of muon interactions which generate a neutron or photon which travels a distance of several centimeters from the muon track before interacting. In this case it is still probable that the interaction can be associated with the incident muon but we do not have a number at this time.

Cosmic Photons

The total cosmic photon flux impinging on the detector is about 1% of the muons; their spectrum at the zenith is shown in the following figure. (Note that here the integral curve at point **E** gives the integral from **E** to infinity (unlike the muon plots). The photon flux has a steeper dependence on zenith angle than the muon data and is modeled as $\cos^3(\theta)$.



In our design, the active detector volume is shielded by the iron shell of the tank and a meter or so of liquid argon. The photon conversion length in the argon is 18 cms (9/7 times the radiation length) and so the material surrounding the active volume amounts to 6 photon interaction lengths, reducing the interactions in the active volume by a factor of 400. The entering photon flux is 1 in 4×10^4 of the muon flux implying that the photon rejection required at the boundary of the active volume is about 6×10^3. Unlike the muon case where the muon tags its entry into the detector and so one may be able to connect an interaction to the parent muon, photon conversions must be rejected on their own terms. A number of parameters are available to do this including the absence of hadronic activity at the conversion point, the presence of a double minimum ionizing track at the conversion point, and the angle of the event with respect to the beam from Fermilab.

We note that the relatively short interaction length for photons means that the rejection required relaxes quickly as one moves inside the active volume. (A meter of argon reduces the photon flux by a factor of 250.) It is also the case that one will be able to identify and measure cosmic photons as a cross-check on their behavior.

References

[1] S. Amerio et al., Considerations on the ICARUS Read-out and on Data Compression, ICARUS-TM/2002-05.

[2] *High Capacity Data acquisition architecture* - Bowden, Votava in http://lartpc-docdb.fnal.gov, document 81. Some of the specific numbers have changed but not the architecture.

[3] *why readout 6 milliseconds* in http://lartpc-docdb.fnal.gov document 160

[4] For use in a DC beam (a muon factory or a beta-beam), the data-acquisition situation is much more challenging. A surface detector would need a data-acquisition capable of transferring about 100 times as much raw data, or of rejecting data below threshold, fitting the wave-forms in real-time and passing fully reconstructed track positions and energy depositions. This latter scheme would require a band-width of 250 kHZ (cosmic muon rate) $\times$ 3,000 (wires seen per muon) $\times$ 4 bytes (wire number, pulse height, position) = 3 Gb/s. This would be within the capabilities of the proposed data acquisition system.

[5] Grieder, P.K.F. Cosmic Rays at Earth. Elsevier Science, 2001