The East-West Cosmic Muon Asymmetry

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Motivation

The constant bombardment of the Earth's atmosphere by cosmic rays creates a constant shower of secondary particles, one of which is the π meson (also known as the pion). Having a lifetime of 2.6×10^{-9}s, pions are extremely unstable and rapidly decay into secondary particles. The primary decay modes of both charged and neutral pions are given by

$$\begin{aligned} \pi^0 &\to 2\gamma, \\ \pi^+ &\to \mu^+ + \nu_\mu, \\ \pi^- &\to \mu^- + \bar{\nu}_\mu. \end{aligned}$$

Charged pion decays are of particular interest. Due to the fact that there are two different charged particles in question (μ^+ and μ^-) and the fact that the Earth possesses a magnetic field, it is simple to see that positively charged particles will be deflected in a direction opposite to the negatively charged ones. Positive muons will be deflected east (referred to as "westerly" muons) and negative muons will be deflected west (referred to as "easterly" muons).

Given that most cosmic rays are positively charged, there should be slightly more positive muons than negative muons. One would thus expect to see an east-west asymmetry. This effect has previously been measured to be on the order of $15-20\%$[1]. This measurement was, however, made at lower latitudes where the rigidity cutoff (that is, the minimum energy required by a particle to be deflected by a magnetic field) is 17GeV/c. The objective of this experiment is to measure this asymmetry in Montreal, where the rigidity cutoff is an order of magnitude less (1.45 GeV/c).

Apparatus

The apparatus used to measure the east-west asymmetry consists of three muon counters arranged in the configuration seen in Fig.1. A muon counter consists of a photomultiplier tube (PMT) in direct contact (with an optical grease intermediary) with a large piece of scintillator wrapped in aluminium and sealed with electrical tape to prevent light leaks.

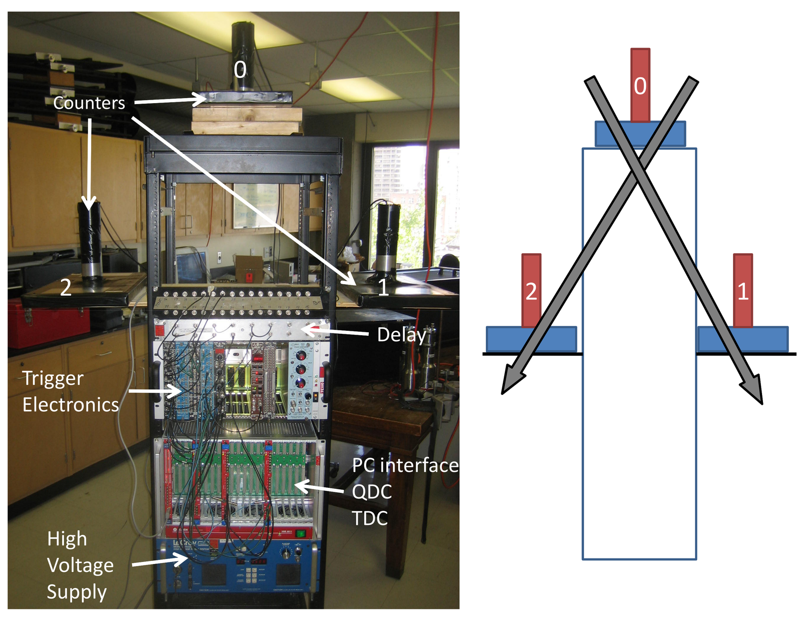

Figure 1: Left: Photo of apparatus with major components identified. Right: Apparatus block diagram. Red: PMTs. Blue: Scintillator. The arrows correspond to either trajectory that muons must take in order to trigger an event. The numbering convention remains the same in subsequent references to the muon counters.

The concept behind this design is simple: an event is registered when a muon is detected by both the top counter and one of the lower ones (*i.e.* such that an event constitutes a muon travelling in one direction or the other). The electronics used to register each event consist of a charge-to-digital converter (QDC) and time-to-digital converter (TDC).

A QDC functions by means of a gate input and one or more signal inputs (referred to as channels). While the gate is open, any signal will be integrated and the value read out to a computer. In the event that there is no signal on a given channel, what is known as the "pedestal" (that is, the residual current on the input) will still be integrated yielding a non-zero result. It is thus important to remove the pedestal in the data analysis by cutting off data on the lower range.

A TDC also requires two (or more) inputs, one constituting the timer start signal and the stop signals. The TDC converts the time difference between the start signal (which is common to all channels) and the stop signal. This value is then converted to arbitrary digital units which can be used to compare, for example, differences in arrival times between different counters.

The passing of a muon between the top and either of the two bottom counters opens the gate on the QDC and starts the TDC. The outputs of the counter PMTs are connected to both a QDC and a TDC. The complete setup is depicted in Fig.2.

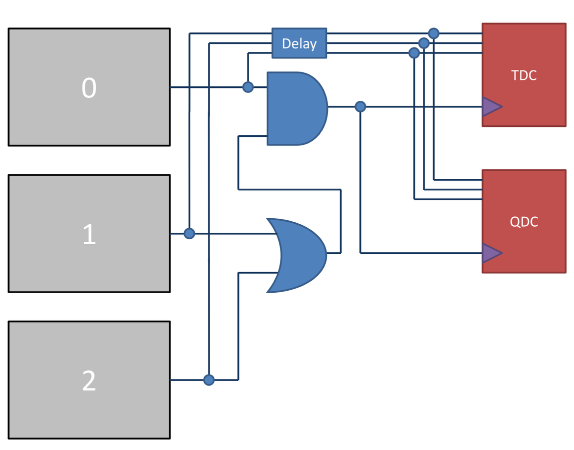

Figure 2: Data acquisition setup. The delay (which allows time for the start and gate signals to be produced) was taken to be 200ns. Note that the purple triangles on the TDC and QDC are the common start and gate inputs, respectively. Any inputs requiring digital logic are first discriminated.

It must be noted that due to the inherent differences in the efficiency of each muon counter, the rates calculated for both lower counters cannot be directly compared. Instead, to calculate an asymmetry, the apparatus must be rotated 180° and another data set must be taken.

Calibration

In order for the flux to be correctly measured, that is, for a muon counter not to miss any events, a high voltage must be chosen for the PMTs such that they react to all incoming photons released by the scintillator, but that the amount of "dark" current is minimal.

The operational voltages for the PMTs were determined using two smaller muon counters (henceforth referred to as "calibrators") with voltages set far into their expected operating ranges ($\approx$ 1800V). The counter to be calibrated is sandwiched between the calibrators. The output of each counter is connected to a discriminator (which turns analogue signals into digital logic levels) such that digital logic can then be applied to the signals.

The counter outputs are sent through the circuit as seen in Fig.3. Doubles correspond to muons passing through the counters where a signal is only registered by the calibrator PMTs whereas triples correspond to a signal received from all three.

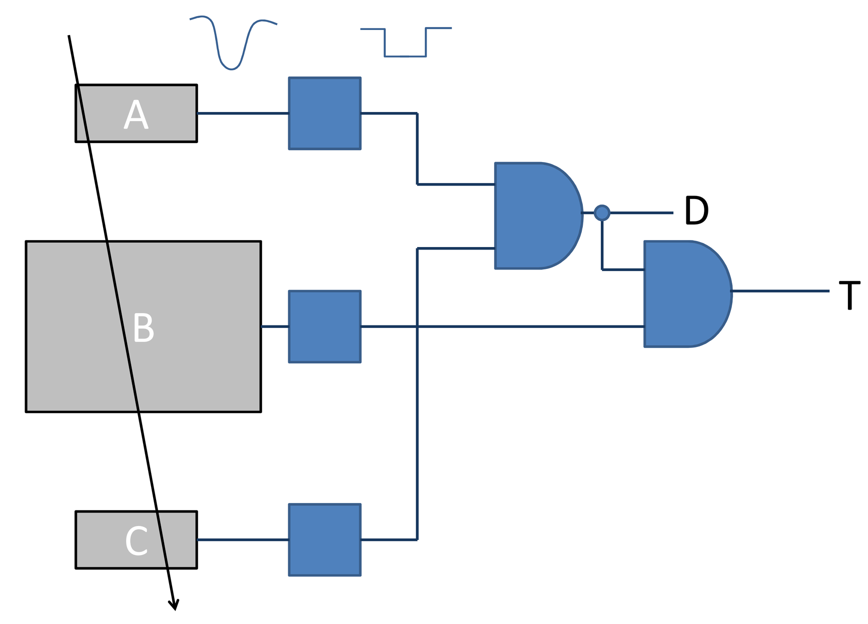

Figure 3: Muon counter calibration circuit. A and C correspond to calibrator counters and B is the counter being calibrated. D is the doubles output, T the triples output. The black arrow represents a muon passing through the calibration circuit. In order to pass through both callibrators, it must also pass through the counter requiring calibration.

The ratio of triples to doubles is plotted in Fig.4. One sees that for high voltages, the curve saturates. This is the region where we are assured that the counter is picking up all traversing muons. We must, however, recall that an operational voltage must be chosen low enough to avoid excessive dark current so voltages are taken close to the inflection point but still well within the plateau.

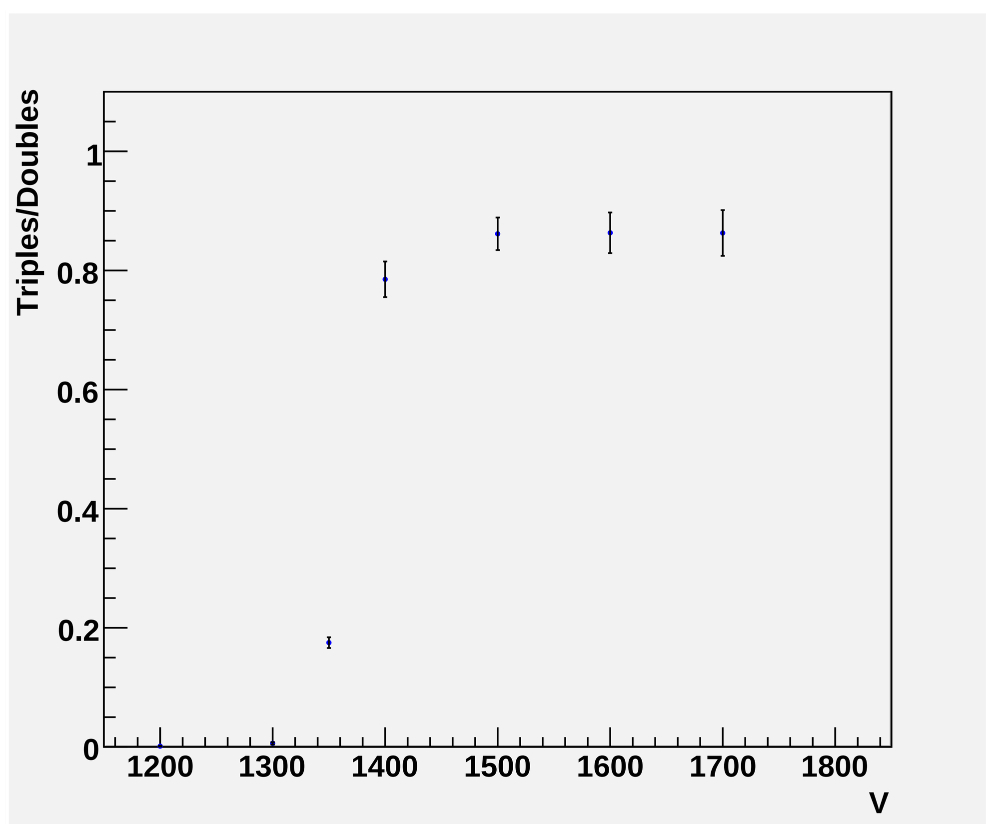

Figure 4: Calibration curve for PMT2. The chosen voltage was 1450V

The charge data were found to be very clean (*i.e.* no noise at the high end or low end), as is seen in Fig.5. Each charge distribution has the form of a Landau distribution, which is expected as this distribution describes the fluctuations in the energy loss of a charged particle passing through a layer of matter. Each bin is filled with the integrated current from a muon pulse (an example of which is seen in Fig.6).

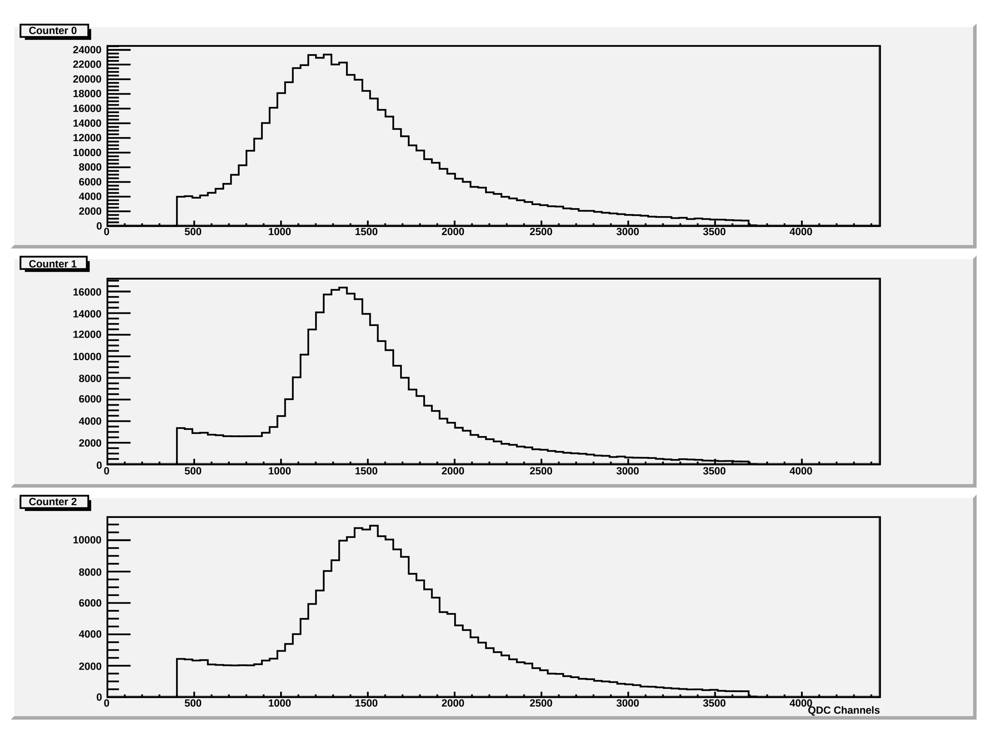

Figure 5: The charge distributions caused by muons. This plot corresponds to the integrated charge values as measured by the QDC. Cuts on the data have been made such that all events lie between 400 and 3700 QDC units such that the QDC pedestal and overflow values do not appear.

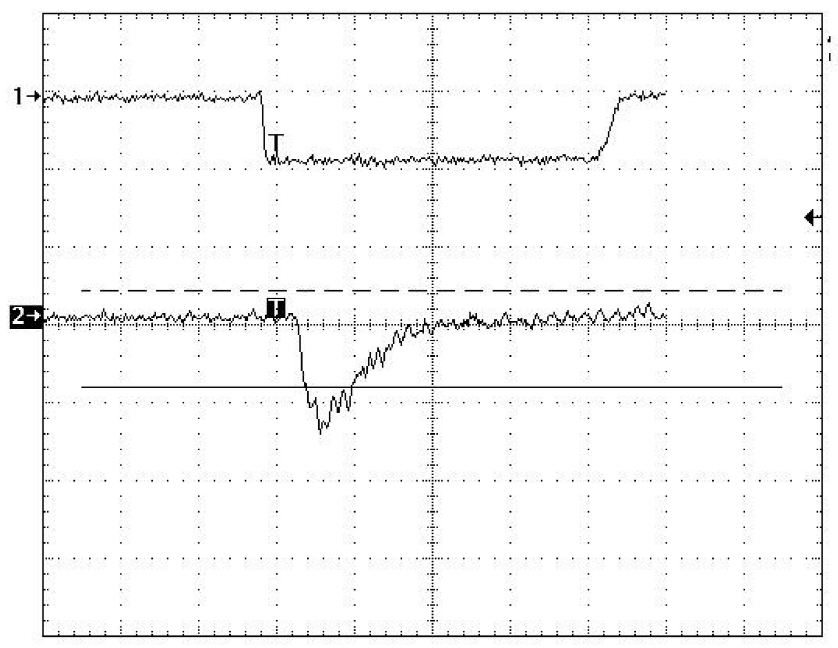

Figure 6: An oscilliscope trace containing the gate signals and counter signal as a muon passes through the apparatus. Trace 1: The gate pulse (width 200ns, 1V/div). Trace 2: The counter signal (100mV/div).

Preliminary Results

The muon flux rate can be calculated two ways. The obvious and simple method of doing so is to divide the total number of valid events in a data set by the duration of the run (*i.e* the pure average). This is a reasonable method of calculating it because over long periods of time, the muon flux is constant as is shown in Fig.7.

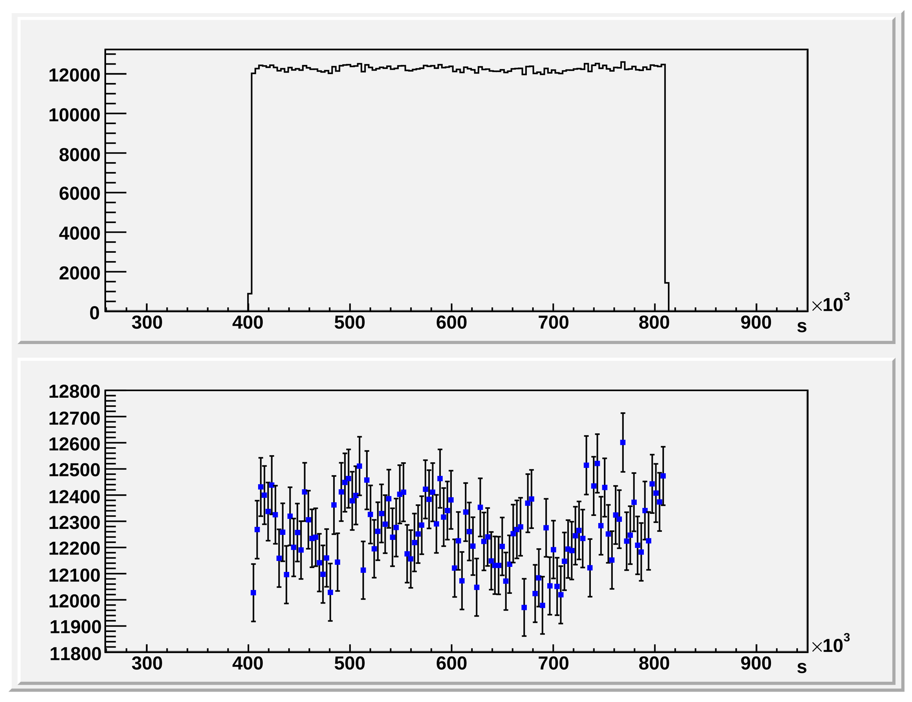

Figure 7: An example of an unmodified data set (*i.e.* no cuts) taken over roughly 4 days. Top: Bin sizes correspond to one hour. The number of events per unit time is seen to be fairly stable. Bottom: The same data set (zero-suppressed) with error bars corresponding to the Poissonian error.

The second is to generate a plot corresponding to the time delay between two events. The curve will be an exponential with a slope whose absolute value is equal to the muon flux rate. Such a curve is depicted below in Fig.8.

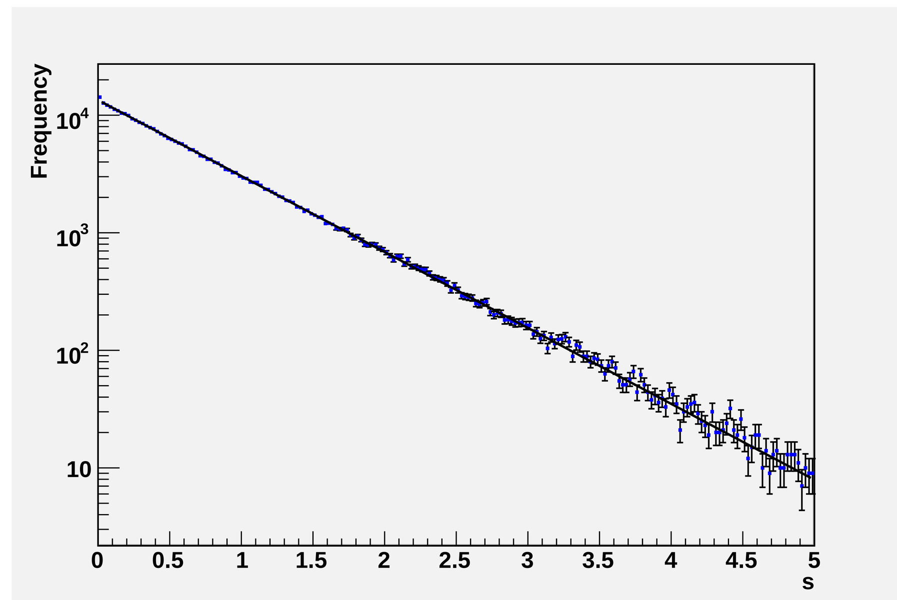

Figure 8: Example histogram of event delay times for muons passing through counter 1. The fit curve is of the form $\exp(\alpha t + \beta)$ with $\alpha = -1.487 \pm 0.003\text{s}^{-1}$ and $\beta = 9.506 \pm 0.002$.

For the above data, the muon flux rate through a given counter was found to be $1.437 \pm .004\text{s}^{-1}$ and $1.487 \pm .003\text{s}^{-1}$ for the direct average and exponential methods, respectively. While not strictly consistent, they differ only by $\approx 3\%$. Given that the lower value originates from the direct average method, one can attribute this discrepancy to dead time (time when the equipment is busy and cannot accept more events) between events on very short timescales within the apparatus. The fit method, however, yielding a function that can describe the expected number of events for very short times between events, automatically compensates for this.

Conclusions

The east-west muon asymmetry can be measured using a fairly simple apparatus consisting of three muon counters, a QDC and TDC. Due to the fact that this effect is very small (expected to be on the order of a few %), long data runs (on the order of several hours to days) must be taken to ensure that the flux rates are statistically significant enough for the ratio to be measured without having to worry about error (which is proportional to $\frac{1}{\sqrt{t}}$, where t is the length of the data run). The main issue with measuring the asymmetry lies in the systematic error, given that the statistical error is known to less than 1%. Therefore, for the next several weeks, measurements will continue in an effort to detect the asymmetry.

References

[1] P. N. Dinh, N. T. Dung, B. D. Hieu, N. Phuc, P. T. Phuong, P. Darriulat, D. Q. Thieu, and V. V. Thuan. Measurement of the vertical cosmic muon flux in a region of large rigidity cutoff. *Nuclear Physics B*, 627(1-2):29 – 42, 2002.