Validation of the Time of Flight Detector of CLEO II

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Abstract

This note describes the details of the time of flight detector of CLEO II. The time of flight system helps us find the flight time of a charged particle. We perform data quality checks on the system to verify its accuracy. We also measure the efficiencies and the resolutions as a function of momentum, scintillators, and z position. Afterwards, we are able to conclude that the time of flight detector works relatively well for the parameters that we check, but there may be a need for further investigation.

Introduction

The time of flight system is used to measure the flight time of a charged particle traveling a distance. With it, we can calculate the speed of a charged particle because speed is distance divided by time. Once we have the speed of a charged particle, we can use it to identify the particle. Different particles at the same momentum have different speeds because their masses differ. For example, lets look at the calculation of beta (β), the fraction of the speed of light, given by Equation 1.

$$\beta = p \Big/ \sqrt{m^2c^4 + p^2c^2} \qquad (1)$$

Consider that the momentum (p) is 1 Gev/c. If we calculate β for an electron, β would be near 1 because an electron has a mass that is approximately 0 Gev/c^2 with respect to the kinetic energy of a proton. On the other hand, if we calculate β for a proton, β would be approximately $1/\sqrt{2}$ because a proton's mass is approximately 1 Gev/c^2.

The time of flight system is important because it helps us distinguish between various charged particles, which include electrons, muons, pions, kaons, and protons. This system is important in the identification of pions and kaons because it can help us identify them at a slightly higher momentum than the dE/dX system, which is based on the energy loss of a charged particle. However, we should note that the time of flight system would perform this task well only until approximately 1 Gev/c. At high momenta, all particles will travel close to the speed of light. This means that we cannot use their speeds to identify the particle.

The purpose of this note is to discuss the details of the time of flight system that I became familiar with this summer. We select data samples that allow us to check the accuracy of the time of flight system, and we perform data quality checks to make sure the time of flight calculation is robust. Specifically, we measure efficiencies and resolutions as a function of several parameters (momentum, scintillators, and z position). However, before I describe these checks, I will describe the geometry of the time of flight system for CLEO II in some detail.

Geometry

The coordinate system for the CLEO II detector is defined by the x, y, and z-axis. The positive x-axis points south to the outside of the ring. The positive y-axis points up. The positive z-axis points west, which is in the positron direction. [1]

The time of flight detector for CLEO II consists of separate barrel and endcap detectors, which conform to the cylindrical geometry of the detector. The barrel, the central part of the detector, consists of 64 scintillators. Each of these counters is 2.794 meters in length, approximately 9 centimeters in depth, and 4.76 centimeters wide. [2] They are configured as a cylinder that is parallel to the beam axis. The inner radius of the cylinder is 0.968 meters. This provides coverage in θ from 34.7° to 145.3°. At the east and west ends of each scintillator, there are light pipes that terminate with photomultiplier tubes (PMT's).

The endcap is the part of the detector that closes off the east and west ends of the CLEO II detector. There are 28 counters on each endcap that connect directly to the photomultiplier tubes. The width of the inner radius of these counters is approximately 6 centimeters, while the width of the outer radius is approximately 19.73 centimeters.

Operation

We perform our analysis on the barrel of the detector, so the following information will describe how the time of flight system works in that region. First, we begin with an electron and positron collision along the beam axis of the CLEO II detector. During this collision, some charged particles are created. These particles can hit one of the counters of the barrel if they have a high enough momentum. Each of the counters consists of a material that will emit a small amount of light when they are hit by a charged particle, so the scintillator will light up at the point of interaction. Photons are created, and they travel the length of the scintillator in the east and west direction. This light is eventually registered in the photomultiplier tubes, which measure the elapsed time from the collision of the electron and positron until the light reaches the photomultiplier tubes. However, this is not the time that we really want. Our real concern is the flight time of the particle from the collision to the position where it hits a scintillator. Therefore, we must correct for the elapsed time of light traveling in the scintillator. Figure 1 shows an example.

Time of Flight Calculation

Let t_1 represent the time from the collision to the counter. T_{EAST} is the time registered in the east PMT. $T_{EAST}=t_1+t_{east}$, where t_{east} is the time of the light travel in the scintillator. We can get t_{east} if we know the z position from the tracking system and the measured speed of light in a scintillator

(0.16 m/ns). A similar equation is used to get T_{WEST}. Therefore, the barrel gives us 2 measurements for the time of flight.
Now, we can solve for t_1.

$t_1 = T_{EAST} - t_{east}$

$t_1 = T_{WEST} - t_{west}$

Once t_1 for both the east and west sides of the detector is found, their average can be taken to get a better flight time of the charged particle. If the detector is operating correctly, t_1 for the east and t_1 for the west should have approximately the same value. Also, note that we have suppressed travel time in the light pipe for simplicity.

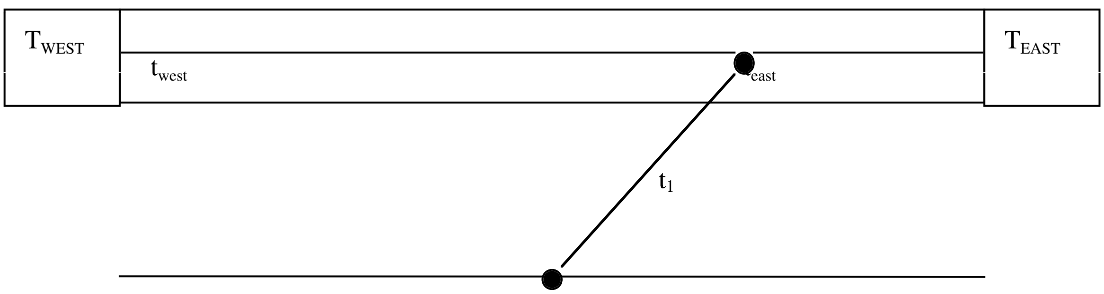

Figure 1. Geometry used in the time of flight calculation.

A first look at Time of Flight

Our goal is to test the accuracy of several parts of the time of flight calculation, so our first task involves calculating beta for the time of flight system. We accomplish this assignment through creating Fortran code that calculates the beta for kaons, pions, and protons. When we compare the results of our calculation to the real time of flight information attained from D^0 data, we discover that the time of flight system performed well for calculating beta on average, as shown in Figure 2. However, due to the background in the D^0 sample, we decide to use a cleaner sample for testing time of flight accuracy. For a detailed description of D^0 selection, see Appendix I.

Bhabha Events

We use bhabha events to check the quality of the time of flight system. A bhabha event is an elastic scatter, in which the electron and positron only change direction upon collision. This means that new particles are not created.

Bhabha events provide us with nice data to work with because they are simple events. A bhabha event only has two tracks that result from the electron and positron collision. Also, it is easy to identify one of these events and there are a lot of them. Since electrons (positively and negatively charged) move very close to the speed of light, the flight time of electrons are easy to calculate without using a lot of information from the tracking system. On the other hand, there are a couple of disadvantages that we need to note about bhabha events. We really want to use the time of flight system for kaon and pion separation, but bhabha events give us only electrons and positrons. Also, bhabha events do not allow us to look at events at low momenta. This means that, in addition to looking at bhabhas, we also have to look at particles that have lower momenta. This can be accomplished with radiative bhabhas. We look at these because a radiative bhabha will have one electron that will release a photon. When this happens, the electron that loses the photon will have a lower momentum

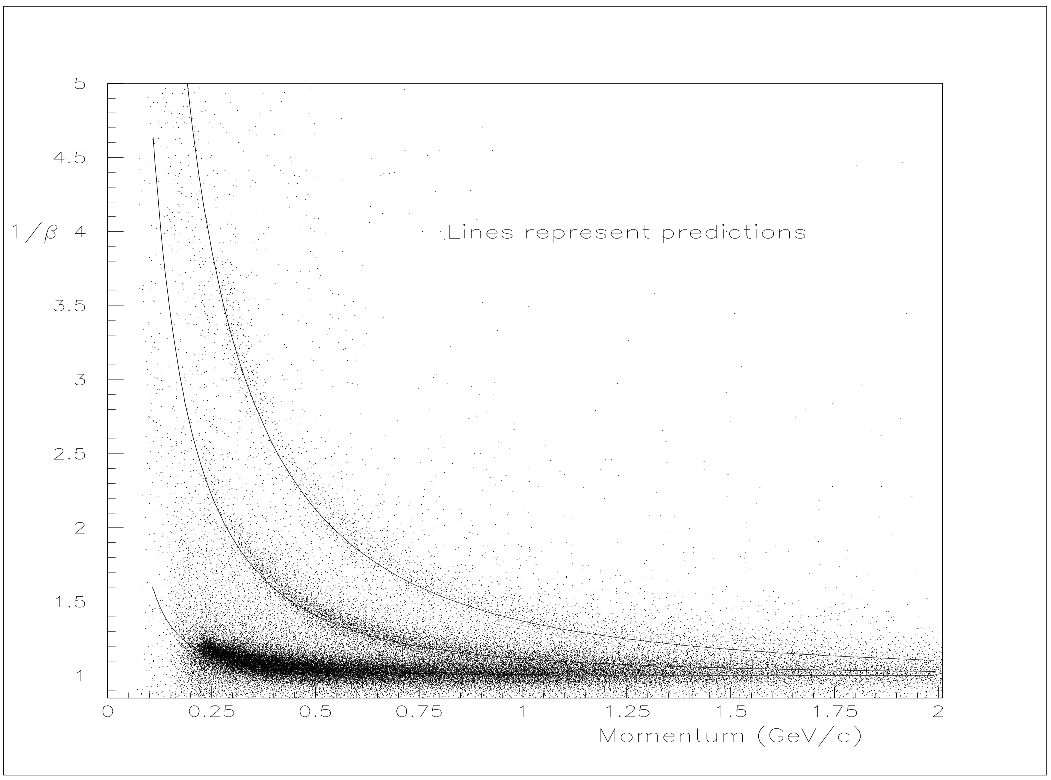

Figure 2. The dots represent the time of flight data, and the lines represent our predictions. As shown, the dots form bands along the lines.

Bhabha Selection

We use simple bhabha selection criteria. We use the following requirements:

- the event only has two tracks
- the momentum is greater than 5 Gev/c but less than 10 Gev/c
- the particles should start from the same place, around the center at 2.5 centimeters in both directions
- the tracks are within the barrel region, between the angles of 34.7 degrees and 145.3 degrees

Shortest Travel Time of a Particle

We want to compare the earliest measured arrival time of the time of flight system with the expected earliest times. This allows us to see if there is any offset of the time calculations. Two extremes should be examined. One extreme is when a particle hits the scintillator perpendicular to the positron/electron collision point and then light travels to the end of the scintillator. The other extreme is when a particle travels directly from the electron/positron collision point to the end of the scintillator. Therefore, we performed the following calculations.

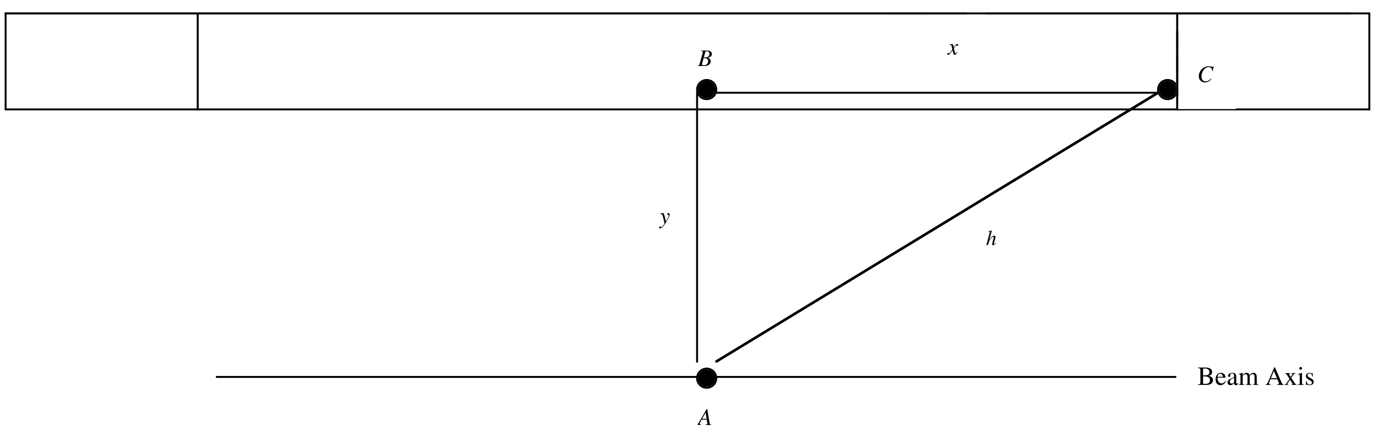

Figure 3. Geometry for calculating shortest travel time of a particle.

Given:

A = positron and electron collision point
B = interaction point of particle and scintillator perpendicular to the collision point
C = particle position at the end of the scintillator
y = distance from A to B, which is the radius of the detector (0.9680m)
x = distance from B to C, which is half the length of the scintillator (1.397m)
h = unknown, distance from A to C

Use Pythagorean's theorem to find *h*.

$$h = \sqrt{x^2 + y^2}$$
$$h = 1.6996\,\text{m}$$

According to previous measurements, the speed of light in a scintillator is 0.16 m/ns, and the speed of light in a vacuum is 0.3 m/ns, which is approximately an electron's speed. So, let *cs* = 0.16 and *cp* = 0.3. Now we can find the travel time along h.

$$t_h = h / cp$$
$$t_h = 5.665 \text{ m/ns}$$

Now, we find the travel time along y and x.

$$t_y = y / cp$$
$$t_y = 3.227 \text{ m/ns}$$
$$t_x = x / cs$$
$$t_x = 8.731 \text{ m/ns}$$

The shortest time is along *h*. We can now compare our estimated time with the measured times from the time of flight system.

In Figure 4, we have the raw times shown in a histogram. The y-axis represents the number of particles, and the x-axis represents the raw times. The histogram created with the solid lines represents the raw time for photons traveling east through the scintillator. The histogram formed by the dashed lines represents the raw time for photons traveling west through the scintillator. The vertical line represents our expected earliest time from the calculation used in Figure 3. Since the turn on time is approximately the same as the expected time, we can conclude that there is not a significant offset in the time. There are a few times that start before our expected time, but there are not enough to think that there is a flaw with the calculation of the time of flight system.

Geometric Coverage

We have calculated the geometric coverage efficiency of the barrel and the endcap. This efficiency is only an approximation of the true efficiency. Since our detector is in the shape of a cylinder, and we know how to find the area of a cylinder, the efficiency is rather simple to calculate.

To get our efficiency, we had to find the ratio of the instrumented area of the detector to the total area of the detector. The instrumented area of the endcap and barrel is the total area of the detector less the holes and gaps between scintillators.

Given:

A_T = total area of the endcap and barrel, 22.0131 m^2

A_{CH} = total area of the cracks and holes in the endcap and barrel, 1.6612 m^2

A_I = instrumented area, our unknown

$$A_I = A_T - A_{CH}$$
$$A_I = 20.3519 \text{ m}^2$$

Our efficiency ratio is A_I / A_T , which is approximately 92.4%. The efficiency ratio for the endcap is approximately 84.2%, and the efficiency ratio for the barrel is approximately 94.9%. We expect the geometric coverage to be a good approximation of the efficiency for the barrel if the scintillators are 100% efficient in detecting tracks. Using 1 PMT hit as the definition of track detection, all losses could be accounted for in the geometric coverage.

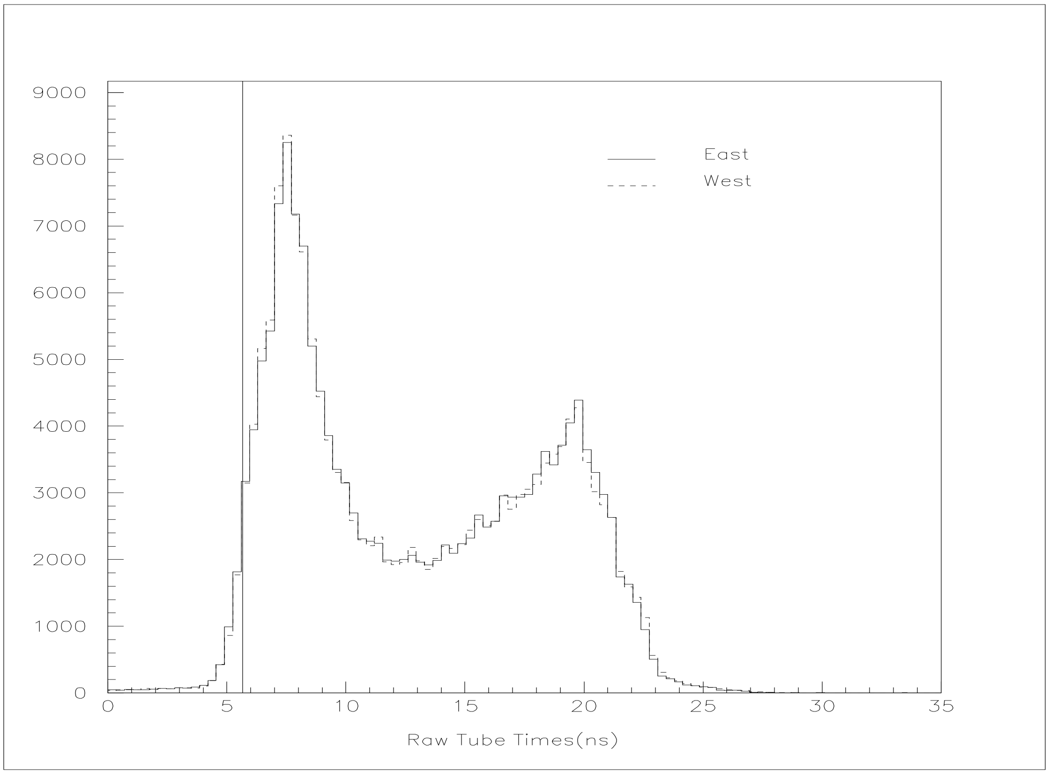

Figure 4. The histogram with the solid lines shows raw times for the east, and the other histogram shows the raw times for the west. The line represents the earliest expected time.

We want to calculate the phototube efficiency given a track points to a scintillator. First, we mathematically extrapolate tracks to the nearest scintillator. Then, we check the scintillator to find out if the time was registered in 1 or 2 phototubes. If at least 1 phototube registers a hit, we count that as a single hit. If both phototubes register a hit, we count that as a double hit. One we have the single and double hits counted, we divide them each by the total number of tracks to get our efficiency.

In Figure 5, the efficiencies for the single and double hits are shown below in Figure 5. Our y-axis represents the efficiency, and our x-axis represents momentum. The opaque circles represent the values for the single hit efficiency, and the open circles represent the double hit efficiency. The single hit efficiency is approximately 95% at the highest momentum, and it is approximately 5 % higher than the double hit efficiency for all momenta. The single hit efficiency at high momentum reaches the maximum expected value as determined by our geometric coverage, which implies that the single hit efficiency is near 100% for all tracks hitting the scintillator. The additional 5% loss when we require double phototube hits is currently not understood. The loss of efficiency at low momentum could be due to the difficulty of extrapolating very curved particles. We did not include energy loss in the extrapolation.

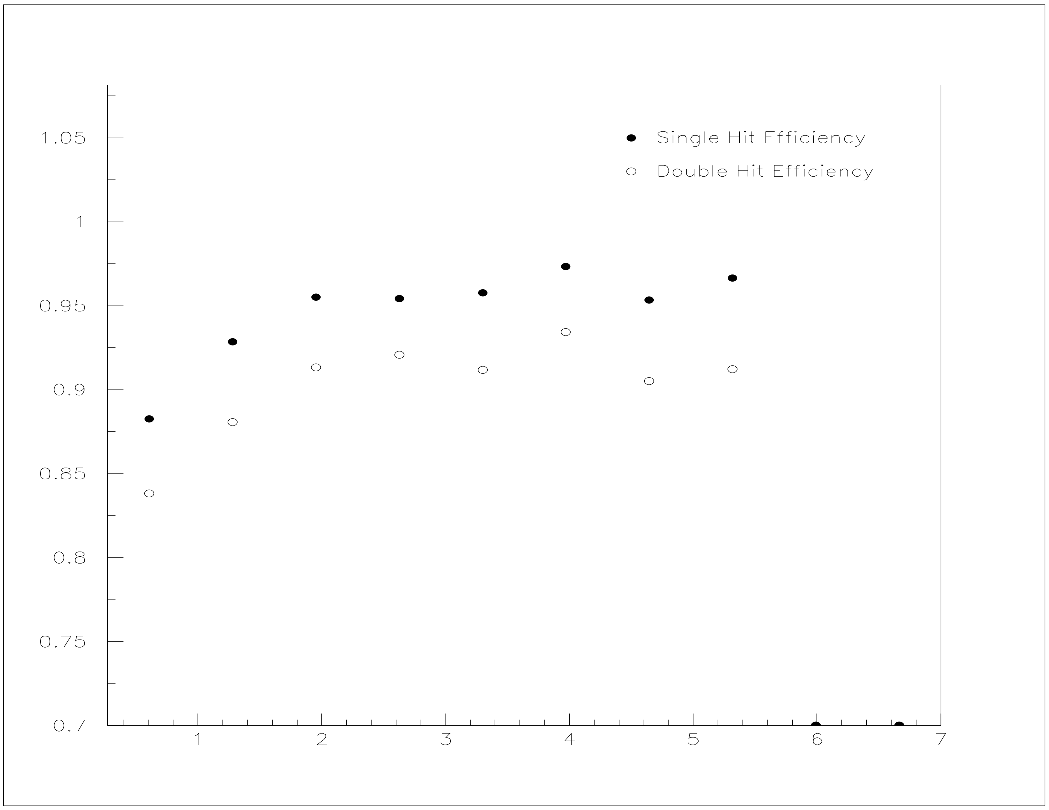

Figure 5. This plot shows the single hit efficiency (opaque circles) and the double hit efficiency (open circles) versus momentum**.**

Z Position for a Charged Particle

We use the tracking system to find the z coordinate for a hit scintillator by using this equation: $Z = R / \tan\theta$. We can also find the z coordinate by using the time of flight information. This can be done in the barrel because we have 2 photomultiplier tubes. The equations that they give us are listed below.

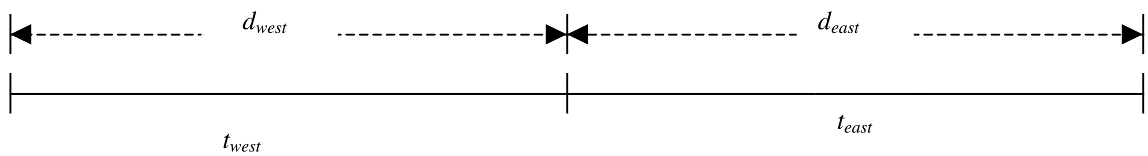

Figure 6. Calculation of the z position of a particle from the measured times.

Given:

$\Delta T = t_{west} - t_{east}$
$c = 0.16$ m/ns, which is the measured speed of light in a scintillator
$L = 2.794$ m, which is the length of a scintillator

We use the given variables to find the distance traveled west in the scintillator.

$$d_{west} = (L - c\Delta T)/2$$

So,

$$Z = (L - c\Delta T)/2 - L/2$$

$$Z = -c\Delta T/2$$

In Figure 7, we compare the outputs of the z calculation based on time of flight with the outputs of the z calculation used by the tracking system. The y-axis represents the z position using time of flight, and the x-axis represents the z position using the tracking system. The line given by y =x represents the prediction of where the particles would be for this plot, if we had a perfect detector. As shown, the particles form a band along the y = x-axis. Assuming that the tracking represents the true z position, this plot shows that the time of flight calculation finds the z position well on average over the length of a scintillator.

Speed of Light in a Scintillator

We would like to calculate the speed of light in a scintillator using time of flight data. To do this, we have to find c_{east} and c_{west}, which represent the speed of light in a scintillator for any distance and time in both east and west directions. Please refer to Figure 5.
$c_{east} = d_{east}/t_{east}$
$c_{west} = d_{west}/t_{west}$
The value of c_{east} and c_{west} should be approximately the same, if the flight time and z position of a charged particle is calculated accurately.

In Figure 8, the plot shows a histogram that is filled with the measured values for the speed of light in a scintillator. The x-axis represents the number of events, and the y-axis represents the measured values for the speed of light in a scintillator. There is a Gaussian fit applied to the histogram. Although the fit is not very good, the mean (0.1602 m/ns) can be well determined. Since the mean is around 0.16 for the majority of the particles, we take this as the value.

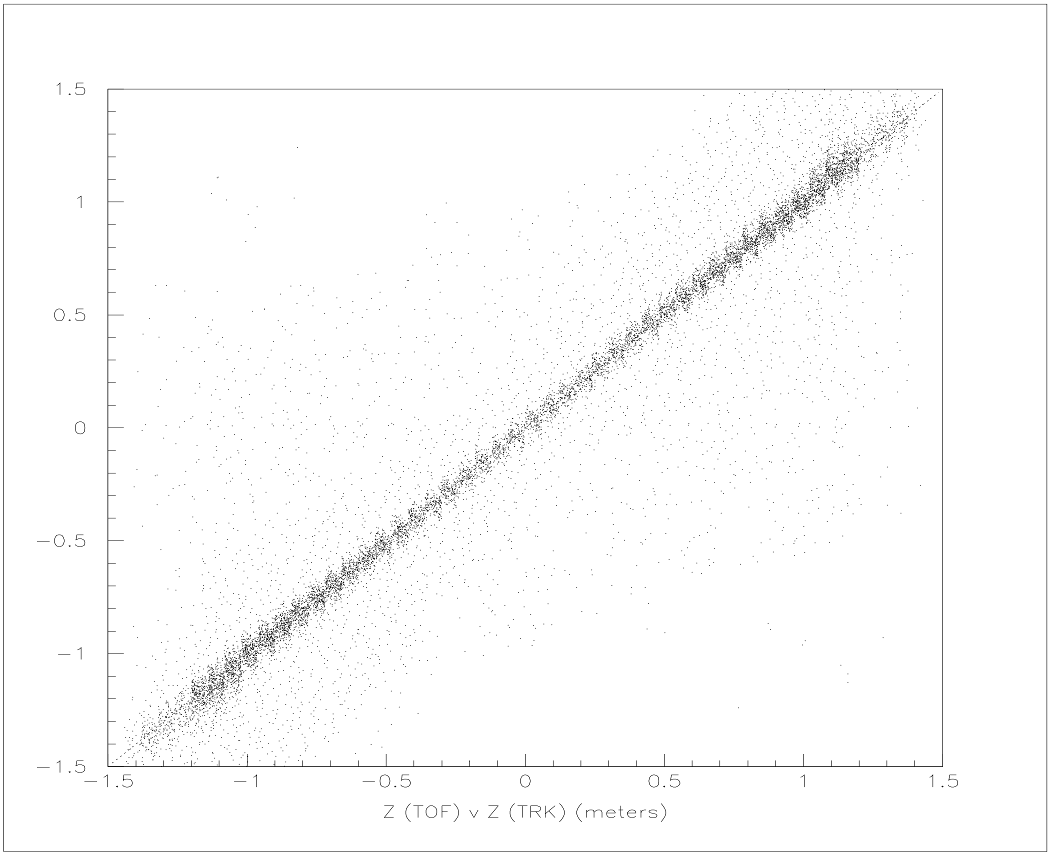

Figure 7. This is a plot of the z position calculated by the time of flight information versus the z position calculated by the tracking system. The z position is given in meters.

The scintillators in CLEO II are made from Bicron-408. [2] The manufacturer of these counters lists the speed of light in a scintillator as 0.19 m/ns. However, it has been shown that the measured value of the speed of light in a scintillator is 0.16 m/ns. This is approximatley a 15% difference in the speeds. It has been explained that the lower speed represents an effective speed of light. [3] The photons scatter and travel longer than the straight line distance. This effectively lowers the measured speed. If the lower speed is truly due to geometry, we need to check that the speed does not vary with the position of a particle in the scintillator.

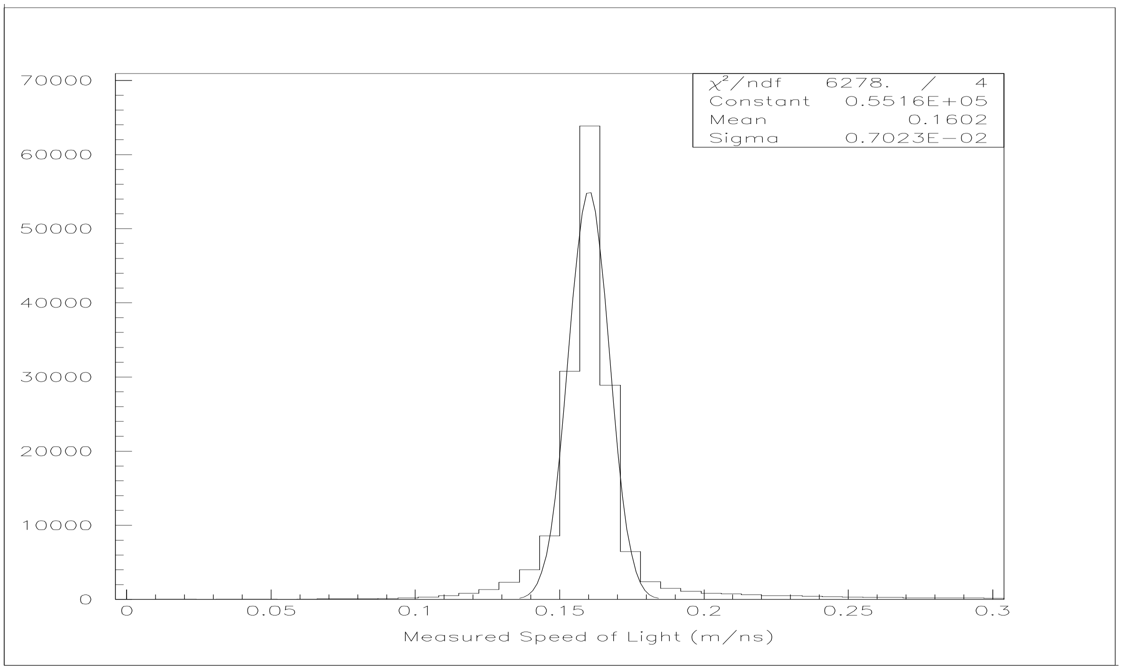

Figure 8. The histogram in this plot shows the values for the measured speed of light in a scintillator**.**

In Figure 9, we have two plots that show the comparison of the speed of light in a scintillator with the distance traveled through the scintillator. The y-axis of the top plot represents speed of light for photons traveling east from the interaction point where a particle hits the scintillator, and the x-axis of the top plot represents the distance traveled east from that interaction point. The y-axis and x-axis of the lower plot has similar representation to the top plot, but it shows photons traveling west through the scintillator from the interaction point. As shown, the particles form a band that reinforces the idea that the measured speed of light in a scintillator is approximately 0.16 m/ns. The band is well defined for most of the length of a scintillator, and for the region (0.397 m to 2.397 m) that is used for good time of flight measurements. Therefore, we can conclude that the measured speed of light of a particle traveling the length of the scintillator for good time of flight measurements is approximately 0.16 m/ns.

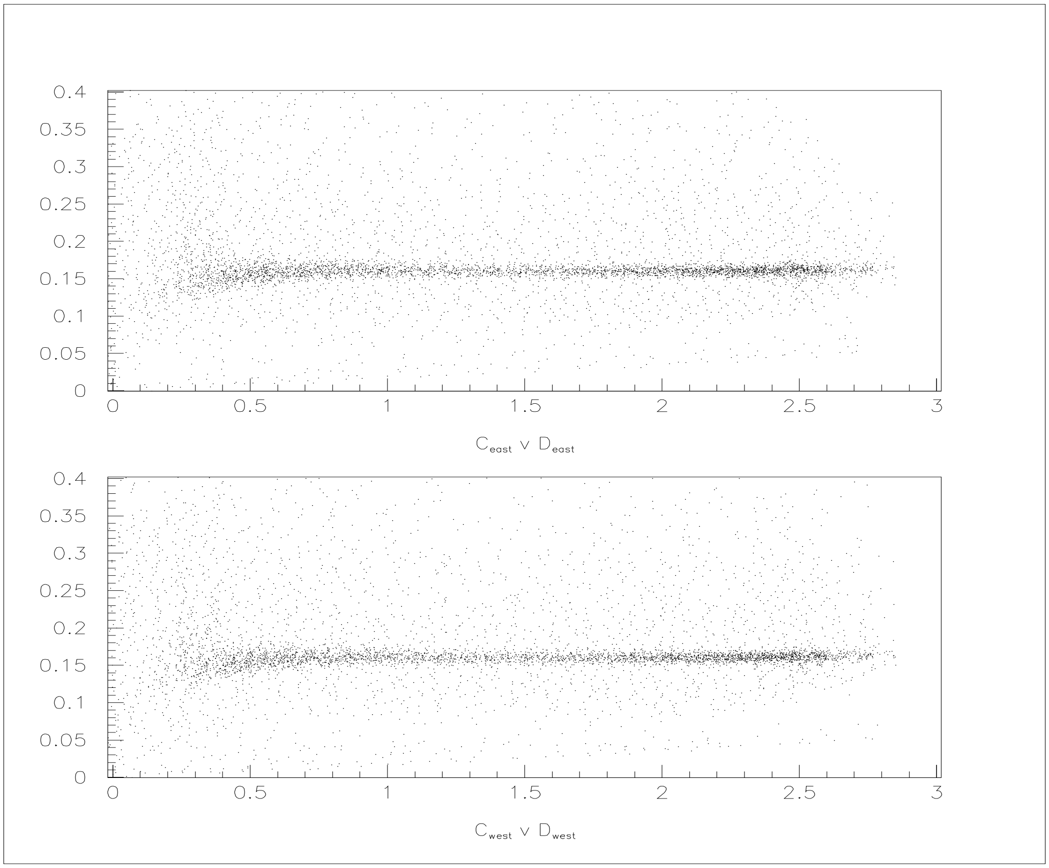

Figure 9. The top plot shows the speed of light of photons traveling east through the scintillator versus the distance traveled east. The lower plot shows a similar comparison for photons traveling west.

Resolution

In this section, we will look at various plots that examine ΔT, which represents our measured time minus our predicted time. It is easy to calculate a predicted time with fast moving electrons.

In Figure 10, we have a plot of ΔT. The x-axis represents the number of events, and the y-axis represents our ΔT in nanoseconds. There is a peak around the region where ΔT has a value of 0. A Gaussian fit is used on the histogram, and it shows that the mean is very close to 0. Therefore, we can conclude that the measured times and predicted times are approximately the same on average. The resolution is 0.258 nanoseconds.

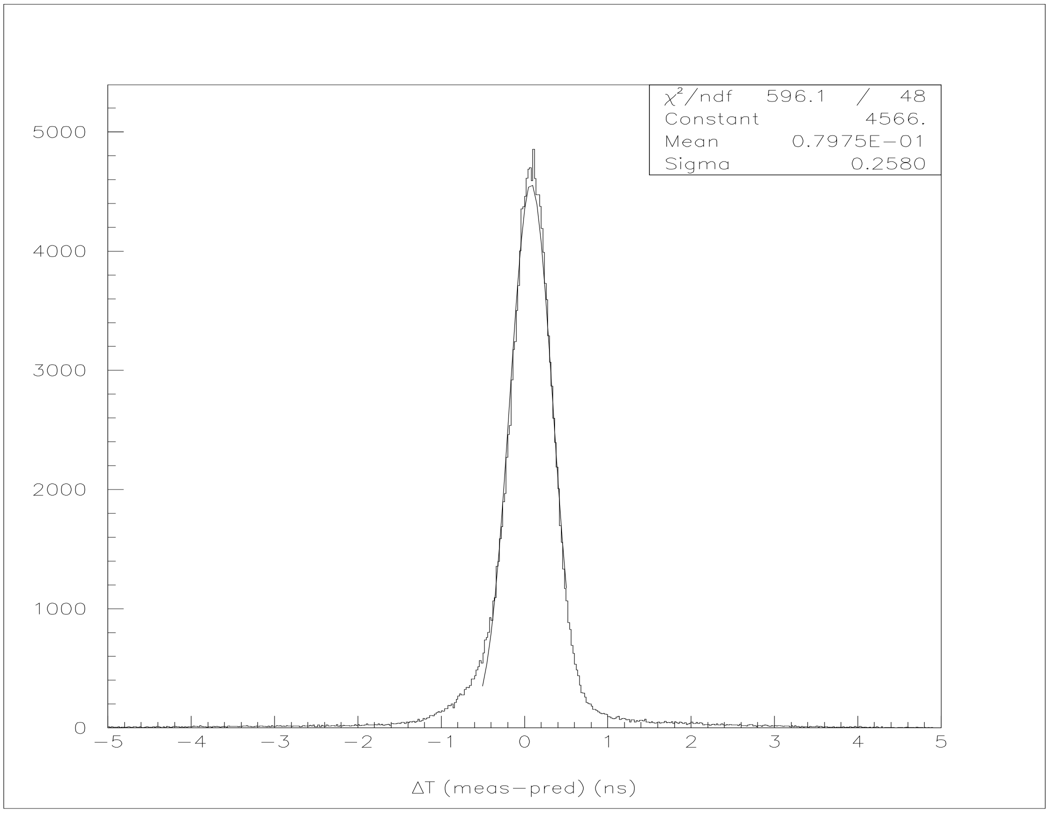

Figure 10. This plot shows ΔT, whose peak is centered at 0.

In Figure 11, we have two plots where we compare ΔT to the distance traveled in a scintillator. The distance traveled in the east direction is represented in the top plot, and the distance traveled west is represented in the lower plot. The y-axis represents ΔT in both plots.

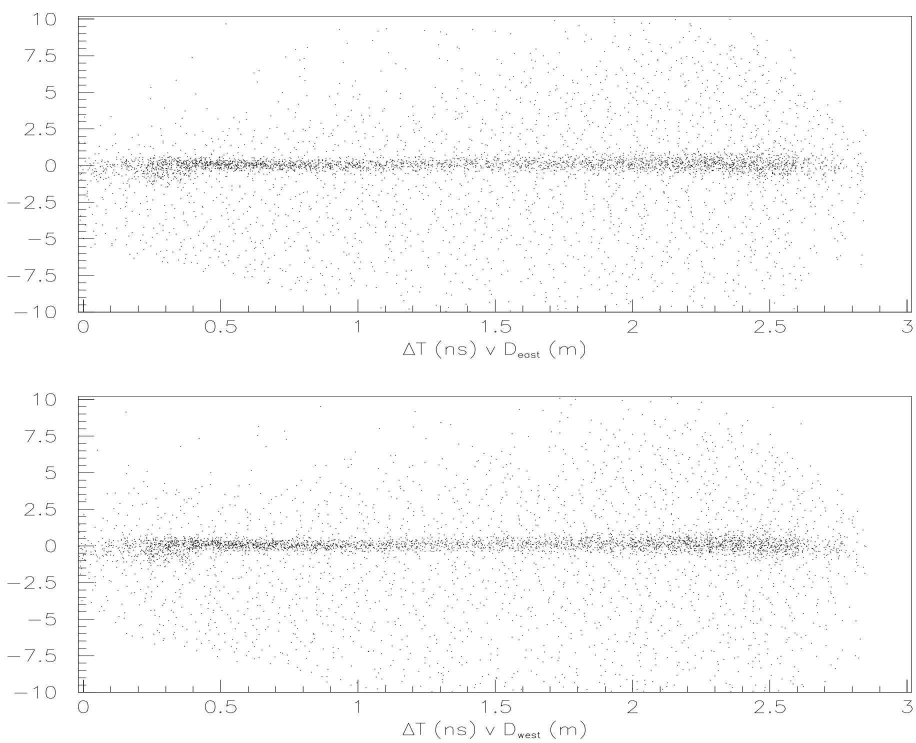

Figure 11. The particles form a thin band that is centered in the area where ΔT has an approximate value of 0 and where the distance traveled mostly covers the length of the scintillator**.**

These plots provide us with a closer look of ΔT. They allow us to conclude that ΔT is approximately the same when traveling the scintillator in either direction. It also shows that the resolution for ΔT is consistent within ±1 meters of z = 0. This is the region allowed for good time of flight measurements.

In our next figure, we have two plots. The top plot shows ΔT versus Δφ, and the lower plot shows Δφ versus the z position. Δφ is the angular separation of the track from the center of the scintillator. We look at Δφ for two reasons. Our first reason is to see how well our extrapolation finds the correct scintillator. Our second reason is to see if the resolution is worse when a particle hits along the edge of a scintillator.

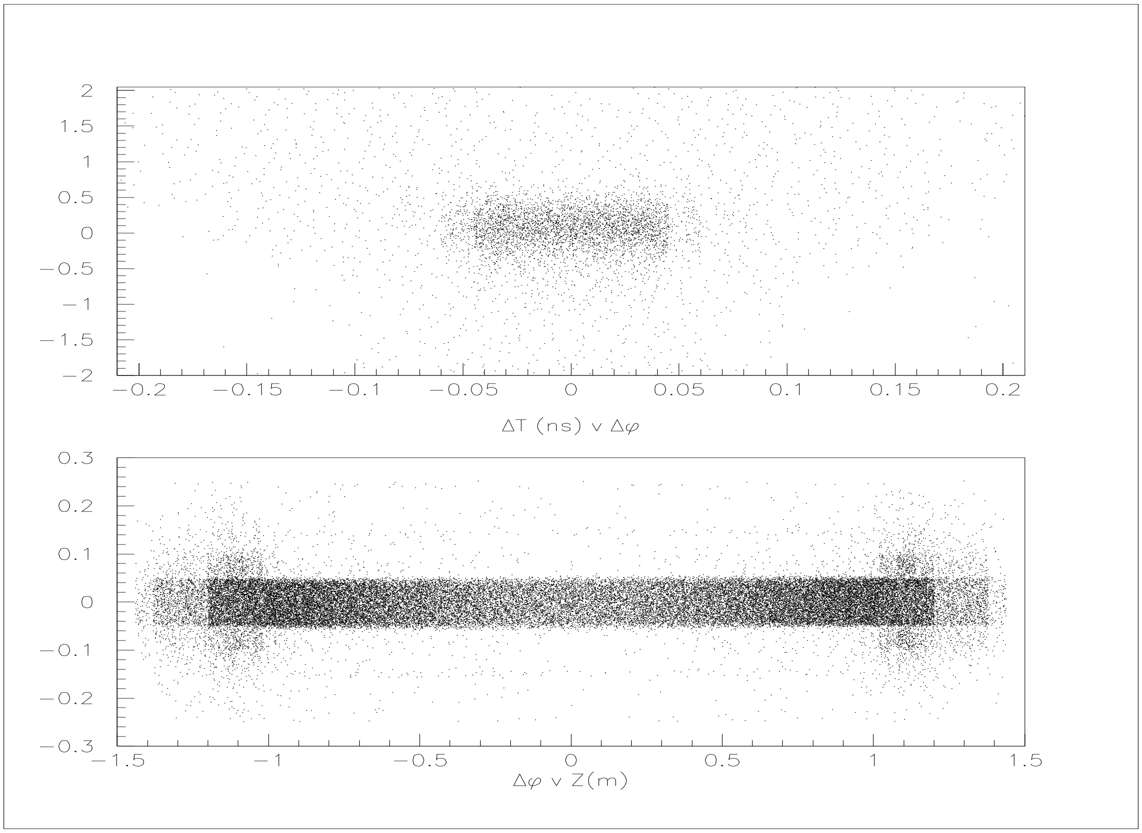

Figure 12. The top plot shows ΔT versus Δφ for all tracks, and the lower plot Δφ versus the z position.

In the top plot of Figure 12, we look at ΔT and Δφ for all tracks. The y-axis represents ΔT, and the x-axis represents Δφ. There are a lot of particles located in the region where Δφ is approximately the angular width of a scintillator. This shows us that most of the tracks hit the correct scintillator. Also, we see that there is not a significant worsening of ΔT near the edges.

In the lower plot of Figure 12, we look at Δφ versus the z position. As shown, there is a strong concentration of particles in the region where Δφ is between –0.05 and 0.05 and when the z position is between –1.0 and 1.0. Outside of ±1 meters, there are significant numbers of particles where the extrapolation failed. These are possibly regions where tracks hit the wrong scintillator, but they are not regions that we have to be concerned about. Good time of flight information is considered to be within the region where the z position is between –1.0 and 1.0 meters. Therefore, we can conclude that Δφ has no serious problems in this region.

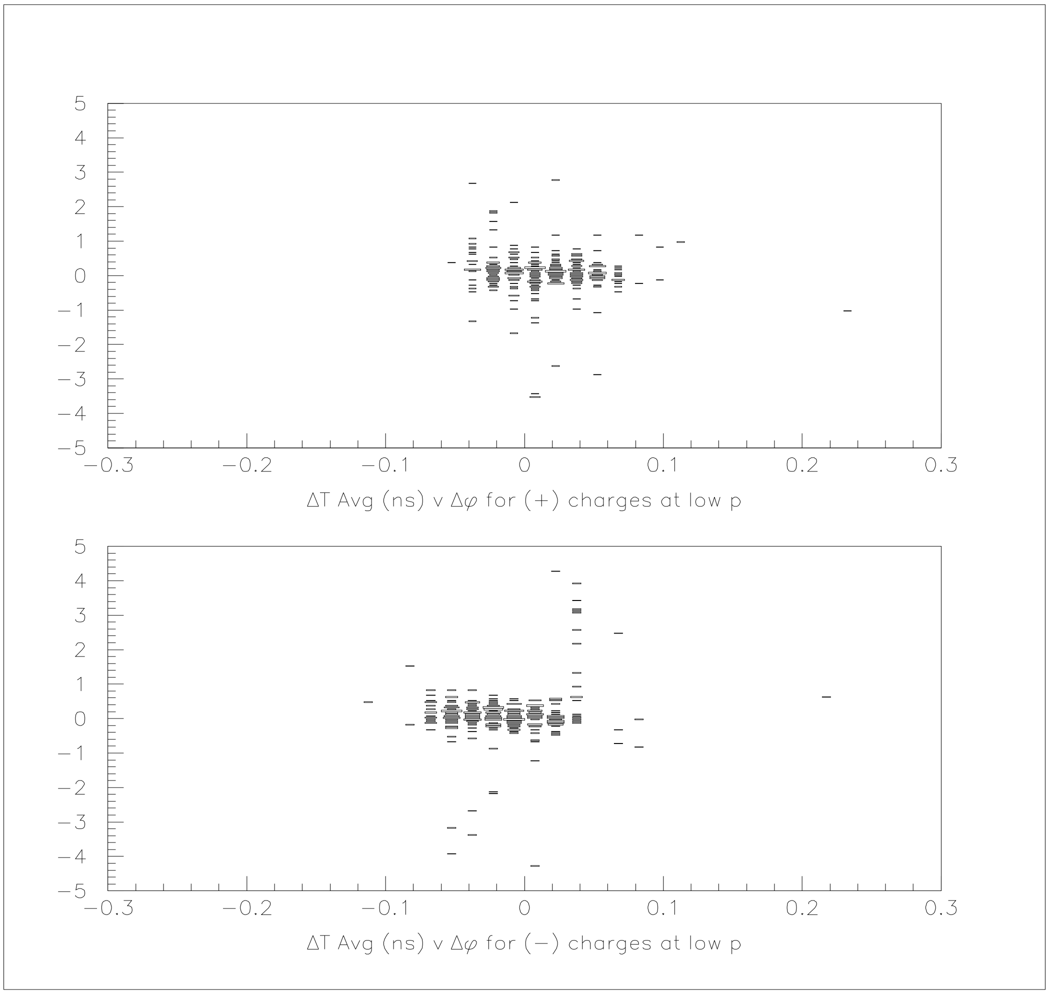

Figure 13. Both plots show ΔT versus Δφ at low momentum. The top plot shows this comparison for positively charged particles, and the lower plot shows it for negatively charged particles.

In Figure 13, we show the ΔT average versus Δφ for particles of different charges. We only look at low momentum particles. The top plot shows this comparison for particles that have a positive charge, and the bottom plot shows this comparison for particles that have a negative charge.

In both plots, the y-axis represents the ΔT average, and the x-axis represents Δφ. Δφ shifts to the right for positively charged particles and to the left for negatively charged particles.Δφ=0. However, there should not be a difference in the top and lower plots. As shown in Figure 11 (top and lower plot), the values for Δφ should fall between –0.05 and 0.05 in which the center is at 0. We suspect that this shift exists due to energy loss and where the particle actually hits a scintillator, not where tracking reconstructs the path based on the initial momentum of the particle. Therefore, we can conclude that one may need to investigate this matter further if they are studying asymmetry.

Summary

In this note, the time of flight detector of CLEO II was described in detail, which includes its geometry and operation. We performed several data quality checks on the system to verify its accuracy. Many of these checks involved calculating predictions for our expectations and comparing the results to actual data. We measured the efficiencies and the resolutions as a function of several parameters, and we saw no serious problems in the time of flight system that is used as good time of flight data. However, since there was an observed charge asymmetry, which may be related to energy loss, future researchers should explore this possibility for particles that suffer larger energy losses.

Acknowledgments

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References

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2. Y. Kubota et. al., NIM. A320 (1992) 86.
3. E.H. Thorndike, Private Communication.

Appendix

We look for D°particles because they can decay into a charged kaon (K), charged pion (π), and pi zero $(\pi\Upsilon)$, and we know that the time of flight system should be able to help us distinguish K's and π's well. However, before we can use the combination of charged K's, charged π's, and π°'s to find D°'s, we have to find the π°'s. A π° decays into two photons. Therefore, we first have to reconstruct π°'s. If the invariant mass of the photon pair, which was calculated by using $E^2 = p^2c^2 + m^2c^4$, was close to the invariant mass of a pi zero (1.35 Gev/c^2) then we can assume that we found a π°'s. Our sample showed approximately a 60% purity of π°'s. This is shown in Figure 14.

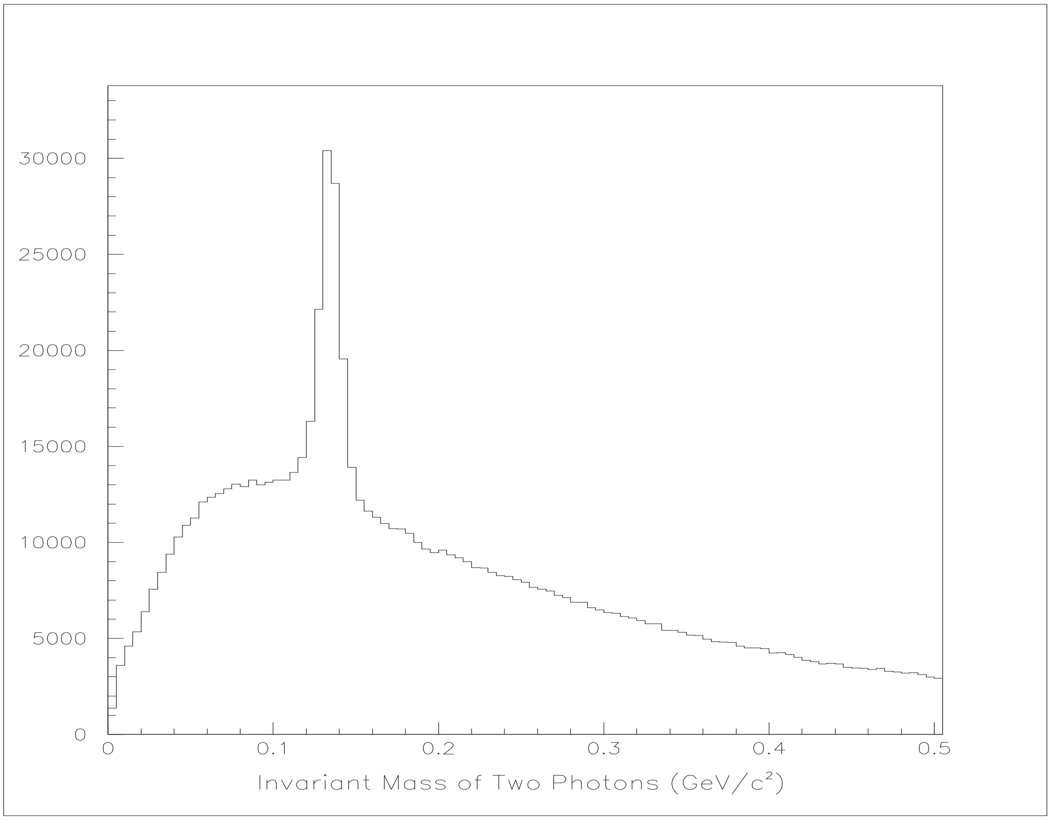

Figure 14. The histogram in this figure is filled with the possible masses for the photon pairs. A peak is shown around 1.35 Gev/c^2. This is the invariant mass of the $\pi°$.

The $D°$particles are reconstructed in a similar fashion. The pions and kaons used for the $D°$'s were selected using dE/dX. The invariant mass of the combination (π ,K , and $\pi°$) has to be close to the invariant mass of the $D°$particle. This is shown in Figure 15.

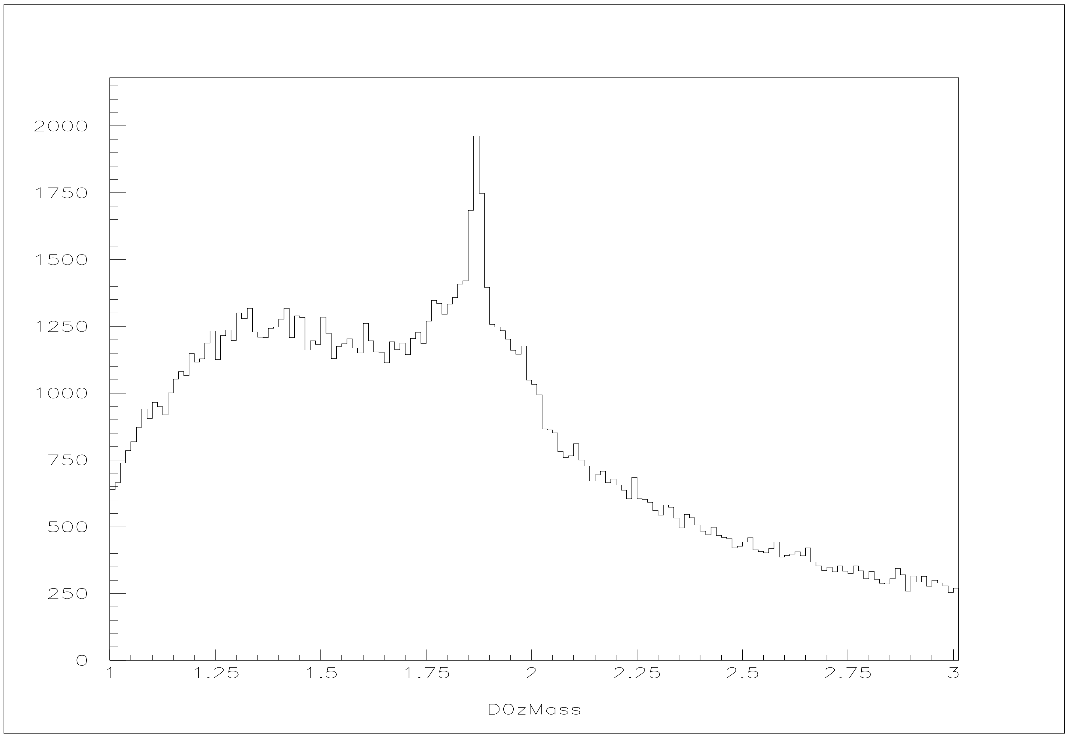

Figure 15. The histogram in this figure is filled with the invariant masses for pion, kaon, and pi zero combinations. A peak is shown around 1.86 Gev/c^2. This is the invariant mass of a D° particle.