Elimination of Cosmic Ray Events for CLEO-c

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Cosmic rays impede the analysis of electron-positron interactions at CLEO-c. Events triggered by cosmic rays take up valuable computer processing time and storage space as well. Though luminosity varies between runs, an estimated thirty percent of events at CLEO are triggered by cosmic rays. A processor working from raw data was created to reduce this background. The program fits cosmic ray candidate tracks as lines through the detector by reconstructing muon chamber hits. The algorithm also includes a series of tests to prevent eliminating an event in which a cosmic ray overlaps with an interaction from inside the detector. The processor signifcantly reduces the number of cosmic rays events in the data stream. Approximately 0.1 percent of events are mistakenly identified as cosmic rays and appear to consist exclusively of beam noise overlapping with a cosmic rays. The processor may be added to other CLEO software in the future.

I. INTRODUCTION

Cosmic rays should not enter data sets used to investigate electron-positron interactions in the CLEO experiment. Such interference creates significant background and could lead to faulty physics predictions. Furthermore, the cosmic ray events consume a valuable part of the computer resources at CLEO. With data streaming in at a rate of 100 events per second, the elimination of cosmic rays events could substantially increase efficiency. Cosmic rays also fill up disk space with experimentally uninteresting events. Although cosmic rays are sometimes studied for their other-worldly origins, the CLEO experiment focuses on events from within the detctor.

Cosmic rays are high energy muons produced in the upper atmosphere. Protons from outer space strike the upper atmosphere and create a shower of particles including pions which quickly decay into muons and muon neutrinos. The muons travel at relativistic speed and rain down on the surface of the Earth at a rate of 100 per square meter per second. The high energy muons pass through the iron layers of CLEO and trigger an event either by leaving a track in the drift chamber or by depositing a significant amount of energy in the crystal calorimeter. An estimated thirty percent of the events at CLEO-c are triggered by cosmic rays rather than by electron-positron collisions. This large background motivates the design of a program to eliminate cosmic ray triggered events from the data stream.

II. RESOURCES OF CLEO

The cosmic ray problem has several solutions. One approach is to include specific cuts against cosmic rays in each individual data analysis project. Another more general method of attack is the design of a specific processor to filter cosmic rays. However, a larger portion of computer resources could be freed if the processor relied only on raw data and discarded cosmic ray events before the advanced tracking software of PASS2. The earlier cosmic ray events can be identified, the greater the data processing efficiency. The processor discussed here will work from raw data and is very fast. Though particle tracks are not available with raw data, CLEO still has several tools to search for cosmic ray events.

The muon chambers are the primary intruments for identifying muons in CLEO. The muon chambers are shielded from the interaction point by successive layers of iron 36 cm thick. Muons are the only charged particles produced in CLEO capable of penetrating these iron layers. Muon chambers are positioned around CLEO so that there are endcap sections on either side of detector and eight sections refered to as octants wrapping around the barrel of CLEO. Figure 1 shows several muon chamber hits in a typical cosmic ray event. The barrel sections are further divided into three concentric units for each octant separated by layers of iron. The geometry of the barrel sections will be the focus because the large majority of cosmic rays enter the detector at a steep angle to the horizontal and have a greater probability of leaving tracks in the octants. The two endcap sections are each composed of a single unit compared to the three depths of each octant. The units each contain three layers of multiplets.

The multiplet is the element that detects a muon hit. Multiplets are composed of wires connected with resistors that are read out from each end to gain further spatial hit resolution. Each layer contains two counter type multiplets and four strip type multiplets. A summary of multiplet distribution is shown in Equations 1-3.

$$TotalMultiplets = BarrelMultiplets + EndcapMultiplets \tag{1}$$

$$BarrelMultiplets = 8octants \cdot \frac{3units}{octant} \cdot \frac{3layers}{unit} \cdot \frac{2CounterMultiplets + 4StripMultiplets}{layer} \tag{2}$$

$$EndcapMultiplets = 2endcaps \cdot \frac{1unit}{endcap} \cdot \frac{3layers}{unit} \cdot \frac{2CounterMultiplets + 4StripMultiplets}{layer} \tag{3}$$

Two coordinate systems should be considered when dealing with the geometry of the muon chambers. In the detector coordinate system, the positive x-axis is directed radially outward of CESR to the South, the positive y-axis is directed vertically upwards, and the positive z-axis is directed West tangent to the beam line. The origin is located at the center of the detector. Since the muon chambers are divided into octants, there is also a local coordinate system for each octant. This will be called the primed coordinate system. The origin of the local coordinate system is also defined to be at the center of the detector. The positive y'-axis is directed radially outward from the detector. The z'-axis is identical to the z-axis. The local coodinate system is also right-handed. Vectors and points in the local coordinate system can be transformed to the detector coordinate system by a rotation about the z-axis. These coordinate systems were selected to reflect the geometry of the muon chambers.

Local octant coordinate systems best describe strip and counter multiplet configuration. The counters and strips run perpendicular to each other similar to lines of longitude and lattitude. In the barrel section, the counters run lengthwise along the beam line and give a x'-coordinate. The strips wrap across the detector and give a z'-coordinate. The y'-coordinate is fixed by the location of the chamber. A counter is composed of 8 anode wires each in a 1cm by 1cm tube of Argon-Ethane gas. The copper cathode strips are stacked above the counters. The number of strips and counters in each multiplet is shown in Table 1. Each multiplet has an ID number to indicate its location and records a hit as a pulse height pair. The multiplets are read out from each end and the hit counter or strip is calculated by using

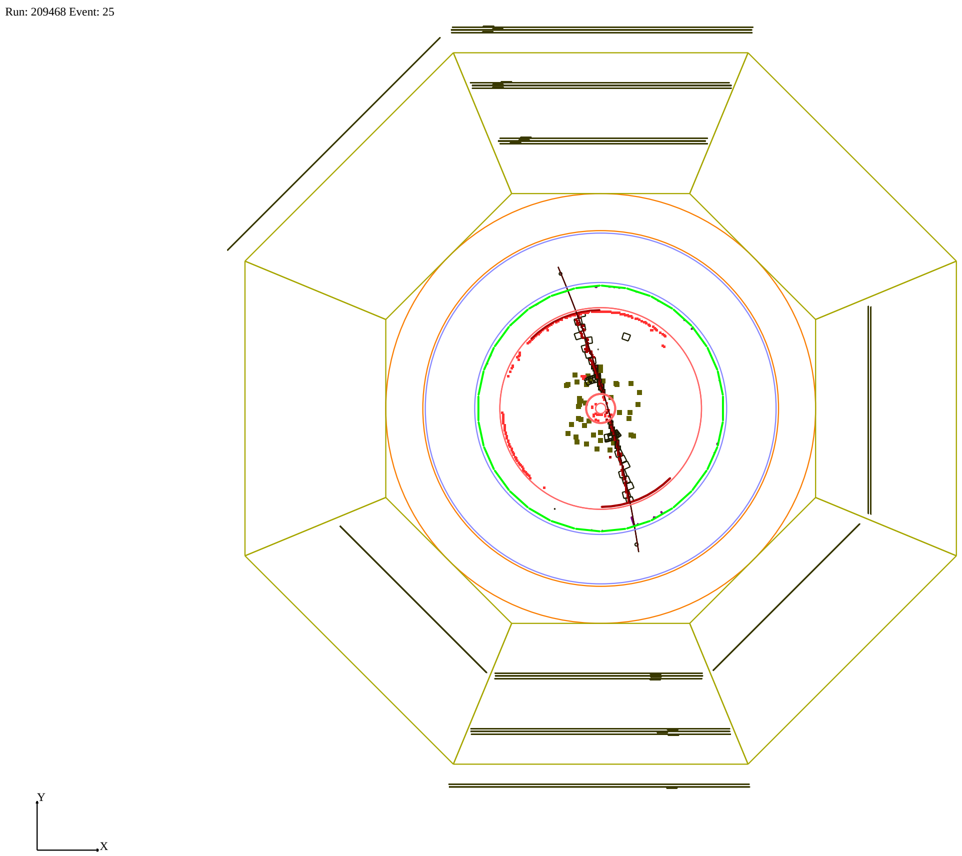

FIG. 1: The front view of event 25 from run 209468 shows a typical cosmic ray event in the CLEO detector. Note the octagonal arrangement of muon chambers in the barrel section. The crystal calorimeter hits and key axial wire trigger hits are shown respectively as circles outside the central drift chamber and the rectangles closest to the drift chamber center.

charge division. The outputs of individual strips and counters are wired together in series and separated by resistors. Each multiplet can be treated as a complex voltage divider. The ratio of pulse heights indicates which counter or strip was hit within the multiplet.

TABLE I: Number of counters and strips per multiplet in the 3 units of barrel muon chambers

Unit	Counter Multiplets (1,2)	Strip Multiplets (1,2,3,4)
Return	10,10	15,15,15,9
Inner	15,10	15,15,15,15
Outer	15,14	15,15,15,15

The spatial hit resolution of the muon chambers is limited by the size of the individual counter and strip elements. Each counter is 8.391cm wide and each strip is 8.128cm wide. However, the three layers in each unit are slightly offset from one another such that the effective resolution of the counters and strips is the width divided by $\sqrt{12}$.

While the muon chambers are excellent for identifying the presence of a cosmic ray muon, the multiplets are not part of the triggering mechanism of CLEO. In many cases, a coincident cosmic ray may cause numerous muon chamber hits and not be responsible for activating the trigger. The essential elements of the trigger process are the neutral energy trigger of the crystal calorimeters and the tracking trigger of the drift chamber.

The crystal calorimeters of CLEO provide information on the energy of particles within the detector. The neutral energy trigger is generally used to identify photons since only charged particles ionize the gas of the drift chamber. Cosmic rays can activate the crystal calorimeter trigger by skimming the drift chamber and leaving a string of crystal calorimeter hits. Muons generally deposit the minimum ionization energy of 100-300 MeV in the crystal calorimeters. In addition to the muon chambers, this characteristic energy deposition is an effective method of searching for muons. One advantage of using the crystal calorimeter in a raw data analysis is that the crystals have excellent spatial resolution and coverage within the detector.

The tracking trigger searches for potential particle tracks in the drift chamber to activate the CLEO trigger. Although the raw data primarily consists of drift chamber wire hits, additional trigger software is used to identify potential tracks prior to the full track reconstruction process. The axial key wire trigger uses pattern recognition to estimate for the number of particle tracks in an event. The 112 key axial wires a physically located at a radius of 25cm out from the beam line in the ninth layer of drift chamber wires. The z-coordinate along the wires is not specified. Every 42ns, software searches for coincidences of drift chamber hits that correspond to known possible particle tracks. Any event activating two or more axial key wire hits causes the trigger to be fire and the event to be recorded. While the muon chambers and crystal calorimeters can be used to search specifically for cosmic ray muons, the key axial wire triggers are important to identify other particles. In order to tag an event as a cosmic ray, it must be certain that the cosmic ray is responsible for each of the key axial wire triggers. Without this information, a legitimate event may be eliminated due to the unrelated coincidence of a cosmic ray overlap. The key axial wire triggers act as a check against the accidental removal of electron-positron interactions.

III. THE PROCESSOR

The processor CosmicsFilterProc7 tags events triggered by cosmic rays. This processor is coded in C++ and acts as an filter for data analysis. The general layout of the program is a series of tests to determine if the event meets the requirements of a cosmic ray followed by a series of checks to ensure that the cosmic ray candidate does not coincide with a electron-positron interaction.

The first step of the program is to reconstruct the muon chamber hits. As the counter and strip multiplet hits are extracted an array stores the number of hits in each octant. A hit is defined as a strip or counter multiplet with a significant pulse height pair signal. The octant with the most hits becomes the primary octant and the octant with the second highest number of hits becomes the secondary octant. Once identified, these two octants provide a framework for the remainder of the program. Uncertainty arises when two or more multiplets of the same type are activated in the same layer. This ambiguity can arise from noise in the muon chambers or a single particle creating a shower of secondary particles while passing through the muon chambers.The conflict is resolved by choosing the multiplet with the heigher pulse height sum.

Each hit is given a key number according to the octant, unit, and layer of the multiplet which encodes its position. Next, a function searches for matching pairs of key numbers for strip and counter multiplets. Once these multiplets are associated, a spatial point can be created by calculating x' from the counter multiplet, z' from the strip multiplet, and y' from the muon chamber configuration. The points are sorted by octant.

A fortran function, LFIT, from the CERN library fits lines to points in the primary and secondary octants. The algorithm uses a two-dimensional least-squares fitter twice to generate a three-dimensional line. The lines are fitted in local coordinates with y' as the independent variable and x' and z' as the dependent variable. Recall that y' is fixed by the multiplet location and that this choice of independent variable takes advantage of the muon chamber geometry. A minimum of three points per octant are required to attempt a line fit. Additionally, the program checks the variance of the fit and will remove up to two points if the variance is proportionally much larger than the resolution of the muon chambers. The selection of points for removal is independent for the $y' - x'$ fit and the $y' - z'$ fit since the strips and counters are distinct elements. The program ensures that at least two points remain for line fitting. The form of the line in local coordinates is given by Equations 4-7.

$$x' = Slope_x \cdot y' + Intercept_x \tag{4}$$

$$z' = Slope_z \cdot y' + Intercept_z \tag{5}$$

$$< x', y', z' > = < Slope_x, 1, Slope_z > \cdot t' + < Intercept_x, 0, Intercept_z > \tag{6}$$

$$-\infty < t' < \infty \tag{7}$$

The local three-dimensional line is transformed to detector coordinates by a rotation about the z'-axis.

Following the line fitting in each octant, the processor collects the beam energy, beam spot, the crystal calorimeter hits in the minimum ionization energy range, and key axial wire hits. As the additional data are extracted, the program calculates the closest radial approach of the fitted lines to the beam spot and each of the key axial wires. The absolute distance between the fitted line and each crystal calorimeter hit is also calculated. These values are essential to the evaluation logic of the program.

An event must satisfy each requirement of a cosmic ray and pass each electron-positron interaction overlap check to be tagged as a cosmic ray. The first criterion of a cosmic ray event is five or more matching counter and strip hits within the primary octant. In addition, at least one point in either the primary or secondary octant must be located in the outermost unit of the muon chambers. Muons produced within the detector are much less likely to reach this outer unit through the successive layers of iron because they run out of kinetic energy as as they ionize a trail through the iron absorber. In contrast, high energy cosmic ray muons often cause muon chamber hits on opposite sides of the detector. The outer unit hit requirement is a way of testing if the muon came from outside the detector. Secondly, at least one crystal calorimeter hit in the minimum ionization range 100 to 365 MeV must be within 1.2m of a fitted line. The cosmic ray requirements are relatively loose to facilitate the selection of cosmic ray candidates. At this point, the program has merely identified a muon of probable external origin.

The additional overlap tests are tuned to strictly select cosmic ray events without drastically compromising the overall cosmic ray identification efficiency. All of the checks involve the key axial wires to ensure that the cosmic ray candidate actually fired the trigger. Once an event is removed from the data stream, it cannot be retrieved or re-examined. Although cosmic rays are troublesome to physics analyses, the accidental removal of a rare electron-positron interaction is much more costly. Therefore, a failure at any of the overlap tests results results in the automatic passage of the event as non-Cosmic in origin.

The most straightforward test counts the number of key axial wire hits. An event is ruled non-Cosmic if there are six or more key axial wire hits. Any event having that many potential tracks is unlikely to be triggered by a cosmic ray alone.

A series of tests are activated if at least two key axial wire hits are found. First, if the radial distance of closest approach between the key axial wire and both fitted lines is greater than 0.5m[1] the key axial wire is considered unaccounted by the cosmic ray candidate tracks. Two or more unaccounted key axial wires constitutes a non-cosmic event. Second, are two spatial checks. If the radial distance of closest approach between the fitted lines and the beam spot is greater than 0.45m the event is tagged non-Cosmic. The expected cosmic ray track is not close enough to the interaction point to confidently account for the two-track trigger. The event also fails the spatial test if the average z-coordinate of crystal calorimeter hits is greater than 0.7m. The key axial wires extend about 0.7m in either direction along the beam line. An average z-coordinate of crystal calorimeter hits larger than this value indicates that the cosmic ray track probably did not come within range of the key axial wires and could not have fired the trigger

Finally, the program checks the event against two specific electron-positron interactions known to occur within the detector. These are Bhabhas, $e^+e^- \rightarrow e^+e^-$, and muon pair production events, $e^+e^- \rightarrow \mu^+\mu^-$. The Bhabha events are identified by either two crystal calorimeter hits with roughly the beam energy or at least one crystal hit with the beam energy and a total energy deposited in the crystal calorimeter of about twice the beam energy or more. The second condition handles the case in which one of the electrons distributes energy across two or more adjascent crystals.

Muon pair events are the most difficult electron-positron interactions to distinguish from cosmic rays. Though the events have completely different origins, a cosmic ray passing within a few centimeters of the interaction point is often nearly impossible to discern from a μ-pair event. Careful sorting often requires the full tracking software of CLEO. Both events leave a string of hits in the muon chamber with corresponding crystal calorimeter hits and key axial wire triggers. Due to this identification difficulty, the program deems any event in which muons appear to pass through the interaction point non-Cosmic. Without reconstructed particle tracks to work with, measuring the closest approach to the interaction point precisely is challenging. However, muon pair events tend to produce tracks that are nearly back-to-back. The program searches for key axial wire hits on opposite sides of the interaction point. Next, the program checks for a pair of crystal calorimeter hits in the minimum ionization energy range, 100-365 MeV, whose average z-coordinate is within 5cm of the beam spot. The combination of these tests locates the path of the muon or muons in the drift chamber to within a few centimeters of the interaction point. At this point, more advanced software is required to establish the exact identity of the event so the event is tagged non-Cosmic until further tests become avaiable.

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[1] The parameters discussed may seem arbitrarily large without an explanation. The closest layer of the muon chambers to the interaction is about 2.14m radially outward. As a result of this long lever arm and the resolution of the strips and counters, there is an inherent restriction in the precision of lines fitted through the muon chambers.

IV. CONCLUSIONS

The processor CosmicsFilterProc7 substantially reduces the cosmic ray background. The actual fraction of cosmic ray events that are identified in a typical CLEO data sample can only be estimated because the total number of cosmic ray events has not been calculated. Each run has a different luminosity and contains tens of thousands of events to analyze. In many cases when a cosmic ray overlaps with an interaction from within CLEO, there exists a degree of ambiguity over which particles caused the trigger to fire. However, human analysis of thousands of events over the course of this project suggests that a typical run contains roughly one-third events triggered by cosmic rays.

A sample of entirely cosmic ray events was used to test the cosmic ray searching efficiency of CosmicsFilterProc7. During this sample, the CLEO detector continued to collect events while the beam line was turned off. No electron-positron interactions were possible without the beam so only cosmic rays could be responsible for the trigger. CosmicsFilterProc7 tagged 6473 events as cosmic rays out of a sample of 8810 cosmic ray events from run 128748. The processor succesfully identified 73.47 percent of cosmic ray events. However, this run with no beam line is uncharacteristic of the CLEO experiment. A normal run must be used to judge the processor's effectiveness in the context.

Run 209468 collected in April 2005 was selected to test the effectiveness of CosmicsFilterProc7 for typical CLEO data sample. This run includes the raw data required by the processor and contains 94668 events. CosmicsFilterProc7 eliminated 25.23 percent of events in 10000 event sample from late in the run. This sample was selected because beam noise is generally higher at the beginning of runs. Approximately 1 event in a thousand is mistakenly tagged as a cosmic ray when other particles may have activated the trigger. However, every example of this mistaken identification seen thus far has been a type of beam noise overlapping with a cosmic ray.

The next challenge for CosmicsFilterProc7 was to sort through a sample of muon pair candidates. These events were selected from run 209468 by a slightly modified version of another processor, P2LumiMonProc. Of the 306 muon pair candidate events identified by P2LumiMonProc in run 209468, CosmicsFilterProc7 passed 305 events or 99.67 percent. The one event rejected by the processor shows evidence of being a cosmic ray accidently categorized as a muon pair event. The high pass rate of muon pairs raises confidence that the accidental elimination of a electron-positron interaction will be a rare occurance.

The results from runs 128748 and 209468 are summarized in Table 2. The sample from run 128748 was taken from the first 10038 events. Note that the samples from run 209468 begin at event 80000 and that the muon pair event samples were selected by P2LumiMonProc from all events of run 209468.

TABLE II: Comparison of cosmic ray identification in samples from runs 128748 and 209468. Run 128748 is a sample of all cosmic ray events with no beam and run 209468 is a typical CLEO data sample with the beam turned on.

Method	Non-Cosmic	Cosmic	Total	Pass Percentage	Reject Percentage
CosmicsFilterProc7, No-Beam	2337	6473	8810	26.53	73.47
CosmicsFilterProc7, Beam	7499	2531	10030	74.77	25.23
μ-pairs, Human Analysis	305	1	306	99.67	0.33
μ-pairs, CosmicsFilterProc7	305	1	306	99.67	0.33

Several possibilities for future exploration exist for this project. First, the parameters of the processor could be further optimized to suit the needs of the individual programmer. The values discussed in this paper can be thought of as defaults that can be modified to give more or less weight specific factors or to adjust the overall selectivity of the processor. Though the majority of CLEO research projects seek to eliminate cosmic rays from the data, some groups hope to study cosmic rays and could use the processor to select cosmic ray events. At some point, the processor may be added to PASS2 to reduce the cosmic ray background across the CLEO experiment.

There is also potential for developing another processor using more advanced tracking techniques to make a further set of cuts on cosmic ray events. For example, the tracking software assumes that all particles originate from the beam spot to account for energy loss in the drift chamber. In the case of a cosmic ray, one leg will be calculated in the reverse direction and the χ^2 value of the fit will reflect the incorrect assumption. The Ring Imaging Cherenkov Detector (RICH) can also be used to ascertain the direction of particles. The photodetectors of RICH are only located on the outside of the chambers so particles entering CLEO from the outside will leave no Cherenkov radiation image. However, this technology can only be used effectively in conjunction with precise particle tracks. Finally, the electrons and positrons traverse CESR in bunches and are only expected to collide at specific times. In contrast, cosmic rays may arrive in the detector at any time. Time can be utilized as a fourth dimension for making cuts. Unfortunately, the most effective method of determining expected interaction times is the recording of the CESR phase as events are processed. The time cut could not be applied in real time unless data from a previous run is used or if researchers are patient enough to go over the entire data set twice.

V. ACKNOWLEDGMENTS

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[1] Barton John J. and Lee R. Nackman. C++: An Introduction with Advanced Techniques and Examples. Addison Wesley, Reading, MA (1995).

[2] D. Bortoletto et al. A Muon Identification Detector for B-Physics near $e^+e^- \rightarrow B\bar{B}$ Threshold. HEPSY 5-91 (October 1991).

[3] Eckel, Bruce. C++ Inside and Out. McGraw Hill, Berkeley, CA (1993).

[4] Y. Kubota et al. The CLEO II detector. Nuclear Instruments and Methods in Physics Research A320(1992)66-113.

[5] Musser, David R. and Atul Saini. STL Tutorial and Reference Guide. Addison Wesley, Reading, MA (1996).