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IV The CLEO-c Detector

1 The CLEO III Detector

The CLEO II detector has been an incredibly productive source of physics since its commissioning in 1989. The success of CLEO II was in large part due to a very good drift-chamber based tracking system and a superb electromagnetic calorimeter. In 1995 CLEO II evolved into CLEO II.V with the installation of a three layer silicon strip vertex detector, a new beam-pipe, and the switch from an argon-ethane gas mixture in the drift chambers to helium-propane. This configuration has also proven very successful, among other things ushering in the era of precision lifetime and mixing measurements made possible by the much-improved tracking system.

TABLE 1. A brief summary of parameters and performance for the CLEO III subsystems described in this Chapter. This is a guide only, and readers are referred to the text of the Chapter for details.

Component	Performance Summary
Tracking	93% of 4π ; $\sigma_p/p = 0.35\%$ at $p = 1 \text{ GeV}/c$. 5.7% dE/dx resolution for min-I hadrons
RICH	80% of 4π ; 87% kaon efficiency with 0.2% pion fake rate at $p = 0.9 \text{ GeV}/c$
Calorimeter	93% of 4π ; $\sigma_E/E = 2.2\%$ at $E = 1 \text{ GeV}$ and $\sigma_E/E = 4.0\%$ at $E = 100 \text{ MeV}$
Muons	85% of 4π for $p > 1 \text{ GeV}/c$
Trigger	Fully pipelined, latency $\sim 2.5 \mu\text{s}$. Based on track and shower counts, topology.
DAQ	Event size: $\sim 25 \text{ kByte}$, max throughput $\sim 6 \text{ MB/s}$

When it became clear that the Cornell Electron Storage Ring (CESR) would soon be capable of delivering significantly higher luminosity, the CLEO II.V $\rightarrow$ CLEO III upgrade project was set in motion. This effort involved keeping the existing CLEO II.V electromagnetic calorimeter, superconducting solenoid, and muon chamber systems, while completely redesigning and replacing all other components.

A diagram of the CLEO III detector is shown in Figure 1, and a summary of the parameters of several key subsystems is presented in Table 1. To an external observer, CLEO III may look very similar to CLEO II.V but in fact it differs significantly. Most notably, we have added a Ring Imaging Cherenkov (RICH) detector which, when combined with the new tracking system, provides superb particle identification. The tracking system itself, consisting of a new central drift chamber surrounding a four-layer silicon strip vertex de-

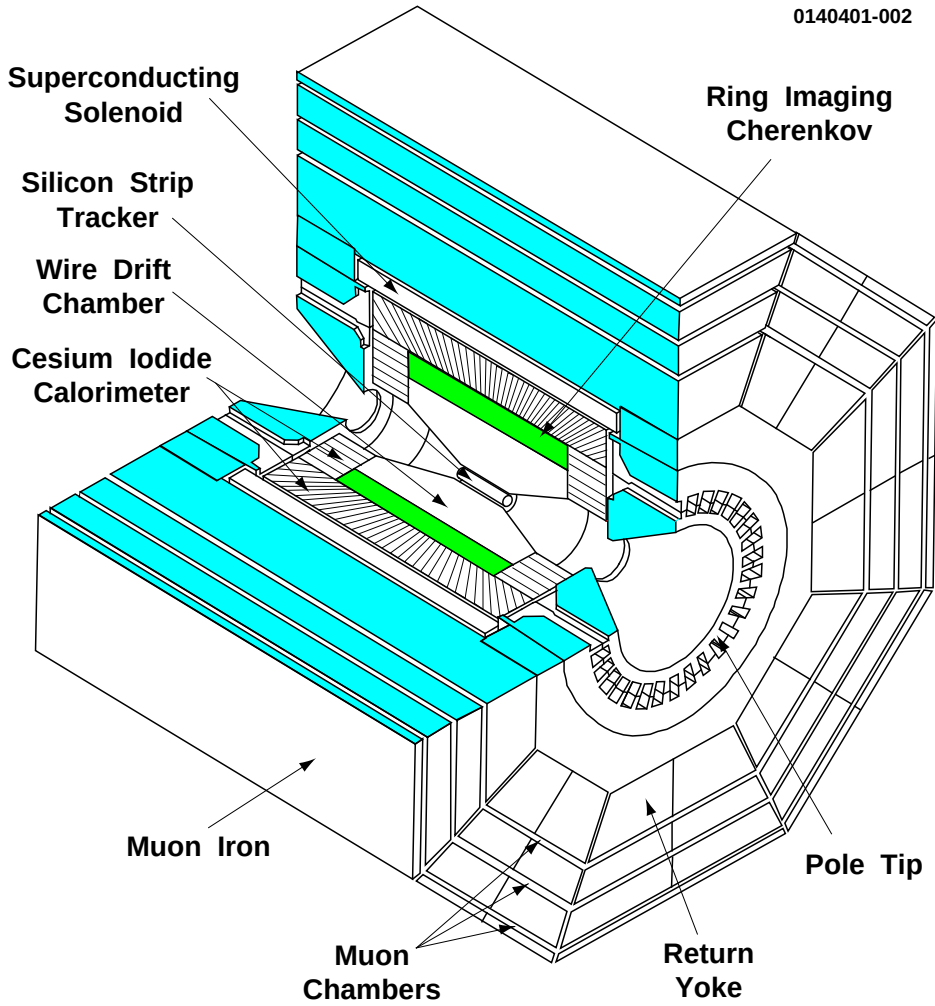


FIGURE 1. The CLEO III detector.

tector, performs as well as the CLEO II.V system in spite of the fact that the lever arm has been reduced to accommodate the RICH. The end-plates of the new drift chamber are much thinner than those of CLEO II which has significantly improved the resolution of the end-cap calorimeter, now on par with the barrel.

The new trigger system was designed to accommodate high-luminosity running. By synchronously pipelining the trigger inputs as well as all intermediate trigger calculation, sufficient latency has been built into the system to perform a single sophisticated trigger decision 2.5 microseconds after a given crossing while maintaining an average event time resolution well below a tenth of a microsecond. Complementing this trigger is a new data acquisition system designed to handle data rates of several hundred Hertz.

The CLEO III detector has been operating for over a year, and has collected 9.2 fb^{-1} on or near the $\Upsilon(4S)$.

This Chapter describes each of the new detector sub-components in detail, and the in-

cluded references provide information about the few CLEO II components that were not redesigned for CLEO III [1].

2 CLEO III Tracking

In the 1999 upgrade, the CLEO tracking system was completely redesigned and replaced. The new system consists of a 4-layer silicon vertex detector [2,3,4,5,6,7] surrounded by a cylindrical drift chamber [8,9,10] in a 1.5 T magnetic field.

2.1 Status of CLEO III Tracking

2.1.1 The Drift Chamber

The drift chamber covers the radial range from 12 to 82 cm, constrained on the inside by the silicon vertex detector and final-focus quadrupole magnets and on the outside by the Ring Imaging Cherenkov counter (RICH). It consists of 47 sense wire layers. Of these, the first 16 are axial (wires parallel to the beam (z) axis) and the remaining layers are grouped into superlayers of 4 layers each, with the superlayers alternating in stereo angle. The drift cells are nearly square with 3 field wires per sense wire and a maximum drift distance of about 7 mm. The gas is He:C₃H₈ (60:40), chosen for its long radiation length and our prior experience with CLEO II.V. The outer wall of the drift chamber is lined with cathode pads with 1 cm segmentation in z .

The drift chamber is essential for momentum measurement and provides some information on the dip angle of the tracks, through stereo layers and cathode strips. It is also the primary device for pattern recognition. Tracks found in the chamber are extrapolated inward for the addition of silicon hits.

The chamber has a position resolution of 85 μm and momentum resolution of 40 MeV/ c at $p = 5.3$ GeV/ c . This performance is due to attention to detail during mechanical construction, the choice of gas, and care in its design. All wire holes in the endplate are placed with a tolerance of 75 μm . The drift cells are designed to minimize asymmetries in the time-to-distance drift function, resulting in smaller corrections and simplified calibration procedures. Asymmetries in the drift function on the $\pm\phi$ sides of each wire (“left-right” asymmetries), which can arise from the strong magnetic field, are minimized by careful choice of the spacing between sense and field layers. Left-right effects are further reduced due to the small Lorentz angle in the He:C₃H₈ (60:40) gas mixture. Variation in the drift function along the length of the chamber is almost eliminated by maintaining a constant hyperbolic sag (within 80 μm) between adjacent sense and field layers. Because the drift function is nearly uniform throughout the chamber, calibration is simple, and the chamber achieved excellent resolution soon after start-up. The hit resolution measured with Bhabha-scattered electrons is shown in Figure 2. It is about 55 μm at the best part of the cell and 85 μm overall. The efficiency averages 98% in the stereo section and 92% in the somewhat noisier axial section.

To minimize multiple scattering, special care was taken to eliminate unnecessary material in the chamber. The radiation length of the He:C₃H₈ (60:40) gas mixture is ≈ 330 m. Sense wires are gold-plated tungsten (20 μm diameter), and field wires are gold-plated aluminum (110 μm diameter). Since studies showed them to be unnecessary, there are no extra field

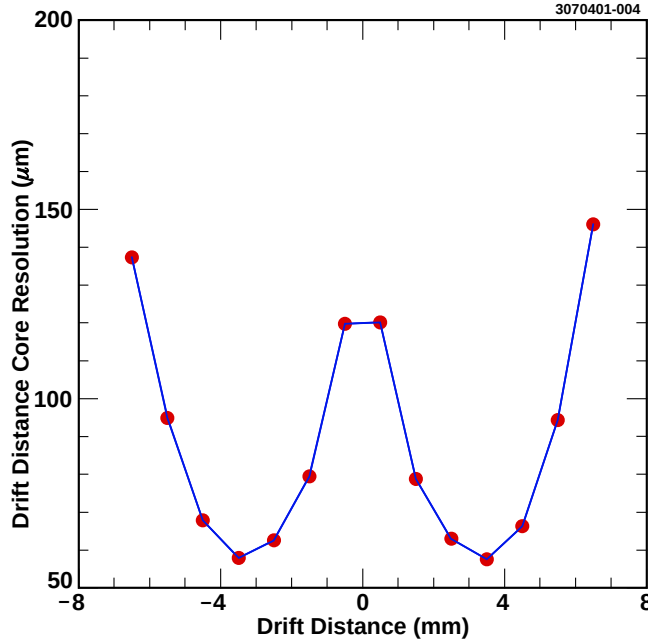


FIGURE 2. The hit resolution as a function of drift distance in the drift chamber. The half-width of the cell is 7 mm.

wire layers where the number of wires per layer is incremented. Finally, to allow the use of the outermost silicon layer in the momentum measurement, the amount of material between the last silicon layer and the first wire layer was kept to 0.12% of a radiation length.

2.1.2 The Silicon Vertex Detector

The primary role of the silicon vertex detector is to provide extremely accurate track position measurements in $r - \phi$ and z as close as possible to the interaction point.

The superb spatial resolution of silicon vertex detectors makes it possible to distinguish the decay vertices of D -mesons in decays such as $B \rightarrow D^{(*)}D^{(*)}$ [11]. In addition, precise measurement of the direction of the slow pion in D^* decays gives a $D^* - D$ mass difference resolution as good as $0.19 \text{ MeV}/c^2$. This precision has enabled CLEO to make the first measurement of the intrinsic width of the D^* [12] and benefits a wide range of CLEO analyses, from $|V_{cb}|$ to $D - \bar{D}$ mixing.

The CLEO III silicon vertex detector consists of four cylindrical detection layers at radii of 2.5, 3.76, 7.0 and 10.1 cm. The detectors are $300 \text{ } \mu\text{m}$ thick with double-sided readout. Wafers are concatenated in z to form rigid ladders which are kinematically mounted on cooled copper end-cones. At each end, the ladders are attached via flex circuits to a hybrid readout board. The readout boards, which are located outside the active tracking volume, host R/C circuits, preamp/shapers and a modified version of the SVX-II chip that includes its ADC, sparsification and readout sections.

The sensor pitch is $50 \text{ } \mu\text{m}$ on the $r - \phi$ side and $100 \text{ } \mu\text{m}$ on the z side. In order to reduce the capacitance of double metal readout, the z strips are chosen to be on the p -type side.

Capacitance is also reduced by narrowing traces and strips in overlap regions, and, on the n -side, by surrounding the $r - \phi$ strips with p -type barriers. The resulting strip capacitance is about 10 pF on both sides, leading to a typical noise level of 600 e^- per channel and a signal to noise ratio better than 15:1 in all channels. Studies using electrons from Bhabha scattering indicate that the intrinsic resolution of the device is better than 11 μm in $r - \phi$ and 24 μm in z .

While the efficiencies exceeded 85% in both $r - \phi$ and z initially (July 2000), the efficiency on the $r - \phi$ side of Layer 1 started to drop several months after the start of the run. At that time, we noticed that the inefficiencies were not uniform over the sensors, but rather fell in distinctive arc-like patterns. The mechanism responsible for the loss of efficiency is currently under investigation. Because of the efficiency drop in the $r - \phi$ layers, it will likely be necessary to replace the SVX for low-energy running. The replacement device under consideration, a small wire chamber, is described in Section 2.2.2.

2.1.3 Tracking System Performance

In this Section we review the performance of the CLEO III tracking system. One goal of the tracking system was to match the momentum resolution of the CLEO II tracking system in spite of the smaller radial extent (95 cm in CLEO II v. 82 cm in CLEO III) of the drift chamber. The momentum resolution for electrons from Bhabha scattering (5.3 GeV/ c) is about 40 MeV/ c . This resolution indeed matches that achieved in CLEO II.

The impact parameter resolution is 43 μm in $r - \phi$ and 370 μm in z . This resolution is somewhat larger than the design goal because of residual misalignment of the vertex detector, though it is adequate for most physics analyses. One of the important design criteria for the tracking system was that the z resolution for the tracks would not significantly degrade the angular resolution of the RICH. As shown in Figure 3, the z -resolution of tracks extrapolated to the RICH is 1.2 mm, sufficient to achieve this goal.

Mass distributions for $K_S^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ are shown in Figure 4 and Figure 5. The widths of the peaks are 2.7 and 6.3 MeV/ c^2 respectively and compare well with expectations.

2.2 Outlook

2.2.1 Tracking at $E_{CM} = 3$ to 5 GeV

In going from a center-of-mass energy of 10 GeV to one of 3 to 5 GeV there is a noticeable softening of the particle momentum spectrum. The momentum distribution of charged particles (p, K, π , e, μ) produced in D_s decays near 4 GeV is shown in Figure 6, overlaid with that of $B\bar{B}$ events at the $\Upsilon(4S)$. The mean momentum is shifted down from 530 MeV/ c to 395 MeV/ c ($\sim 25\%$) and the D_s decays yield very few events with momenta above 1 GeV/ c .

At lower center-of-mass energies, minimizing material is even more crucial than at the $\Upsilon(4S)$ because multiple scattering saturates the momentum measurement error for low momentum tracks. The “cross-over” momentum, for which contributions to the momentum resolution from multiple scattering and from spatial resolution are equal, is roughly 1.5

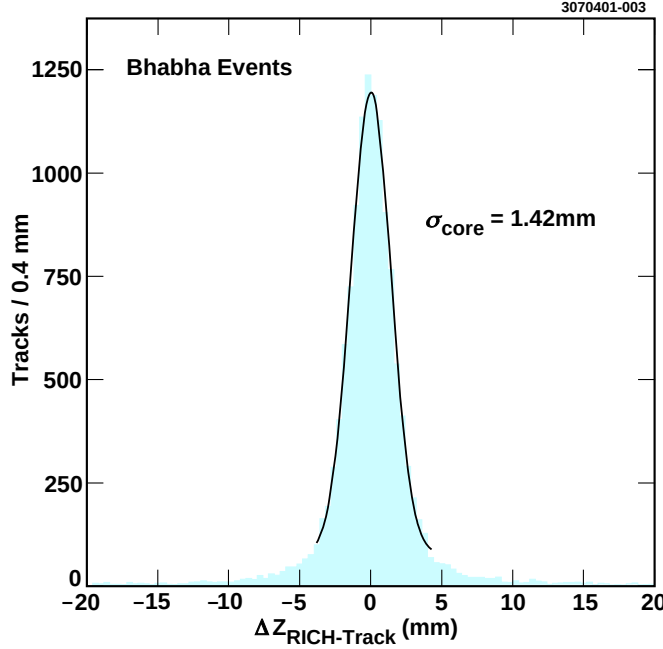


FIGURE 3. The difference between the z coordinate of electron tracks extrapolated to the RICH and the z coordinate measured in the RICH itself. The z resolution of the RICH contributes about 0.7 mm to Δz .

GeV/ c . Note that both contributions to the momentum resolution vary inversely with the magnetic field strength, so this cross-over is unaffected if CLEO decides to run at, for example, 1.0 T. Figure 6, would then imply that multiple scattering dominates essentially all momentum measurements for CLEO-c in the charm regime. In addition, particles may range out before reaching the drift chamber; for a center-of-mass energy near 4 GeV, about 2% of particles have momentum below the typical range-out momentum of 65 MeV/ c .

The role of vertexing will be reduced because vertex separations will be too small to be resolved with conventional detectors. For example, at the $\psi(3770)$, the average flight path of D^0 mesons is 18 μm and that of $D^\pm$ mesons is 41 μm . For comparison, data taken at $\sqrt{s} \sim 10.6$ GeV will produce these charmed meson with average flight paths in excess of 100 μm . On the measurement side of the ledger, the CLEO II.V silicon vertex detector had a 2-D resolution on decay length of 70-90 μm ; in 3-D this would be perhaps 25% smaller. Because the resolution needed to distinguish these charm decay vertices in CLEO-c is not readily achievable, superb inner tracking resolution is less important than at the $\Upsilon(4S)$.

The CLEO solenoid field strength is currently 1.5 T. Mass resolution is inversely proportional to field strength and would therefore benefit from maintaining the high field. However, a lower field strength has at least two advantages for tracking:

- At 1.5 T tracks with small transverse momentum ($p_\perp \sim 60\text{-}80$ MeV/ c) have degraded reconstruction efficiencies because they reach only the inner layers of the main drift chamber; with the lower field these tracks will penetrate further into the main drift chamber, and their reconstruction efficiencies will be correspondingly higher.

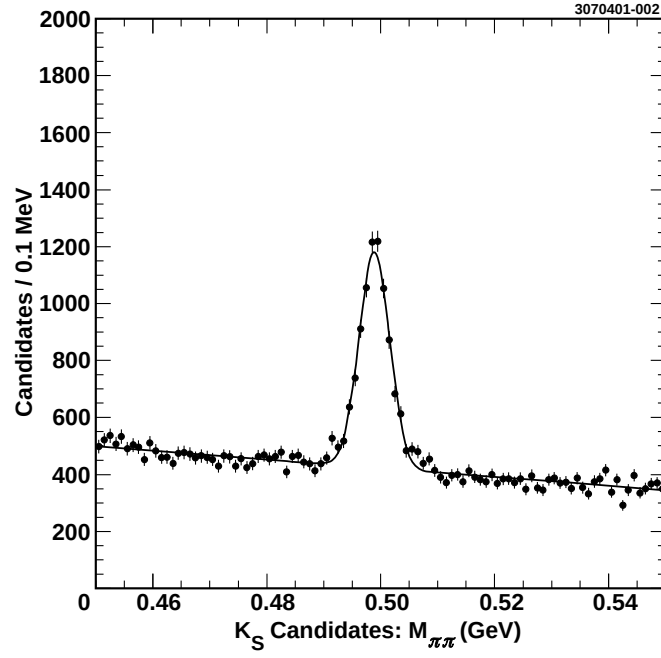


FIGURE 4. The $\pi\pi$ invariant mass distribution.

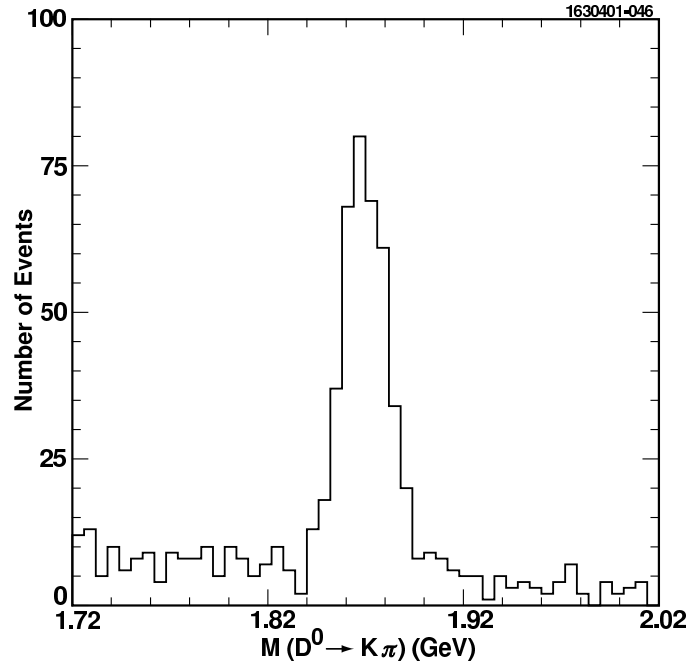


FIGURE 5. The $D \rightarrow K\pi$ invariant mass distribution.

- In addition at 1.5 T particles with $p_{\perp} < \sim 180$ MeV/ c curl in the chamber, complicating

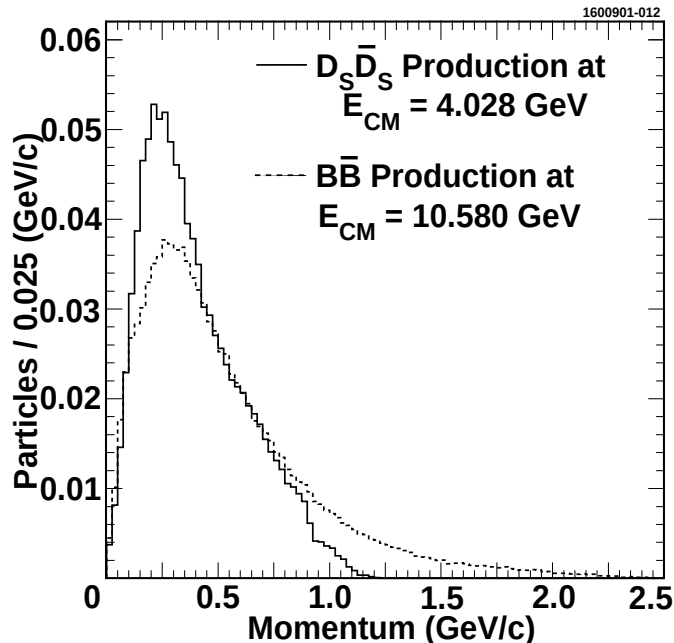


FIGURE 6. The momentum distribution of charged particles produced in $D_s \bar{D}_s$ and $B \bar{B}$ events near threshold. The spectrum of tracks from the decay of $D \bar{D}$ events produced at the $\psi(3S)$ ($E_{\text{CM}}=3.770$ GeV) is very similar to the spectrum shown for $D_s \bar{D}_s$. For $D^* \bar{D}^*$ and $D^* \bar{D}$ production at $E_{\text{CM}}=4.028$ GeV, the spectra are nearly the same, with the addition of a prominent peak near 50 MeV/c associated with soft pions from $D^{*+} \rightarrow D^0 \pi^+$.

pattern recognition for both the curling track and other tracks in the event; lowering the field strength will reduce the number of these “curlers”.

These considerations, in addition to considerations of machine operation, have led us to choose a 1.0 T solenoidal field for the CLEO-c running.

We therefore find that the CLEO III tracking system, in particular the new main drift chamber, is very well-suited to low energy running. The silicon vertex detector is less important for charm-threshold running than it was for studies at the $\Upsilon(4S)$, and for some low energy analyses its material would cause the very softest tracks to range out.

Moreover, the declining efficiency of the $r - \phi$ sides of the silicon vertex detector may force replacement of it with another inner tracker. A wire vertex chamber can have less material than the CLEO III silicon vertex detector, and based on our experience (and spare parts) from the main drift chamber, it could be built with dispatch. This option is described in the following section. As the next year’s running unfolds the performance of the silicon vertex detector will be carefully monitored to allow for an informed decision on its removal and replacement.

We note that the physics studies investigated for CLEO-c assume that the silicon vertex detector will be in place. As detailed in the following section, we expect that a wire chamber can give nearly identical results.

2.2.2 The Wire Vertex Chamber Option

2.2.2.1 Mechanical Considerations

A new wire vertex detector could be built to replace the CLEO III silicon vertex detector. Several requirements constrain the design of such a chamber. Material must be minimized, especially in the region separating measurements from such a vertex detector and main drift chamber. Because the silicon vertex detector currently provides the only longitudinal direction (z) information for tracks that curl at radius less than 0.45 meters ($p_{\perp} = 67$ MeV/ c observed in main drift chamber in a 1.0 T field), a new vertex detector must provide this z information. Cathode readouts could provide this z information but there would be complications: additional material would be required to support the cathodes, and there would be noise pick-up on the associated anode channels as has been experienced with main drift chambers of CLEO II and CLEO III.

The inner radius of the wire vertex chamber must clear the flange on the existing interaction region beam pipe at 4.1 cm. The outer radius must clear the existing inner skin of the main drift chamber at 11.8 cm. The endplates must follow the $\cos\theta=0.93$ line defining the fiducial volume of CLEO III and provide clearance for the “magic flange” connecting the interaction beam pipe to the focusing quadrupole beam pipe. Finally, because it would be necessary to complete construction for an Fall 2002 installation, existing wire holding crimp pins and insulating bushings would be used to avoid serious design and procurement delays.

A preliminary design shows that we can build a small cell, all stereo, device with six read-out layers meeting the above constraints. An isometric view of the proposed chamber is shown in Figure 7. Cell design would be similar to the main drift chamber but the cell size (sense wire spacing) would be reduced from 14 mm to 10 mm. The reduced cell size not only allows six layers but provides sufficient granularity; there would be a total of 300 cells with the number of cells ranging from 34 in the first layer to 66 in the sixth layer. Cell size can be held nearly constant throughout the new chamber by having a different number of cells in each layer. Layers would share bordering field wire layers. However, left-right asymmetries in the time-to-distance function can be minimized as in the main drift chamber. Specifically, detailed adjustments of the layer radii and stereo angles can provide constant cell heights at $z=0$, nearly constant aspect ratios (cell height/width) over the length of the layers, and compensation for differences in the defining field layer wire densities.

With a constant stereo hyperbolic sag of 4 mm, the stereo angle would range from 10.3° in the innermost field wire layer to 15.4° in the outermost field wire layer. Alternatively described, the ratio of z to $r - \phi$ components of the spatial measurement would range from 0.074 in the first sense layer to 0.103 in the last. As shown in Table 2, this will provide a nearly constant resolution of z_0 (measured at the primary vertex) of approximately 680 μms . In contrast, the silicon vertex detector, with a “realistic” resolution that takes into account the loss of resolution due to misalignment and the loss of $r - \phi$ efficiency in layers 1 and 2, provides a superior z_0 resolution: 107 μm at $p_T = 1.36$ GeV/ c . As expected, the continued degradation of the $r - \phi$ channels of the silicon vertex detector will have no effect on the resolution in z_0 . The predictions in the tables of resolutions were obtained with a Monte Carlo that takes into account Gaussian smearing functions for each of the active elements and multiple scattering in the gas, wires, silicon, beam pipe, and support cylinders. The inner wall of the proposed chamber in these simulations is taken to be 1 mm of aluminum;

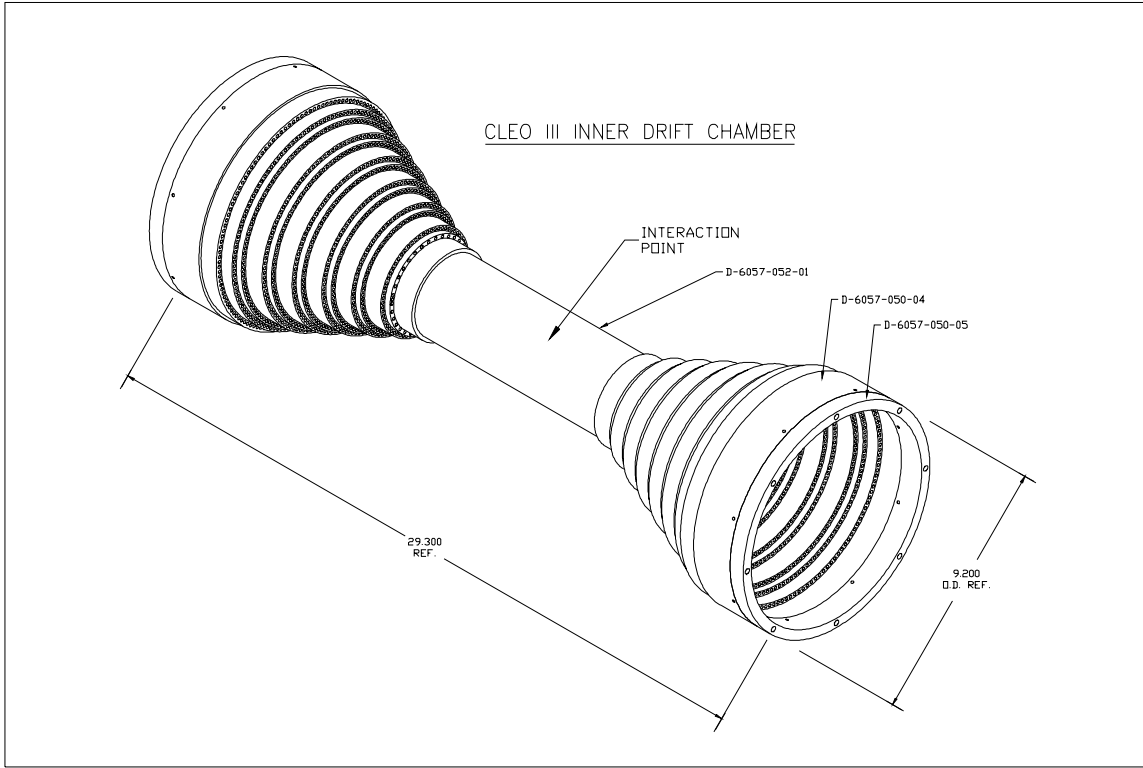


FIGURE 7. An isometric view of the proposed inner wire chamber.

another option for this wall is described in the section on prototyping.

TABLE 2. Resolution in z_0 , at $\cos(\theta)=0$, for various detector options, in *microns*. Uncertainties are at the level of one micron.

z_0 resolution (10^{-6} meters)										
inner detector	track momentum (GeV/c)									
	0.25	0.35	0.49	0.69	0.97	1.36	1.91	2.68	3.76	5.28
silicon (design)	179	128	94	71	55	46	40	36	34	33
silicon (realistic)	317	228	179	144	122	107	101	96	94	94
silicon (no $r-\phi$)	321	237	181	143	122	108	99	95	94	93
inner drift chamber	806	738	702	685	684	680	672	667	668	665

Replacement of the silicon vertex detector with a wire vertex detector would provide nearly equivalent momentum resolution due to reduction of scattering material within the measurement volume. The silicon vertex detector contributes about 1.6% X_0 between the beam pipe and the drift chamber inner wall. This scattering material is distributed over

TABLE 3. Fractional momentum resolution, in %, at $\cos(\theta)=0$, for various detector configurations.

momentum resolution, σ_p/p (%)										
inner detector	track momentum (GeV/c)									
	0.25	0.35	0.49	0.69	0.97	1.36	1.91	2.68	3.76	5.28
silicon (design)	.31	.32	.32	.33	.33	.35	.41	.47	.56	.69
silicon (realistic)	.32	.31	.32	.33	.35	.37	.43	.53	.67	.91
silicon (no $r-\phi$)	.34	.33	.34	.35	.39	.45	.53	.68	.89	1.24
inner drift chamber	.32	.32	.32	.33	.35	.39	.45	.56	.71	.96

the radial extent; material comes roughly equally from the four silicon layers and a carbon fiber support layer placed between the 3rd and 4th layers. By comparison, the wire vertex detector would contribute 1.2% X_0 , of which 1.1% X_0 would be concentrated in the structural inner radius wall of aluminum. As shown in Table 3, the substantial reduction of scattering material within the measurement volume results in a momentum resolution of 0.39%, at $p_\perp = 1.36$ GeV/c. By comparison, the resolution achieved with the (realistic) silicon detector, 0.37%, is only slightly better while the momentum resolution will degrade to 0.45% for a silicon vertex detector with only z information.

Similar to the case of single particle momentum resolution, the proposed vertex wire chamber would provide comparable mass resolution and reconstruction efficiency for typical D^0 decays. Figure 8 shows the mass distribution for $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ generated at the $D\bar{D}$ threshold with a recoiling $\bar{D}^0$ that decays generically. A combinatoric background remains after imposing a loose 4-particle total momentum requirement and perfect particle identification. We compare the case of an optimistic projection of the silicon vertex detector performance (efficient only in layer 4 in $r-\phi$ and layers 3 and 4 in z) with the case of installing the wire vertex detector. With the wire vertex detector, the width increases by 10% from 4.9 MeV/c to 5.4 MeV/c while the detection efficiency decreases by 6%. However, in the case where the silicon efficiency falls to zero, the width increases to 6.7 MeV/c and the efficiency decreases by 26% relative to the optimistic projection. We have also investigated $D_s \rightarrow \phi\pi \rightarrow KK\pi$ (all charged) at the $D_s\bar{D}_s$ threshold. This shows similar results when comparing the performance of the silicon and wire vertex detectors. Therefore, the proposed wire chamber would provide slightly degraded performance when compared to the “optimistic” projection of future silicon performance but would provide improved performance when compared to a poorer future silicon performance. These results do not take into account possible improvements in reconstruction efficiency due to improved pattern recognition that takes advantage of the wire vertex detector.

Improvements in pattern recognition at low momentum are expected with the installation of the wire vertex detector. Pattern recognition is improved by limiting curvature variations due to energy loss within the tracking volume. For example, a 60 MeV/c pion will lose ~ 8 MeV/c in the 4th silicon and support layer alone. In addition, the wire vertex detector

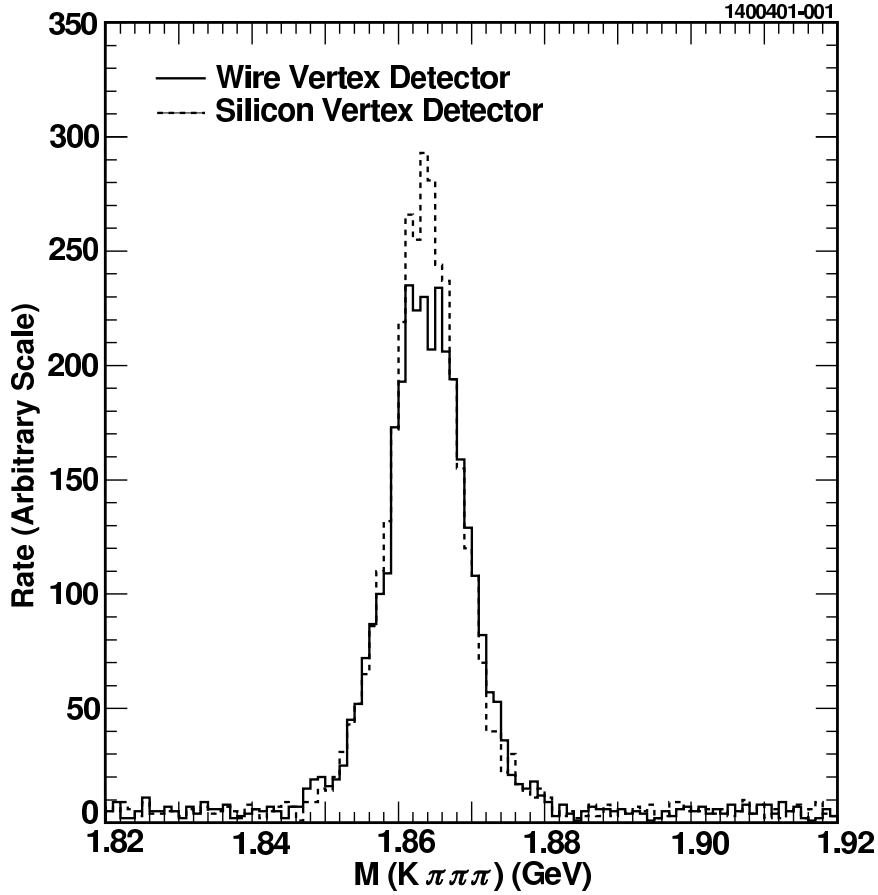


FIGURE 8. Reconstructed $K\pi\pi\pi$ mass shown for two detector configurations: CLEO III with the silicon vertex detector and an optimistic projection of the efficiency (dotted), and CLEO III with a wire vertex detector (solid).

provides extra layers to improve the pattern recognition. A track that has $45 \text{ MeV}/c$ (observed in the main drift chamber) will curl at layer 13 providing only about 10 layers for $r - \phi$ pattern recognition. Even a fully efficient silicon vertex detector is not used in the initial stage of pattern recognition because of electronic and radiation noise. Silicon hits can only be added to established tracks. However, the six layers in the wire vertex detector could all contribute to the initial stage of $r - \phi$ pattern recognition. The efficiency of the $r - \phi$ stage of the low-momentum pattern recognition would be improved and the z projection would be determined simultaneously.

2.2.2.2 Prototypes, Testing, Timeline

The new wire vertex detector shares many features with the CLEO III main drift chamber: wire, pins, bushings, gas, basic cell geometry, endplate material, and readout. Therefore, for most issues, the CLEO III main drift chamber is the prototype chamber for this new inner chamber. However, we have identified, and studied, three important differentiating features of the new wire vertex chamber: the stereo angle is larger than in the main drift chamber,

the cell size is smaller than in that larger chamber, and the inner cylinder must be thin but mechanically strong.

The large stereo angles do not cause concerns about the cell geometry; these concerns are well addressed by our experience with the CLEO III main drift chamber. Rather, stringing at large stereo angles could cause kinking of the aluminum field wires at the point of the angle change at the inside end of the crimp pin. In addition, abrasion can occur because the wire is dragged over this corner, under tension, by a distance equal to the wire strain, 0.03 inch. These conditions could lead to local wire stress and, ultimately, broken wires. Wires were strung in a test stand at the tension to be used in the new wire vertex chamber (100 grams) and at the maximum r - ϕ to z slant of 0.10. No inelastic distortion was observed indicating that the stereo angle is not large enough to be a problem.

The minimum distance between sense and field wires is 5 mm for new wire vertex chamber rather than 7 mm as in the main drift chamber. This raises a concern that the chamber will be more susceptible to high voltage breakdown both inside the chamber and in the HV distribution circuit especially because the required operating voltage does not scale linearly with the cell size. The gas gain is determined by the electric field at the sense wire surface, which, in the model of a cylindrical tube, is $2V/(d \ln(d/D))$ where V is the voltage difference, d is the sense wire diameter, and D is the cell size (cylinder outer diameter). The electric field increases by only 5% when the cell size is lowered from 14mm to 10mm. Therefore, the operating voltage of the new wire vertex chamber must be 2000 volts in order to provide the same gas gain as the main drift chamber operated at 2100 volts.

A ten cell test chamber was constructed using the same modified components that are proposed to be used in the new wire vertex chamber with endplates stepped to create the same wire-to-endplate geometry as proposed.

This test chamber was operated, in dry air, at above 2200 volts for four days. Below 2300 volts there were no trips and no observable currents (less than $0.005 \mu\text{A}$ per 5 wires). When operated at 2400 volts, the current increased to $1 \mu\text{A}$ per gang of 5 wires. The chamber could not be “processed” to run at this voltage, *i.e.*, the current did not decrease with continued operation at this voltage. This test demonstrated that we can expect stable operation of the new wire vertex chamber at 2000 volts.

The inner cylinder of the new wire vertex chamber is required to be very thin to minimize scattering material. However, it must provide all the support between the two endplates because the outer skin is limited to 0.005 inches of Mylar in order to minimize scattering between the two wire chambers. A 1 mm thick aluminum inner cylinder would contribute only 1.1% X_0 but tests were required to determine whether an aluminum cylinder of this thickness could support the loads.

A prototype aluminum inner cylinder, with wall thickness starting at 3 mm and then reduced to 2 mm and finally 1 mm, was tested for possible distortion due to strain relief during machining and a possible buckling failure precipitated by the asymmetric forces present during installation. After the inner cylinder wall thickness was reduced to 1 mm, the maximum difference of measures of the diameter, at varying azimuth, at the longitudinal center, was less than 0.1 mm. This distortion, only 10% of the wall thickness, is acceptable for both mechanical stability and the electric field in the first wire layer. During installation, the chamber must tolerate being supported at two points: at the top of the outermost ring (maximum z) on each of the two endplates. This distribution of support creates a torque

on the inner cylinder of 40 inch-pounds about the x axis. To avoid buckling, the sagita of the bending of the cylinder must be less than the wall thickness when this 40 inch-pounds torque is applied to the cylinder. As shown in Figure 9, we have measured a linear response to applied torque up to 320 inch pounds, 8 times the expected torque. At the 40 inch-pounds, the sagita is only 0.013 mm. This demonstrates that a 1 mm thick aluminum cylinder is strong enough for our needs.

A stronger cylinder, with less radiation thickness, could be made of beryllium, which would roughly double the costs of construction and add some uncertainty to the schedule. We have studied the benefits of the reduction in radiation thickness of the inner wall from the 1.1% of the aluminum to the 0.3% of the beryllium. There is no appreciable change in the momentum resolution because all the measurements all the measurements of the track's curvature occur outside the inner wall in either case. There is a sizeable reduction in the resolution on the angle of the track leaving the interaction region, but this has little impact of the mass resolution which is dominated by momentum resolution. There is also a very small reduction over part of the solid angle in the projection resolution into the RICH detector, but this is only useful for the 20% of the tracks that do not leave a direct signal in that device. While we continue to investigate this beryllium option, there does not appear to be physics justification for the added expense and uncertainty.

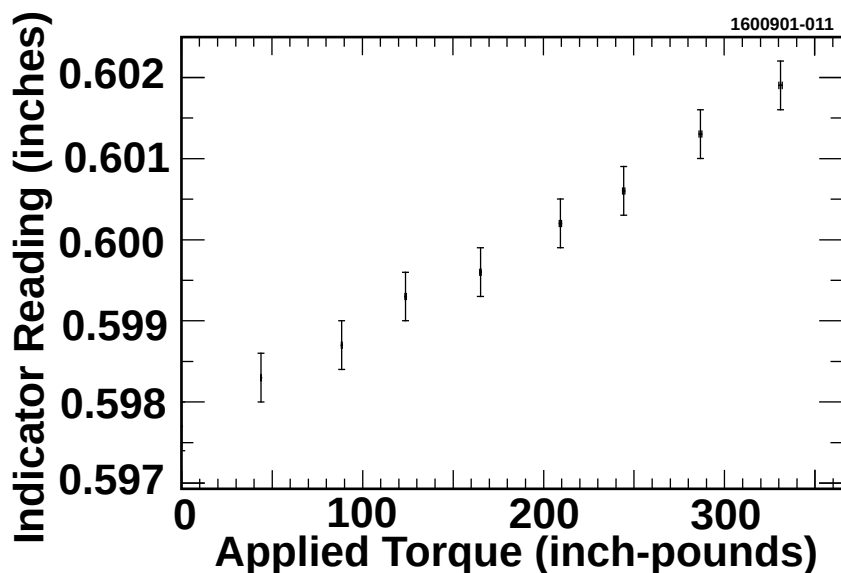


FIGURE 9. Indicator reading (offset not subtracted) measuring the sagita of the bending of the cylinder in response to the applied torque.

We have worked up a detailed time estimate for this producing this new wire vertex chamber, for which we foresee hiring no sort-term personnel (*e.g.*, wire stringers). The total elapsed time would be roughly 60 weeks, of which some has already been accomplished, such as securing bids from vendors. The largest single component to the timeline is the manufacture of the stepped endplates which the *vendors* estimate at 13 weeks. Such a schedule would have the chamber completed and tested by late summer of 2002.

2.2.2.3 Electronics Issues

Based on our experience with the CLEO III main drift chamber we believe we know what to expect for the wire vertex drift chamber. Operation of the axial layer electronics guides our (hopefully) modest extrapolation to the smaller radius layers of a small wire vertex chamber. Apart from a smaller cell and smaller layer radius, we expect the requirements for the electronics to be similar. The smaller radius and absence of the silicon (as shielding) may lead to higher noise rates in the new wire vertex chamber, although we note that the rate of lost particles and synchrotron radiation is expected to be significantly lower at the energies of CLEO-c than for CESR operating on the $\Upsilon(4S)$ (see the following section). In our experience, the noise rate in the main drift chamber is dominated by electronic pickup, not by ionization from machine backgrounds. The smaller drift cell has a shorter maximum drift distance and drift time (≈ 200 ns). There is also less charge collected in the smaller cell. The dynamic range of the charge measurement is adequate for the smaller expected ionization, and the 0.5 ns least count TDC with 32 μ s of dynamic range is completely fine.

Because of the similarity to the main chamber, it is possible to instrument the proposed wire vertex chamber using electronics based on the same design. As a significant savings in cost and time, some spare components from the main drift chamber can be used or modified.

For the preamps we foresee using a scheme similar to that used in the inner 16 layers of the main chamber. As there, we will read out only one side of the sense wires, alternating east and west readout by layer because of tight space constraints. Small diameter (0.110 in) HV coax would provide the connection between the sense wires and the HV distribution cards, which would be mounted at the location of the current silicon crescent crates, or on a cone concentric with the beam line near the first four axial layers of the main chamber, if space permits.

Preamp cards would mount on the HV distribution cards. Because of mounting constraints, we anticipate a new design for the 12-channel preamp cards. The preamp circuits would be built from spare parts and existing printed circuit boards fabricated for the main chamber, although we budget for replacement of these spares. Our baseline circuit design is identical to that of the axial preamps of the main drift chamber, which are identical to the stereo layer preamps but with faster transistors at the input stage to accommodate the capacitive loading due to the coax cable. Because of increased capacitance of longer cables, it is possible we may wish to choose a different input stage transistor. After this optimization, we will have the final circuit for the preamps.

The preamps will interface to modified data boards, which need to be located on both east and west poles of the CLEO III detector. A total of eight 48-channel data boards are required to instrument 300 channels. The modifications to these boards are simple, so we will be able to use existing spares. First, as there is no need for the trigger discriminators, we can disable them to reduce digital switching noise on the board. Second, because of a smaller drift cell, we can adjust the timing discriminators to have a shorter minimum pulse width. This pulse width is “self-imposed dead-time,” set to eliminate multiple time hits in the same cell from the same beam crossing. (This can occur for two tracks traversing the same cell, but no attempt is made in track reconstruction to use such hits.) For the main drift chamber the pulse width was set to approximately twice the maximum drift time. We may wish to reduce the pulse width further to ameliorate occupancy related dead time for

the new wire vertex chamber. The modification is a single capacitor or resistor replacement per channel. Third, we are investigating a change in the charge gain to allow a pulse height measurement if the new inner drift chamber is operated at higher gas gain to provide better noise immunity.

To minimize coupling to ubiquitous potential external noise sources, we plan to locate the boards for the new wire vertex chamber in a separate crates from the boards of the CLEO III main drift chamber and muon systems. We envision two data crates using the locations of the present readout crates for the silicon vertex detector. The necessary chassis and cooling hardware is mostly in hand, but some additional parts may be required. We can use the two existing spare backplanes to assemble the data crates, and we will budget for two additional spares for the these data crates. We are investigating whether the use of linear power supplies for the data boards will provide better noise immunity. If not, we will obtain additional power supplies used in the current data crates. There are sufficient spare transition boards, which provide the connection to the TDCs, through which the data boards are read. We do not plan a connection to the trigger system, but the data boards can accommodate this if there is a future need.

The discriminator and charge integration outputs would be routed to LeCroy 1877S FastBus TDCs. There are sufficient empty slots in the FastBus crates from the main drift chamber. We will obtain the four TDCs from our working spares and repair broken spares, either ourselves or through an outside vendor. It is also conceivable to remove TDC modules from the muon system, since the outer muon system beyond seven interaction lengths will have little utility for the CLEO-c running, where muons from charm decay are too soft to penetrate. However, we assume here that the muon system will be left intact.

High voltage would be supplied by the LeCroy power supplies used for the main drift chamber. Additional channels in the existing system are available for the six independent voltages required. Additional HV patch panel connectors and high voltage cables can be assembled from existing parts.

In summary, we can instrument the proposed wire vertex chamber with electronics nearly identical to that used in the main CLEO III drift chamber. We do not anticipate any difficulty with this plan, extrapolating from our experience with the current main drift chamber electronics, especially the axial layers. Some modifications to the data boards are envisioned to accommodate the smaller drift cell and possibly higher occupancy. As a significant cost savings some spare drift chamber components can be used and/or modified.

2.2.2.4 CESR-c Backgrounds

In CLEO II and CLEO II.V running the introduction of the silicon vertex detector greatly reduced the occupancy in the wire chambers. There is therefore some concern that removing the CLEO III silicon vertex detector will lead to a large occupancy in the CLEO III wire chambers, particularly a small, inner wire chamber as described in the previous sections. We have run simulations of the CESR-c lattice ($\sqrt{s} \sim 4$ GeV) and compared the synchrotron radiation and lost particle "source effectiveness" for this machine with CESR-3 ($\sqrt{s} \sim 10.6$ GeV). We find that synchrotron radiation is essentially non-existent in CESR-c, as one would expect given the steep dependence of such radiation on beam energy. For particles, the "source effectiveness" is down for CESR-c by a factor of more than 100. We have also

checked for Touschek scattering, caused by interactions of particles within the beam bunches which go as $1/\gamma$ and thus a larger concern at the low energy machine, and find this source to be of similar size as the particle background. Work is still proceeding on this simulation, but all indications are that the rates in both the main drift chamber and new, inner wire chamber will be modest.

The other source of “background” is the electronic noise of the CESR/CLEO environment. However, we have operated devices at radii similar to those of the proposed wire vertex chamber in the past and do not see this as problematic.

One might nonetheless ask how increased occupancy would affect the performance of the proposed chamber. The primary purpose of the new wire vertex detector is tracking, so the most important information is the arrival times of electrons drifting to the wires. Such timing information should be valid with up to 1 MHz of rate per channel (or a 1 μ sec average inter-arrival time. This limit is based on two independent parameters. First, the trigger latency is on the order of 2.5 μ sec and we can only store 16 hits in the TDCs; therefore we start to lose valid hits if the inter-arrival time started to be on the order of a microsecond. Also, the drift time in the cell is roughly 200 nsec; clearly timing information is meaningless if more than one hit occurs in that time period. However, 1 MHz is an enormous rate, and it is doubtful that *any* drift chamber could work in such an environment. [For reference, the singles rates in the main CLEO III chamber during recent $\Upsilon(4S)$ running were ~ 1 KHz.] It is also true that such a large occupancy would slow down readout for the drift chamber TDCs, although most of the out-of-time hits would be removed by the sparsification code running in the crate CPUs.

Of course, it would be useful to also read out the charge associated with each hit. This would primarily allow us to suppress electronic noise which tends to have negligible integrated charge. While we are not relying on dE/dx measurements from the wire vertex chamber, these measurements will certainly be used if they are available. If CLEO and CESR were to return to higher energies at some point, then the charge information could also be used to discriminate against hits from synchrotron radiation.

Assuming that in the CESR-c running the dominant source of charge deposition in the chamber is from charged particles, we estimated that about a singles rate of ~ 10 kHz the pile-up from false hits will raise the base-line by 20% of the typical charge from a minimum ionizing track. This would degrade the usefulness of the charge information. One could overcome this and extend the rate for which charge is meaningful to hundreds of kilohertz by shortening the shaping time and storing the information in a pipeline for eventual readout. This poses three concerns: we must not compromise the timing information by introducing noise from ADC clocks; this would require a large research and development effort, with perhaps a year’s time from conceptual design to implementation; the cost of this new electronics would be large, although not prohibitive if the physics goals warrant it. At present we are not pursuing this type of solution to a problem we are confident does not really exist.

3 The CLEO III Hadron Identification System

Particle identification is very important for many physics goals of the CLEO-c program. The drift chamber and RICH subsystems complement each other extremely well to provide

excellent hadron identification over the entire relevant momentum range. The measurement of specific ionization in the drift chamber provides good particle separation at low momenta, and the RICH detector separates hadrons at higher momenta as well as complementing low momentum particle-ID.

3.1 Specific Ionization in the Drift Chamber

The resolution of specific ionization (dE/dx) measurements is primarily determined by gas composition and the size and number of charge measurements. To deal with the non-Gaussian charge distribution, charges from the lowest 5% and the highest 25% pulse-height hits for each track are discarded and the remaining 70% are averaged to get the raw dE/dx measurement. In CLEO III, there are 47 layers, and layers often give more than one sample.

It is worth noting that CLEO III uses the same gas, He:C₃H₈ (60:40), that was used in CLEO II.V in a similar chamber. Thus, while some aspects of CLEO III calibration are not yet complete, we have detailed experience and expectations. CLEO II.V was the first large experiment to use a helium-based gas [13,14].

There are several differences between CLEO II.V and CLEO III operation. Increased high voltage results in somewhat increased gas-gain saturation effects; these have only a small effect on resolution. There is a modest increase in the residual O_2 in the chamber gas; special studies with varying O_2 levels demonstrate that the effect on resolution is negligible. The most notable changes are in fact due to the excellent design of the current chamber, making it considerably easier to calibrate.

Basic charge (dE) calibration involves both an electronic (via charge injection) and an empirical (via Bhabha events) gain calibration. The empirical gas gain is determined run-by-run and wire-by-wire (averaged over many runs).

For dx calibration, we scale each charge by $\sin\theta$ and also normalize by the geometric path length in the $r - \phi$ projection of the drift cell. Some residual empirical corrections due to magnetic field and collection effects are also required. These $r - \phi$ corrections are the only corrections which vary hit by hit.

The final step is an additional dE calibration to account for gas-gain saturation. This effect is caused by charge screening due to the linear charge density along the wire. We first apply a “cosine correction” appropriate for the dE of electrons which is a function of dip angle only. We then do a “saturation correction” which depends on the actual charge density of the track. Note that the presence of this non-linear correction requires one to be careful when interpreting sigma/mean as a resolution.

3.1.1 Current Performance

The current state of the CLEO III dE/dx calibration is illustrated by plotting the particle bands versus momentum in Figure 10. The performance in CLEO III is very similar to CLEO II.V with a preliminary resolution for minimum-ionizing pions of 6.0%. We expect that the ultimate performance will be superior to CLEO II.V as well as surpassing that of the BaBar and Belle [15] chambers.

Since CLEO II.V data is very similar and fully calibrated, we can use these to make predictions for CLEO III. Note that we use real CLEO III tracks with the actual dip angle and

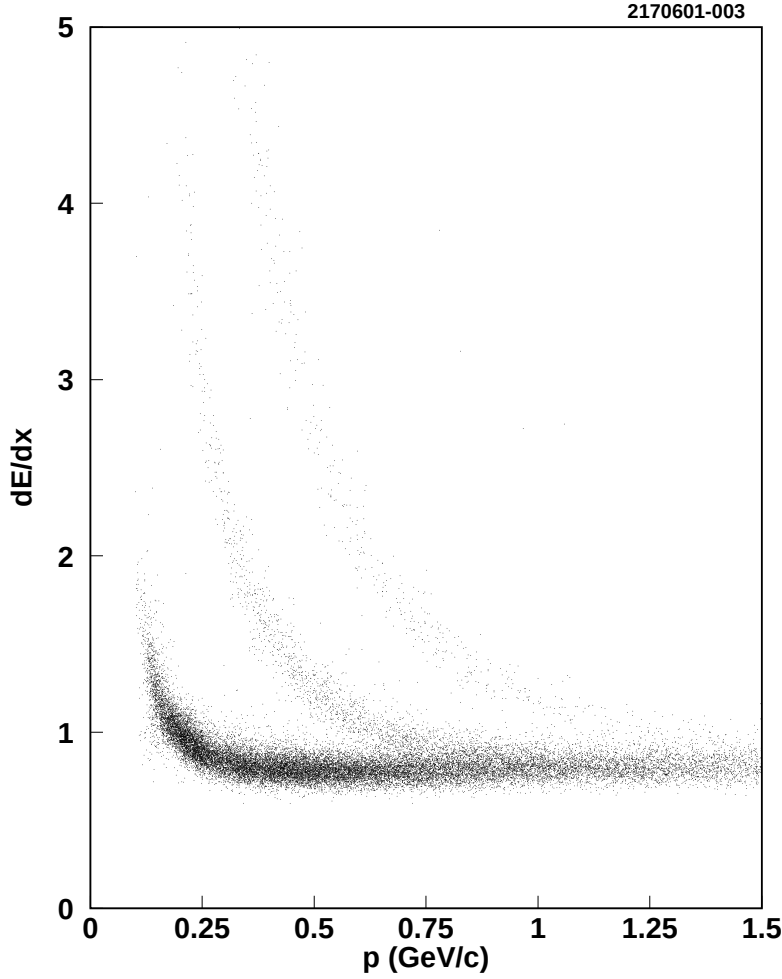


FIGURE 10. CLEO III dE/dx versus momentum showing the π , K and p bands. Leptons are suppressed where possible. The dE/dx scale is chosen to be 1 for electrons and positrons from Bhabha events.

number of hits found as inputs; all that is taken from CLEO II.V is the resolution function. The expected CLEO III $\pi - K$ separation versus momentum is displayed in Figure 11.

Based on our detailed understanding of dE/dx , we can state with confidence that the performance will be as good in the new CLEO-c era. A lower magnetic field will reduce the size of some cell corrections, but have essentially no direct effect on dE/dx . There will be an indirect benefit since low p_T tracks will cross more layers before curling and hence have more charge samples. In addition, this will help limit curling tracks which might otherwise increase cell occupancy.

DR-III provides excellent tracking coverage. For barrel tracks with sufficient transverse momenta, all 47 layers are traversed. At maximal $\cos\theta = 0.93$, only 25 layers are crossed. Due to the increased path in the $r - z$ projection, the resolution does not drop as fast as naively expected due to this decrease in samples. In fact, the resolution at $\cos\theta = 0.93$ is only about 10% worse than at normal incidence.

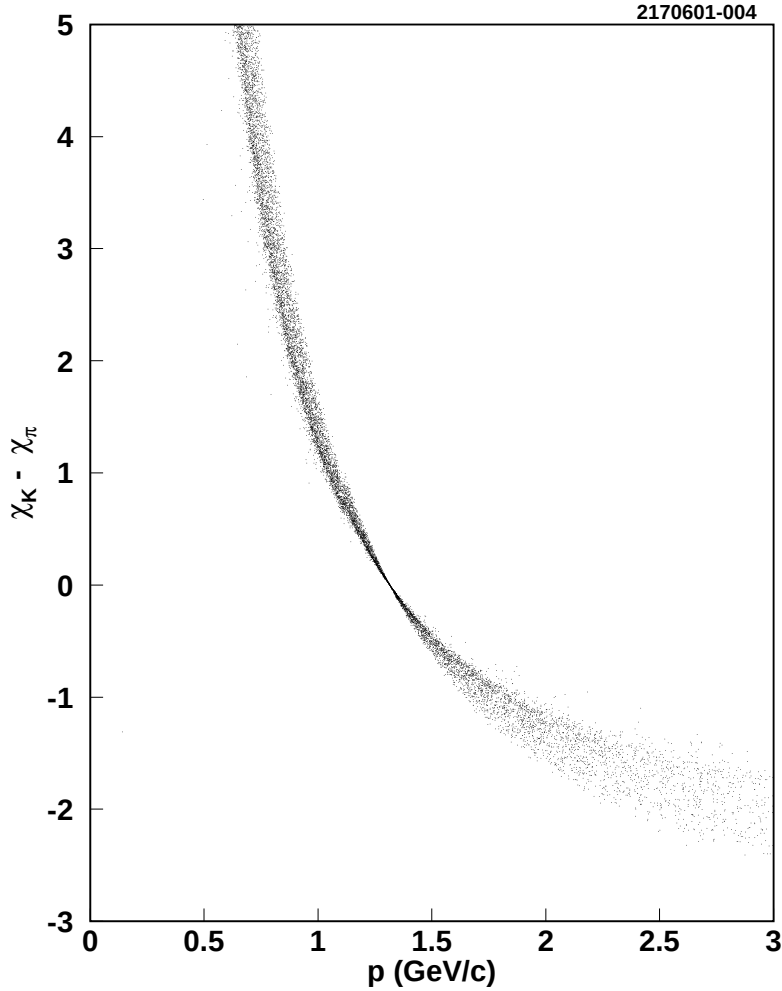


FIGURE 11. The π/K separation from dE/dx , in standard deviations, that is predicted by the final CLEO II.V resolution function, for CLEO III hadron tracks. Smearing at a given momentum is due to variations in the number of samples and the dip angle.

The dE/dx particle identification works best for slow particles. The calculated energy of soft tracks is also most affected by the mass assignment; techniques such as neutrino reconstruction via four-momentum balance benefit from this being correct. At higher energies, dE/dx is quite limited; this motivates the use of a Cherenkov radiation detector to supply needed separation power.

3.2 RICH

The most significant improvement in the CLEO III upgrade was the insertion of a Ring Imaging Cherenkov (RICH) detector between the new drift chamber and the old crystal calorimeter. The solid angle coverage of the RICH is 83% of 4π , and tracks with transverse momentum above 0.12 GeV/c will reach the RICH radiators when the magnetic field is

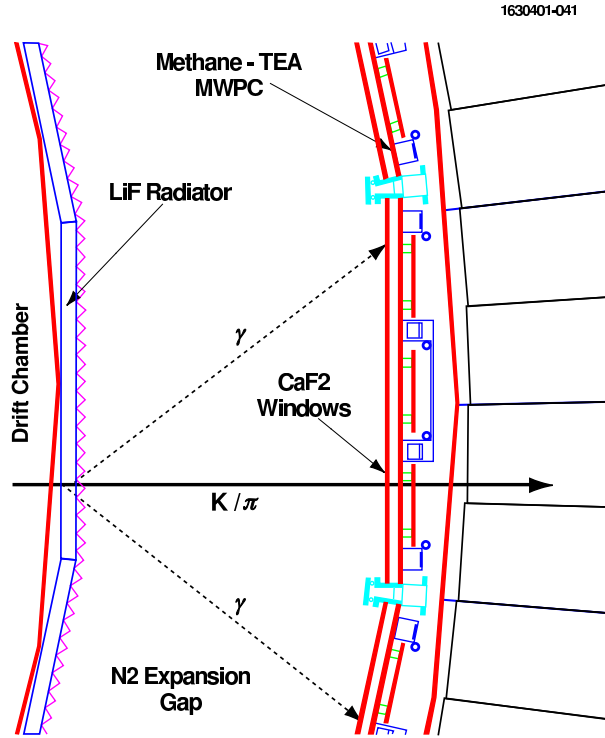


FIGURE 12. r - ϕ cross-section view of the CLEO III RICH detector.

lowered to 1 T.

The RICH detector elements are shown in Figure 12. Charged tracks pass through LiF radiators (on average 1.7 cm thick) and produce Cherenkov photons. Out of 14 rows of LiF crystals the four central rows are equipped with “sawtooth” radiators to overcome total internal reflection of Cherenkov photons in the LiF radiator at near normal track incidence. Sawtooth radiators have triangular grooves on the surface (see Figure 12). The photons travel through the expansion gap filled with nitrogen and enter the multi-wire proportional chambers (MWPC) through CaF_2 windows. The chambers are filled with a methane-TEA gas mixture. The Cherenkov photons in a narrow VUV range (135-165 nm) are converted into photo-electrons. The charge is multiplied by the usual proportional wire chamber mechanism. The position of the photon conversion is measured via charge induced on cathode pads (there are 230,400 pads in total). The number of dead channels is about 4%, which includes channels effected by one broken wire in the detector. Sample Cherenkov ring images are displayed in Figure 13.

Each cathode pad is input to a VA-RICH electronics chip residing on the detector where the pad signals are amplified, shaped and multiplexed before being sent to the VME based digitization system. There the signals are digitized, coherent noise is subtracted (on per chip/per ADC basis) and the data are sparsified. The average incoherent noise is $500 e^-$ compared to an average signal pulse of $21,000 e^-$.

About 25% of tracks intersecting RICH radiators miss the RICH chambers because of the edge effects at large z and because of the dead regions due to the support structure and

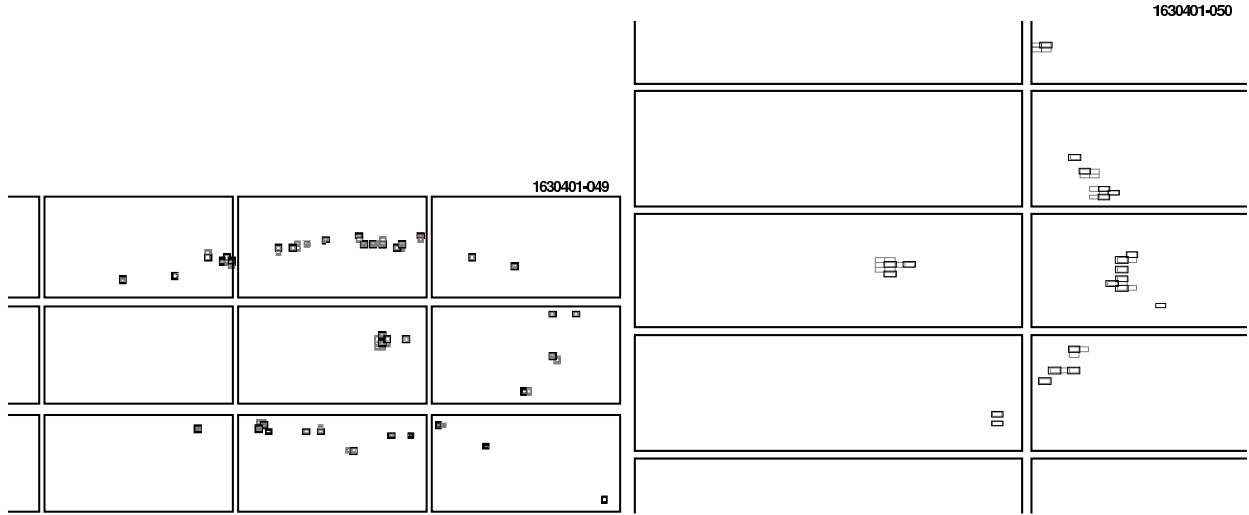


FIGURE 13. Cherenkov images produced by track crossing sawtooth (left) and flat (right) radiators. The small squares indicate charge detected in pads of RICH wire chamber. Large rectangles outline 24×40 pad arrays. Hits in the middle of the images are due to the charged track crossing the wire chamber. The other hits are due to Cherenkov photons. The flat radiator image consists of half of the Cherenkov ring, with the other half trapped in the radiator by total internal reflection. The sawtooth radiator image consists of two Cherenkov images distorted by refraction on two sides of the tooth.

anode wire spacers. The remaining tracks cross the active region of RICH chambers and record a hit, and the hit position is measured by the center-of-gravity method for the pad cluster.

3.2.1 Current Performance

The resolution of the RICH depends on the polar angle of the track in question. Averaged over Bhabha electrons the measured resolution is 12.2 (14.7) mrad for sawtooth (flat) radiators. The Cherenkov photon yield per track measured for Bhabha electrons is shown in Figure 14. The measured mean yield after background subtraction is 11.9 (10.6) photons per track for sawtooth (flat) radiators (again with some polar angle dependence). The data compare very well with the Monte Carlo simulation. Most relevant for particle identification is the resolution of the track-average Cherenkov angle. The resolution measured for Bhabha electrons is shown in Figure 15. Again, the data agree with Monte Carlo simulations very well, illustrating that the detector performs according to its design specifications.

To evaluate the RICH performance in hadronic environment we use a sample of $D^0 \rightarrow K^-\pi^+$ decays produced via $D^{*+} \rightarrow \pi^+D^0$ (charge conjugate decays are also used). The charge of the slow pion from the D^* decay identifies which track is the kaon (pion) in the subsequent D^0 decay. Combinatorial background is reduced by use of dE/dx cuts and then subtracted by fitting the D^0 peak on top of smooth background in the $K^-\pi^+$ mass distribution (see Figure 5).

To distinguish kaons from pions we use the likelihood ratio. Taking the logarithm of the

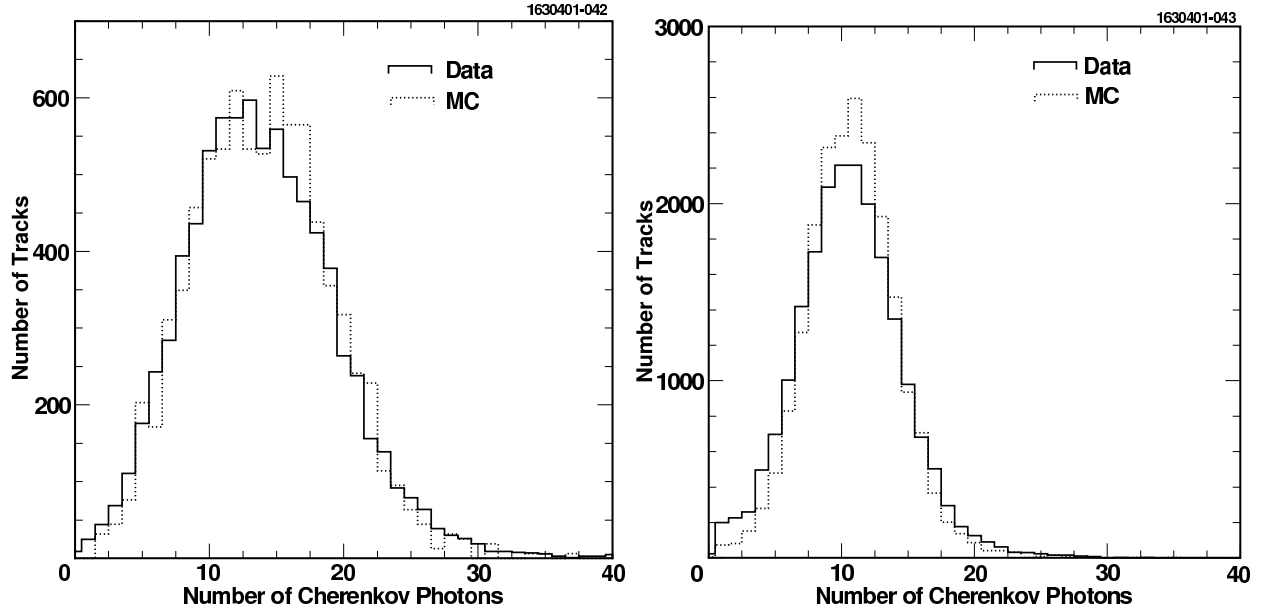


FIGURE 14. Number of Cherenkov photons detected for Bhabha electrons for sawtooth (left) and flat (right) radiators. The data (MC) are represented by solid (dashed) histograms.

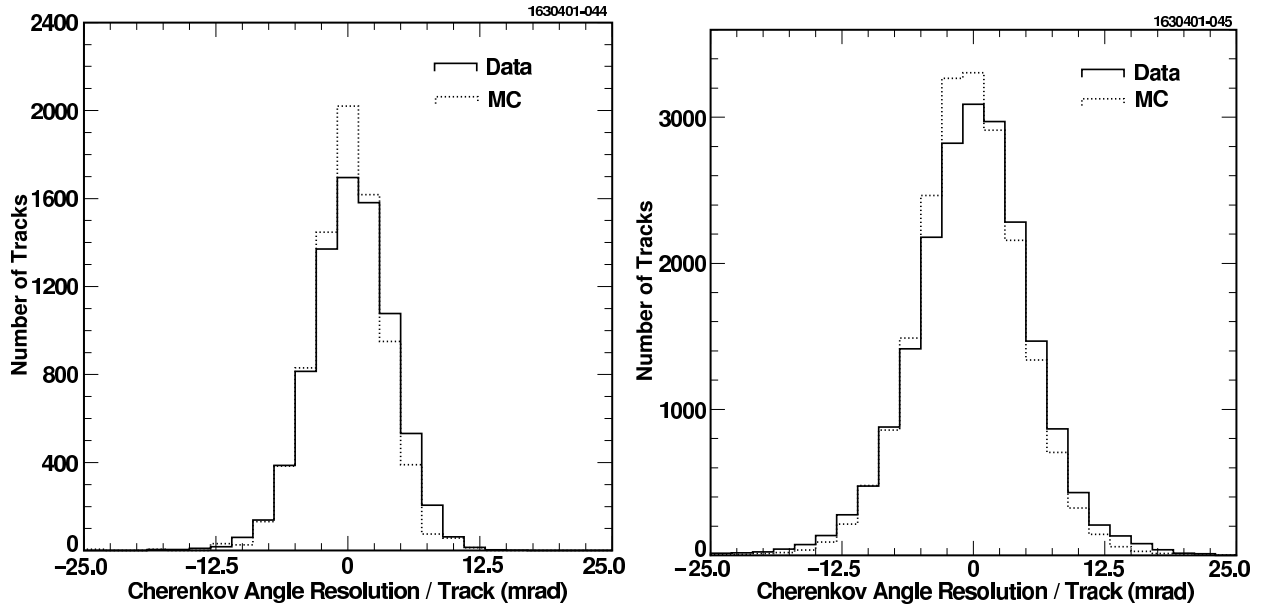


FIGURE 15. Cherenkov angle per track measured for Bhabha electrons for sawtooth (left) and flat (right) radiators. The data (MC) are represented by solid (dashed) histograms.

likelihood ratio and multiplying it by -2 we obtain a variable equivalent to the chi-square difference in the Gaussian approximation: $\chi_K^2 - \chi_\pi^2$.

We plot the measured fraction of kaons (pions) as a function of the cut on $\chi_K^2 - \chi_\pi^2$ as

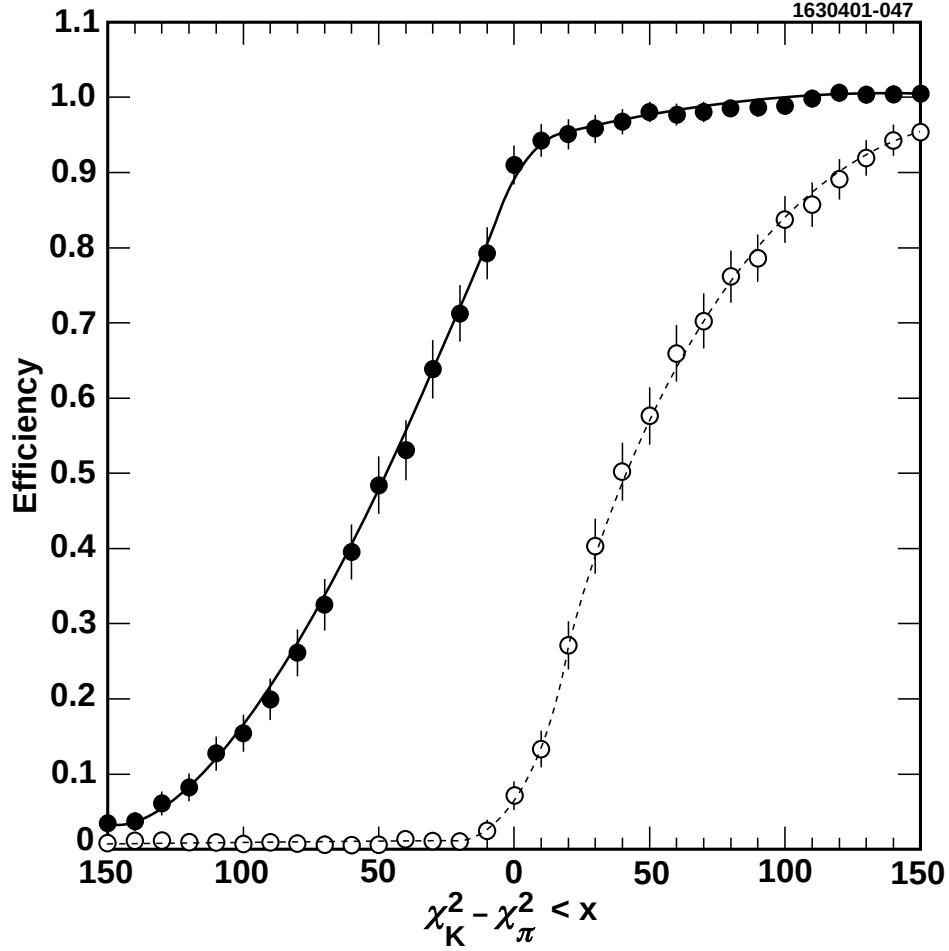


FIGURE 16. Kaon efficiency and pion fake rate measured for various cuts on the χ^2 difference between kaon and pion mass hypotheses for tracks with momentum in between 0.7 and 2.7 GeV/c.

shown in Figure 16. For example, for the cut $\chi_K^2 - \chi_\pi^2 > 0$ we identify 92% of kaons with the pion fake rate of 8%. These results are very encouraging especially since they were obtained before the final alignment of the tracking system. Momenta of tracks in this study extend from just above kaon radiation threshold to 2.7 GeV/c. Below kaon radiation threshold, the RICH can be used in a threshold mode. The fraction of kaons (pions) passing the cut restricting number of photons assigned to the pion hypothesis is shown in Figure 17.

3.3 Outlook

The RICH detector is a great success. The performance is well understood and well simulated by the CLEO III Monte Carlo, and the RICH reconstruction software is in excellent shape. The RICH detector, together with dE/dx from the drift chamber, will provide excellent hadron identification over all particle momenta relevant for CLEO-c running.

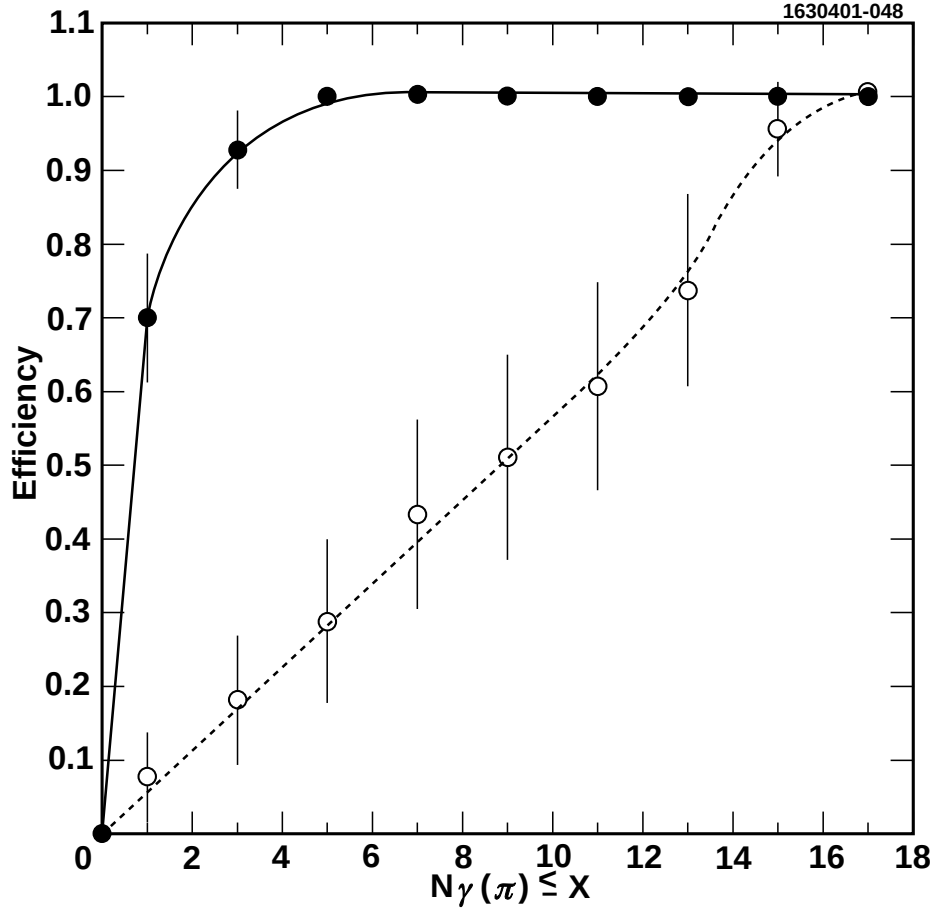


FIGURE 17. Kaon efficiency and pion fake rate measured for various cuts on the number of photons assigned to pion hypothesis for tracks near and below the Cherenkov radiation threshold for kaons ($p < 0.6$ GeV/ c whereas the kaon radiation threshold is 0.44 GeV/ c).

4 The CLEO III Electromagnetic Calorimeter

4.1 System Description

The CLEO III/CLEO-c CsI calorimeter is fully operational and an excellent match to the needs of tau-charm physics. For CLEO II and CLEO III, the 7800-crystal cesium iodide electromagnetic calorimeter has played crucial roles in the hardware trigger, Level3 software trigger, online and offline luminosity determinations, event classification, π^0 -finding, electron identification, and ν -reconstruction. The energy and position of each shower are used for the photon candidate momentum measurement, its position for matching to charged particle tracks, and its lateral shape for rejection of non-electromagnetic showers. CLEO-c will need and benefit from all these capabilities in similar ways. The CLEO III/CLEO-c detector configuration provides minimally-obstructed, near-optimal-resolution coverage in the regions $|\cos\theta| < 0.8$ and 0.85-0.93 (expanded from CLEO II's $|\cos\theta| < 0.7$, limited by material

blocking the endcaps and barrel ends). The endcap-barrel transition region ($0.80 < |\cos \theta| < 0.85$) completes the detector's nearly full hermeticity; this narrow region has worse energy resolution because photons are obstructed by substantially more material than elsewhere.

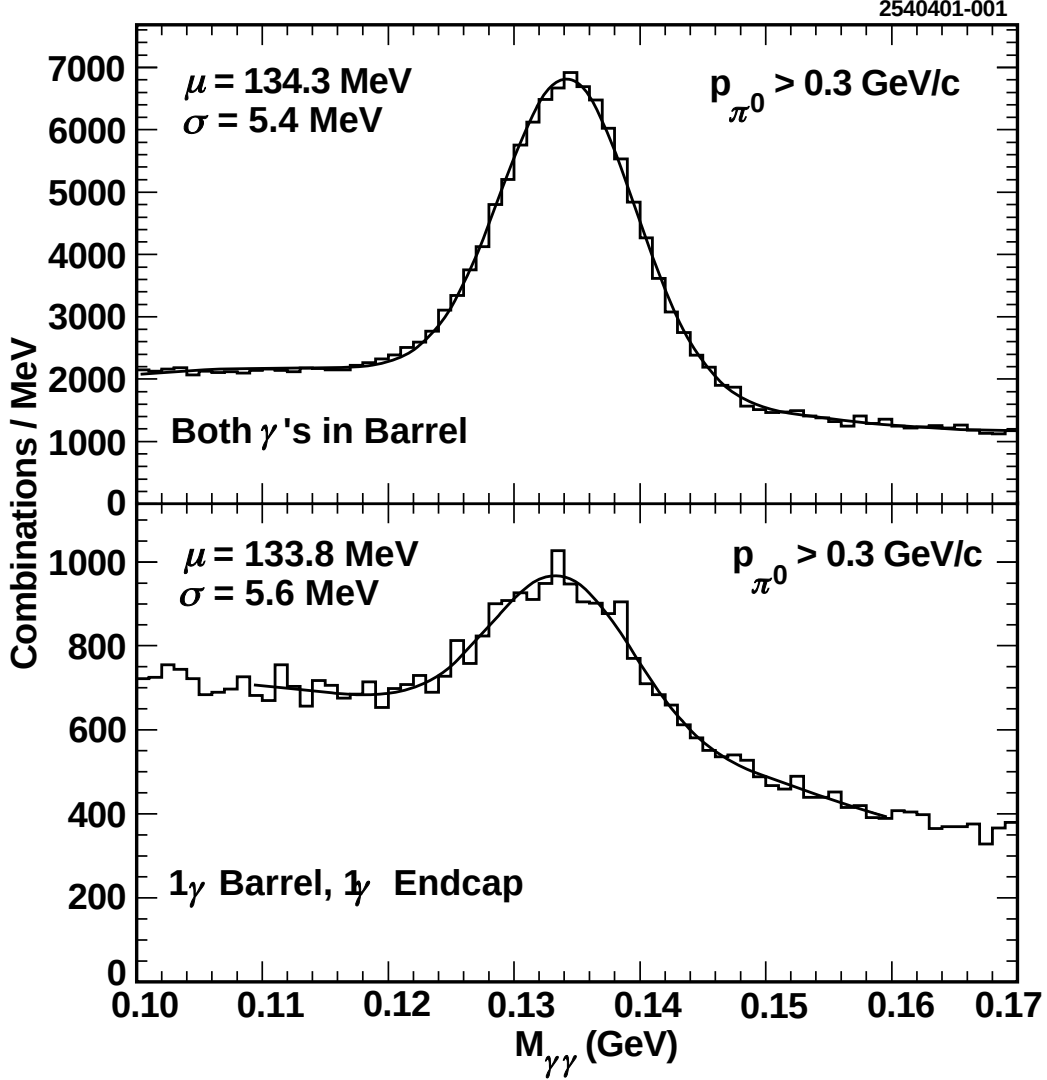


FIGURE 18. $M(\gamma\gamma)$ resolution for π^0 candidates in CLEO III $\Upsilon(4S)$ data.

4.2 Performance and Outlook

Calorimeter performance achieved in CLEO III matches the level of CLEO II in photon energy resolution ($\sigma_E/E = 1.5\%$ at 5 GeV, 4% at 100 MeV, and 7% at 30 MeV) and mass resolution in $\pi^0 \rightarrow \gamma\gamma$ decays ($\sigma_{\gamma\gamma} = 5\text{--}7 \text{ MeV}/c^2$, depending on photon energies and locations). Figure 18 shows $\gamma\gamma$ mass distributions for moderate momentum ($p > 0.3 \text{ GeV}/c$) π^0 candidates in CLEO III $\Upsilon(4S)$ data, separately for barrel-barrel and barrel-endcap combina-

tions. This momentum range is typical of the low multiplicity tau-charm decays. Note that the barrel-endcap resolution almost matches that of barrel-only photons and that barrel-endcap combinations add $\sim 8\%$ more π^0 's. Comparing to three other experiments operated in the tau-charm energy region: the CsI energy resolution is somewhat better than Crystal Ball and nearly a full order of magnitude better than BES II or Mark III. Angular resolution (~ 10 mrad) is also better than any of these detectors, and the CLEO III/CLEO-c calorimeter has a factor of ten higher segmentation than Crystal Ball, facilitating more discriminant shape determinations and easier particle isolation. The separate strengths of previous tau-charm detectors, charged particle tracking and electromagnetic calorimetry, are combined and improved upon in CLEO-c energies, final state particles will be more spread out, making showers more isolated and hence easier to use and accurately reconstruct. The many difficulties introduced by hadronic shower split-offs faking photons (e.g. π^0 combinatoric background, false energy in ν -reconstruction) will be correspondingly smaller in CLEO-c.

5 The CLEO III Trigger System

A schematic view of the CLEO III trigger system is shown in Figure 19 [16,17,18]. Data from the calorimeter and drift chamber are received and processed in separate VME crates by the appropriate circuit boards to yield basic trigger primitives such as track count and topology in the drift chamber, and shower count and topology in the electromagnetic calorimeter. The information from both systems is correlated by global trigger circuitry which generates an L1Pass strobe every time a valid trigger condition is satisfied. The L1Pass signals are conditionally passed by the data flow control circuitry to the gating and calibration modules for distribution to the data acquisition system. In addition, luminosity information is obtained from the digital calorimetry subsystem and provided to the CESR accelerator via the global trigger.

5.1 Tracking Trigger

The tracking component of the CLEO III trigger consists of two distinct elements: axial and stereo.

5.1.1 Axial Tracking

The limited wire-count in the axial portion of the CLEO III drift chamber makes it possible to build a tracker that examines the complete set of 1696 wires, grouped into 16 radial layers, for all possible valid patterns caused by tracks having momentum transverse to the beam greater than 200 MeV/c. Patterns from tracks missing the central axis of the beam pipe by as much as 5 mm were included.

The trigger bins the data into 42 ns wide time slices, which is three times the crossing time of the accelerator. This discretization is sufficient for the time resolution required by the trigger, namely to determine the time of the interaction, with a fixed offset, to within 100 ns. Pattern recognition is performed by the AXTR boards for the entire axial portion of the drift chamber every 42 ns.

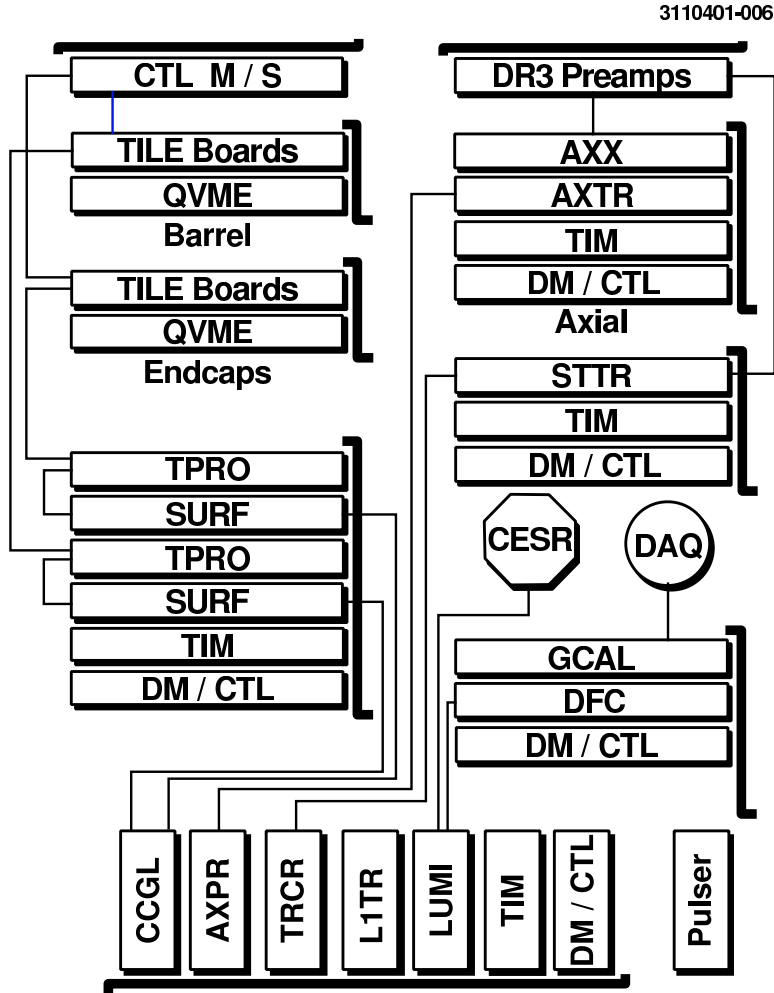


FIGURE 19. Overview of the CLEO III Trigger System.

The axial processor (AXPR) takes the 112 ϕ tracking bits from the AXTR boards and processes these every 42 ns to produce a 7 bit track count, a 48 bit array which represents the azimuthal event topology, and a 2 bit time stamp.

5.1.2 Stereo Tracking

There are too many (8100) wires in the stereo section of the drift chamber for the stereo tracker to examine every wire individually. Instead, the stereo tracker receives 1 bit for every 4 by 4 block of wires. The U and V super layers are tracked separately.

The stereo block definitions (which patterns within a 4 by 4 block are defined as track segments) and the stereo road definitions (which groups of U or V blocks is considered a valid track) were generated from simulated tracks having transverse momentum greater than 250 MeV/c. In order to satisfy a block pattern, a hit must be present on at least 3 out of 4 layers, allowing high track finding efficiency for realistic wire hit efficiencies. Stereo roads do not allow for missing blocks.

Topological information from both the axial and the stereo tracking trigger hardware is received by two Tracking Correlator (TRCR) boards.

The TRCR system overlays and correlates the U, V and Axial projection bits to form a final set of 48 correlated azimuthal projection bits as well as high and low momentum track counts. The derived TRCR output information is pipelined and placed on the backplane in the Level 1 decision subrack.

The stereo tracking trigger provides high efficiency per track, and good background rejection. The combined axial + stereo tracking trigger is much less sensitive to backgrounds than the inner axial tracking trigger alone, while maintaining an efficiency of greater than 99% for single tracks.

5.1.3 Event-time derivation

Considerable effort has been expended to understand the details of the timing behavior of the axial tracking hardware.

The implementation of the timing algorithm involves monitoring the tick-by-tick track count as an event evolves through the detector. A finite state machine, implemented in an Altera “MAX” 7000 series ISP-FPGA device, examines the 7 bit track count (calculated on the same board) and senses when this quantity starts to drop off after reaching a maximum. This point in time will, in most cases, be exactly one discriminator width later than the arrival time of the first hit on a track, which in turn is a good measure of the event time.

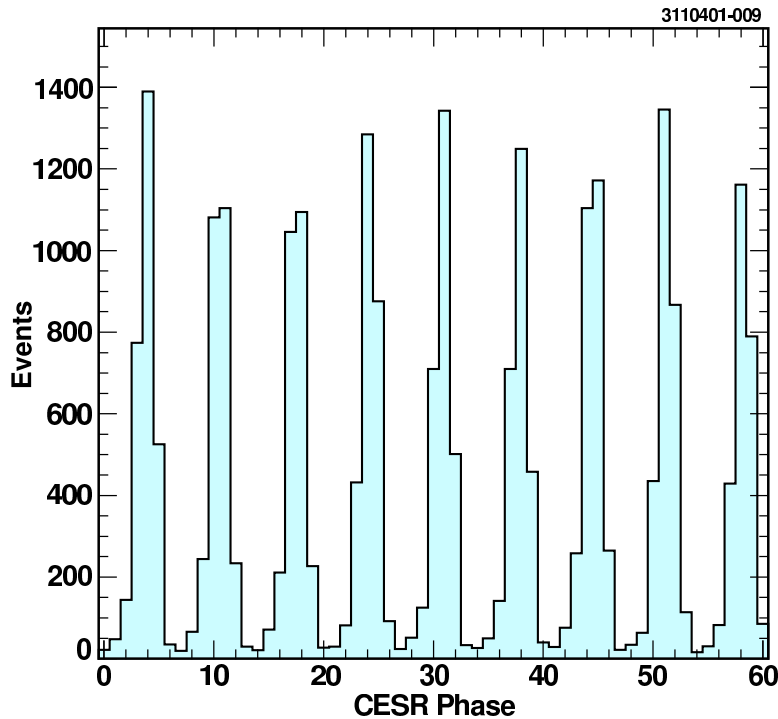


FIGURE 20. The beam structure of the Cornell Electron Storage Ring as recorded by the CLEO III trigger timing extraction hardware.

This time extraction method works extremely well. Figure 20 is a plot of timing buckets (each one 42 ns wide) on the horizontal axis versus number of events on the vertical axis, for all events in an early CLEO III era run. The timing bucket assigned to each event is extracted from the trigger based on the hardware described above. It repeats after 61 buckets since this is the number of unique 42 ns time increments that correspond to a complete revolution of a beam particle in CESR. The nine peaks correspond to the timing structure of the beam. A careful analysis of these peaks, taking into account the known underlying CESR beam structure, indicates that the resolution we achieve is in fact slightly better than we had expected based on simulation.

5.2 Calorimeter Trigger

The calorimetry subsystem of the CLEO III Trigger incorporates both analog and digital electronics to provide pipelined trigger information every 42 ns with a latency of approximately 2.5 μ s. Analog processing is employed to address the quantization error caused by split energy deposition in adjacent calorimeter cells, and digital field programmable gate arrays are used extensively to filter and categorize the calorimeter energy topology. Timing, geographical, and energy information are all available for use in the calorimeter trigger.

5.2.1 Analog Calorimeter Trigger

The CLEO III calorimeter (CC) comprises 1,656 doped CsI crystals in the detector “endcaps” and 6,144 crystals in the “barrel”. The light output from a crystal turns on rapidly, then decays with a 900 ns time constant. Four photodiodes are mounted on each crystal; each photodiode is viewed by a separate charge-sensitive integrating preamplifier. Preamplifier outputs are not cleared after an event, but decay exponentially to ground with a 180 μ s time constant.

To reduce the difficulties associated with simulation of the trigger, and to increase its flexibility, the CC trigger was redesigned for CLEO III. Complications associated with boundaries in the calorimeter are reduced by creating overlapping “tiles” by forming analog sums of signals from groups of 64 CsI crystals. A photon striking the calorimeter will deposit nearly all of its energy in at least one of the groups of crystals summed into a tile. Naturally, a signal in a single crystal will appear in four different tiles; it is the task of the tile processors (TPRO) to account for this. A diagram of the path for a single crystal’s signal through the CC trigger electronics is shown in Figure 21.

5.2.2 Digital Calorimeter Trigger

The tile processor (TPRO) boards receive data from as many as 384 (overlapping) active tiles in the calorimeter barrel and 120 tiles in the endcaps. The first task of the tile processor is to filter event data so that overlapping, or adjacent, tiles which contain energy are reduced to a single hit. After filtering the data, the tile processor then determines the number of showers and their positions in the calorimeter. The algorithm run by the TPRO boards is a compromise between angular (and energy) resolution and the desire to limit the amount of information to be processed by the trigger. The tile processors remove all but the highest threshold tile in a group of contiguous or overlapping tiles, and project the two-dimensional

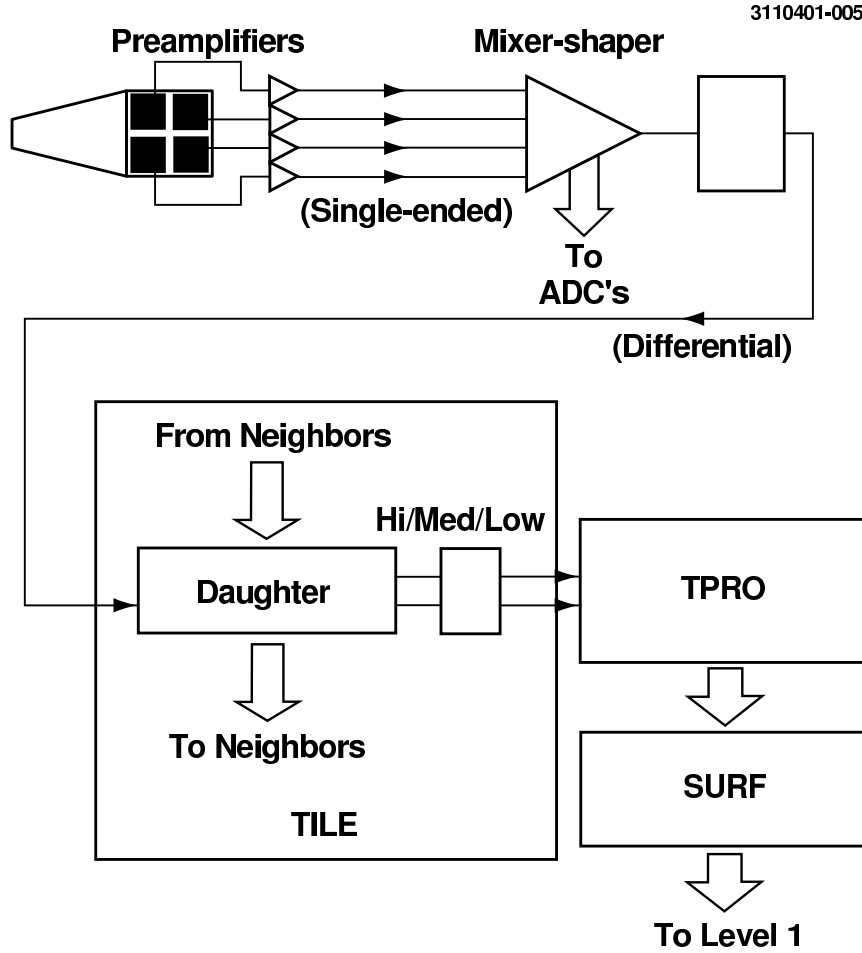


FIGURE 21. Signal path for one crystal. Signals from preamps peak $3 \mu\text{s}$ after formation, then return to ground with a $180 \mu\text{s}$ time constant. Signals from mixer-shaper controllers are differential, peak $2.5 \mu\text{s}$ after onset, then return to ground with an $8 \mu\text{s}$ time constant. A daughter board prepares copies of its mixer-shaper signal to send to neighboring boards. It then forms an analog sum of signals from four mixer-shaper cards. The summed signal is shaped into a bipolar pulse which is discriminated. For signals which exceed thresholds, logic pulses whose leading edges coincide with zero-crossings of the bipolar pulses are sent to the tile processors. Results from the system's tile processors are combined by the SURF boards, then sent to the Level 1 trigger.

tile information into one-dimensional distributions in θ (parallel to the electron/positron beams) and ϕ (around the circumference of the calorimeter barrel).

5.3 Global Level-1 Trigger

The Level 1 Decision and Data Flow Control system of the CLEO III Trigger produce and distribute a trigger decision every 42 ns based on input from the calorimetry and track-

ing subsystems described above. Programmable trigger decision boards (L1TR) monitor this information, and can be configured as desired to respond to a wide variety of trigger conditions. Tracking and calorimetry information is received and channeled through variable-depth pipelines to time-align the data; tracking is available in approximately $2\ \mu\text{s}$ while calorimetry requires over $2.5\ \mu\text{s}$. The time-aligned information is presented on a shared backplane, where several L1TR modules have access to the information for performing independent trigger condition evaluation.

All L1TR boards see the same input information on the Level-1 backplane. The Trigger Logic section allows the user to define 24 independent trigger “lines”, each a (potentially complex) combinatoric function of the 179 inputs. Each of the 24 trigger lines is routed through a 24 bit prescaler to a 40 bit scaler.

5.3.1 Trigger Lines

In the present mode of operation we typically run with a set of about eight trigger lines. The definitions of these lines and their relative rates are shown in Table 4. The total trigger rate at an instantaneous luminosity of $\mathcal{L} = 1 \times 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ is between 80 and 90 Hz depending on beam conditions. The “Barrel Bhabha” rate is about 20 Hz.

TABLE 4. Current definitions of the CLEO III trigger lines. Also shown are the prescale factors and the final rate of each line relative to the “Barrel Bhabha” line. Note that the lines are not exclusive, meaning the total rate will be significantly less than the sum of the individual rates.

Name	Definition	Prescale	Relative Rate
Hadronic	$(N_{\text{axial}} > 1) \& (N_{\text{CB low}} > 0)$	1	0.41
μ -pair	two back-to-back stereo tracks	1	1.40
Barrel Bhabha	back to back high showers in CB	1	1.0
Endcap Bhabha	back to back high showers in CE	8	0.23
electron + track	$(N_{\text{axial}} > 0) \& (N_{\text{CB med}} > 0)$	1	1.48
τ /Radiative	$(N_{\text{stereo}} > 1) \& (N_{\text{CB low}} > 0)$	1	2
Two Track	$N_{\text{axial}} > 1$	10	0.69
Random	random 1 kHz source	1000	1

5.4 Outlook

The function of the CLEO III trigger depends on getting sensible signals from the CLEO III drift chamber and calorimeter as well as from the CESR timing system. Since the inputs to the trigger will be unchanged during tau-charm running, the hardware will function as it does now.

The tracking trigger as presently configured is highly efficient for tracks with radius of curvature larger than 55 cm, which corresponds to a $p_T > 250$ MeV/ c at 1.5 Tesla. Although the average momentum of interesting tracks will be somewhat lower in CLEO-c than it was for $\Upsilon(4S)$ running (see Figure 6), this would be offset by the anticipated lower magnetic field of the detector solenoid.

The average shower energy will be lower in CLEO-c, making CC energy sharing among tiles potentially more important. Proper use of sharing makes the threshold turn-on curves significantly steeper allowing better threshold control. For the CLEO III running in the $\Upsilon(4S)$ region, we did not implement this feature because enabling inter-tile sharing among daughter boards caused significant timing jitter in the calorimeter trigger signals. During the recent installation shutdown we have modified the electronics boards to better balance the capacitance in the signal inputs. Preliminary cosmic ray tests indicate that these changes have significantly improved the time-alignment of the shared calorimeter trigger signals. This will be further studied using colliding beams, and we hope to start using sharing in the upcoming Υ resonance running. Some further minor modifications may be necessary to make this feature fully operational for CLEO-c running.

One hardware concern for the future is the lack of spare TPRO boards and the difficulties found with the present connection scheme of boards to backplanes. We hope to have sufficient spares and a new mating scheme before the start of CLEO-c running.

6 The CLEO III Data Acquisition System

6.1 Requirements

The CLEO data acquisition system consists of two equally important parts. The slow control system monitors the data quality and the detector performance while the data collection system is responsible for the data transfer from the front end electronics to the mass storage device.

The general requirements for the slow control and monitoring system are easy to define. The system has to provide sufficient flexibility to allow the detector experts to implement online data quality checks and monitor the performance of their detector component. Run control, alarm and message handling as well as calibration constants management are other important components of this part of the data acquisition system.

In order to establish the performance requirements for the data collection system we need to know the cross sections of the physics processes which CLEO-c will study as well as expected CESR luminosity. The key parameters for the DAQ system are the expected trigger rate, the acceptable detector dead-time as well as the average event size. These quantities constrain the read-out and digitization time of the front-end electronics as well as the data transfer bandwidth the data acquisition system has to provide.

The read-out time is defined as the time between the trigger signal and the end of the digitization process in the front-end electronic modules. For each event accepted by the trigger this causes dead-time and hence it is desirable to keep the read-out time as short as possible. An average read-out time of 20-30 μ s at a trigger rate of 1000 Hz would result in a detector dead-time of less than 3% which we consider acceptable.

The product of event size and trigger rate sets the scale for the data transfer bandwidth the data acquisition system has to provide. On the $\Upsilon(4S)$ resonance we observe an average event size of about 25,000 Bytes (Figure 22). Data from the silicon vertex detector and the RICH detector make up about half of that. As our understanding of the CLEO III detector improves we expect to see a further reduction in event size. While 15 - 20 kBytes/event are more likely we will for the following discussion assume a conservative average event size of 25 kBytes.

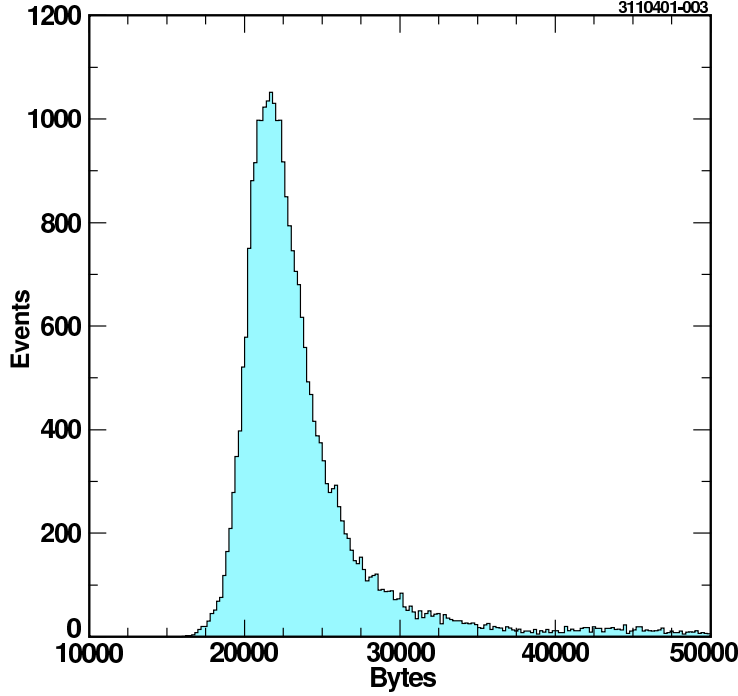


FIGURE 22. CLEO III Event size on the $\Upsilon(4S)$ Resonance.

The second ingredient necessary to define the data bandwidth requirements is the expected trigger rate. In order to get an estimate for this quantity we need to determine the relevant physics cross section and we need to make some assumption on the CESR luminosity. Being conservative in this case means to err on the high side so we will assume

$$\mathcal{L}_{inst}(\psi'') = 5 \times 10^{32} \text{cm}^{-2} \text{s}^{-1} \quad (1)$$

and

$$\mathcal{L}_{inst}(J/\psi) = 2.5 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}. \quad (2)$$

Using $\sigma(e^+e^- \rightarrow \psi'') = 10 \text{ nb}$ and 20 nb for the continuum cross section at 3.77 GeV we find

$$\sigma_{\text{Physics}} = 30 \text{ nb}. \quad (3)$$

The cross section for Bhabha scattering up to a maximum angle Θ_{max} is given approximately by [19]

$$\sigma_{\text{Bhabha}} \approx \frac{8\pi\alpha^2}{s} \frac{1}{(1 - \cos \Theta_{\text{max}})}. \quad (4)$$

For the CLEO III detector $\cos \Theta_{\max} = 0.93$, corresponding to a Bhabha cross section of 70 nb on the $\Upsilon(4S)$ resonance. This agrees well with our measured cross section of 67 nb. Scaling to $\sqrt{s} = 3.77$ GeV this yields

$$\sigma_{\text{Bhabha}} \approx 500 \text{ nb} . \quad (5)$$

The μ pair production cross section is

$$\sigma_{\mu} = \frac{86.8 \text{ nb}}{3.77^2} = 6 \text{ nb} . \quad (6)$$

Including a similar cross section for τ pair production as well as $\sigma_{\gamma\gamma} \approx 18$ nb we obtain a total cross section at the ψ'' energy of

$$\sigma_{\text{Total}} = \sigma_{\text{Physics}} + \sigma_{\text{Bhabha}} + \sigma_{\mu,\tau,\gamma\gamma} \approx 560 \text{ nb} \quad (7)$$

Machine related backgrounds are expected to be small compared to this. Only a small fraction of the Bhabha events will be needed for calibration purposes. Since the CLEO III trigger system provides the option to pre-scale individual trigger lines as function of the polar angle we expect that the majority of these events will not be read out. We estimate the effective cross section to be approximately 160 nb. At an instantaneous luminosity of $5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, this corresponds to a trigger rate of 80 Hz. Combined with the average event size of 25 kBytes this yields a required data transfer bandwidth of 2.0 MBytes/s.

At the lower energy of the J/ψ resonance the expected luminosity is a factor of two smaller but the cross sections are huge. While the Bhabha and μ pair cross sections scale with the square of the energy the e^+e^- annihilation cross section is significantly enhanced due to the presence of the resonance. The exact cross section depends on the beam energy spread of the accelerator. Using the anticipated energy spread of 8×10^{-4} at 3.1 GeV center of mass energy we find an effective J/ψ cross section of 900 nb. Combined with the other processes we assume a total cross section of 1000 – 1100 nb corresponding to a trigger rate of ≈ 250 Hz and a data transfer bandwidth requirement of 6.25 MBytes/s.

6.2 Current Performance

A block diagram of the CLEO III data acquisition system is shown in Figure 23.

For each event accepted by the trigger, approximately 400,000 detector channels have to be digitized. Front-end data conversion is performed in parallel and local buffers on each data-board hold the data for later asynchronous readout by the data acquisition system. Data sparsification is performed directly on the data-boards. The Data-Mover, a dedicated module in each front-end crate, assures transfer times below 500 μs and provides a second buffer level. Both Fastbus and VME are supported at this level. Approximately 30 front-end crates are needed for the CLEO III detector. Using inexpensive data links based on the Fast Ethernet protocol a fraction of the data is sent to a final trigger stage (Level 3) implemented in software on a fast workstation. The Level 3 decision is sent back to the front-end crates. Upon acceptance by Level 3, the event fragments are transmitted from the crates to the Event-Builder. Completely assembled events are transferred to mass storage and a fraction of the data is analyzed online by a monitor program to quickly discover problems with the CLEO III detector and to ensure the quality of the data written to tape.

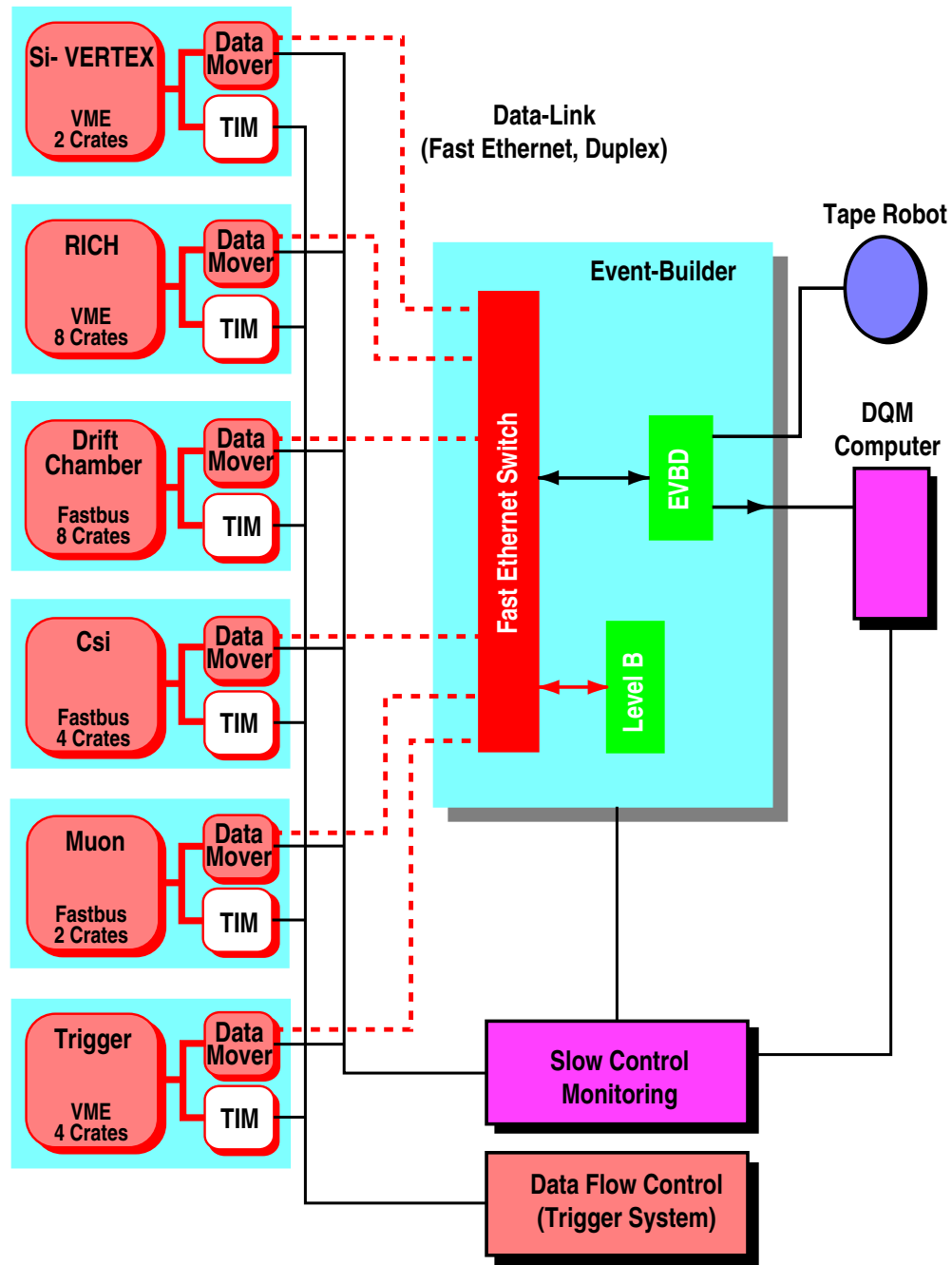


FIGURE 23. Architecture of the CLEO III Data Acquisition System.

The flow of event data through the data collection system is controlled by a simple control protocol. The basic philosophy is to re-arm the experiment to wait for the next trigger only when sufficient buffer space is available to receive a new event. In the architecture adopted for CLEO III this means a free slot at the data-board level.

Independent from the main data path, a slow control system monitors the individual detector components. Run control as well as the initialization of the detector sub-systems are also be part of slow control.

The CLEO III data acquisition system has been in operation since early 1999. With the exception of the maximum read-out rate, which we are not able to test with the current CESR luminosity, most parameters meet or exceed the original design goals. Some details are given in Table 5.

TABLE 5. Key Performance Parameters of the CLEO III DAQ System.

	Design Goal	Achieved Performance
Maximum read-out rate	1000 Hz	150 Hz (data taking) 500 Hz (random test trigger)
Average Eventsize	25 - 40 kBytes	25 kBytes
Average Read-Out Time	20 - 25 μ s	30 μ s
Data Transfer Bandwidth	4 MBytes/s	6 MBytes/s
Level 3 Throughput	1000 Hz	130 Hz

The readout induced detector dead-time for a trigger rate of 100 Hz is shown in Figure 24 confirming an average event readout time of approximately 30 μ s. The data transfer rate for a typical CLEO III run on the $\Upsilon(4S)$ resonance is between 2 and 3 MBytes/s (Figure 25).

In the current configuration the CLEO III data acquisition system can operate at trigger rates up to ≈ 150 Hz, significantly below the design rate of 1000 Hz. At recent CESR luminosities this bottleneck, caused by the Level 3 trigger software, is not a problem. A recent upgrade of the online computer facilities this past Summer as well as improvements to the Level 3 trigger algorithm(s) are expected to increase the maximum rate to 300 Hz. A potential problem at such high rates, namely the limited throughput of our Ethernet based eventbuilder, has already been addressed by the installation of a Gigabit Ethernet connection between the network switch and the main online computer. Should further increases in throughput become necessary, this can easily be accomplished by replacing the computer running the Level 3 software with a faster machine.

The main purpose of Level 3 is a reduction of beam gas and beam wall background events. During the last run on the $\Upsilon(4S)$ these events made up ≈ 50 % of the trigger rate. Due to the increased cross sections we expect a more favorable ratio of physics to background events for the upcoming runs on the narrow Υ resonances. We will study whether Level 3 is still useful.

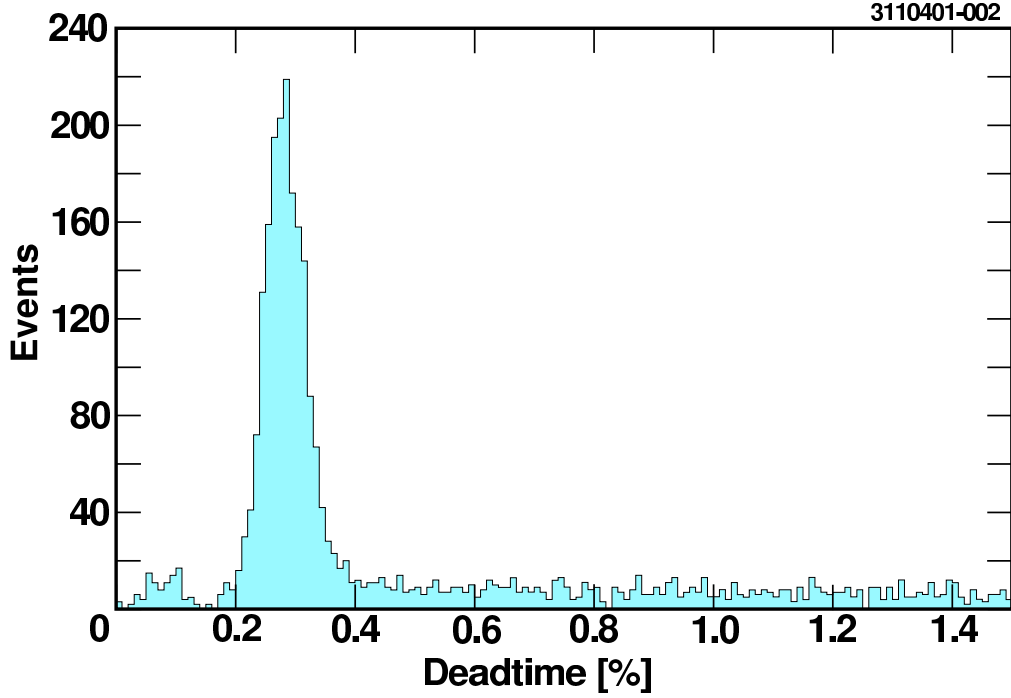


FIGURE 24. Read-out induced detector deadtime (in %) at a trigger rate of approximately 100 Hz.

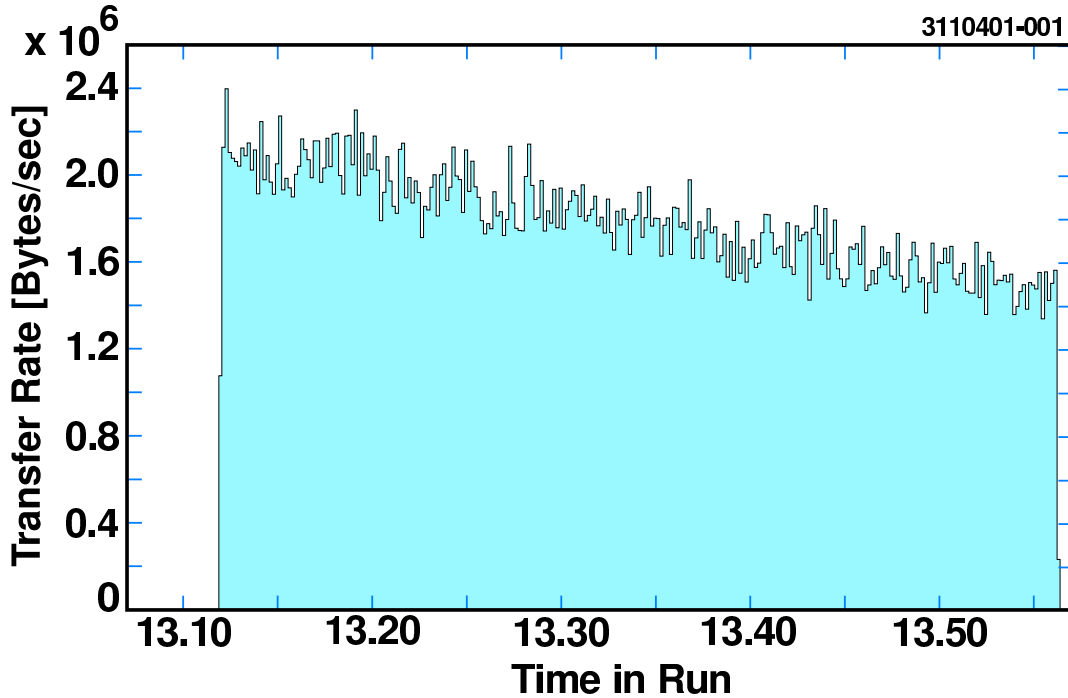


FIGURE 25. Data Transfer Rate (Bytes/s) during a typical CLEO III Datataking Run. The variations in Transfer Rate are due to changing beam currents.

6.3 Outlook

We can compare the performance the CLEO III data acquisition system achieved on the $\Upsilon(4S)$ resonance with the different requirements at a charm factory. Readout speed and

data transfer bandwidth will certainly be sufficient for the electroweak aspects of the CLEO-c program, as well as for running on the narrow Υ resonances. In the charm factory mode, CESR will operate with lower beam currents. Hence we expect this background rate to be significantly reduced and a software trigger processor such as Level 3 will be obsolete. These statements, of course, depend heavily on beam and vacuum conditions and we will certainly maintain the capability to operate Level 3 should that become necessary.

The large physics cross section on the J/ψ resonance poses special problems. Assuming a 1 MeV beam energy spread, and the PDG values of $\Gamma_{tot} = 87 \text{ keV}$, $B(\psi \rightarrow e^+e^-) = 6\%$, the effective production cross-section of $\sigma = 1 \mu\text{barn}$, corresponding to a 110 Hz rate at $L = 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. As noted in other sections, this corresponds to collecting $\sim 10^9 J\psi$ events in a run of roughly six months. This rate has already been achieved and is comfortably under the DAQ design specification of 1 kHz, allowing a large margin for the unforeseen. Unlike the situation at the $\Upsilon(4S)$, the typical event from the DAQ stream will be a physics quality event with typical event size. This will result in 1-2 % read-out related detector downtime, which we consider acceptable. The situation is helped some if we replace the silicon vertex detector with a new wire vertex chamber, as outlined in Section 2.2.2. Assuming an event size of 12 KByte for J/ψ running predicts an average throughput rate to tape of 1.3 MBytes/sec, compatible with our current disk and tape writing technology. Further, several straight forward and inexpensive upgrade options exist, so the DAQ system should require no major upgrade for any of the CLEO-c program.

One area in which CLEO III is vulnerable is its shortage of spare readout components, particularly TDCs, which read out the CsI calorimeter, the muon system and the drift chamber(s), and Fastbus crate hardware. We hope to augment our supply of these prior to CLEO-c running.

7 Computing in the CLEO-c Environment

For most of the physics program of CLEO-c the computer needs will not be significantly larger than for running in the Υ energy region. Periodic upgrades of hardware and software would continue to be needed, as would additional storage capacity for the new data collected and processed. On the other hand, running on the narrow J/ψ resonance and collecting on the order of 10^9 events poses special problems in processing, storing, analyzing and simulating the data.

7.1 Processing and Storage of Data

The overwhelming majority of events taken at the J/ψ will be “interesting” and worthy of further analysis. The event sample to be stored and analyzed will therefore remain close to the target figure of 10^9 events. At the $\Upsilon(4S)$ the interesting physics cross section is much lower and backgrounds account for the vast majority of events taken. Over the last year of $\Upsilon(4S)$ running, CLEO has stored some 0.8×10^9 events, with a total of roughly 25 TB written to tape. Therefore, the raw data storage requirements for the proposed J/ψ running are comparable to what we have already proven capable of handling. The retrieval pattern for this data for the processing (*i.e.*, getting physics quantities from the raw information)

will no doubt be different in that a greater fraction of events get fully analyzed, and therefore less I/O bandwidth might be required for an equal amount of processing. This means that we do not require any new technologies, and that an extension of currently used methods will be sufficient.

The 10^9 events are not very useful if we cannot process them in a timely fashion. Taking into account the background events in the recent $\Upsilon(4S)$ data sample and our ability to quickly sort out calibration events such as Bhabha scattering, we project we will process 2×10^8 physics events in 16 weeks using our present capacity (120 Netra boxes). The J/ψ sample will have five times this data sample, but with somewhat lower event multiplicities. Given the increase in processor speed that is foreseen between now and taking the data set, we have every indication that a new farm with a number of nodes comparable to the current farm should complete the processing of the full data set in a year.

Typically we store “hot” processed information (*i.e.*, most needed and useful quantities) on disk and keep all the information in “cold” storage on tape. The lower multiplicity at the J/ψ will lower our requirements, and we could certainly store all J/ψ “hot” processed output on disk. This will become less expensive over time as the price of disk space falls. Note that although the price of disk space decreases, the raw disk access speed is not increasing as rapidly, meaning that a system that parallelizes the storage over many disks will be highly desirable.

Assuming the size of the cold storage remains at 80Kbytes/event, we will need a further 80 Terabytes of storage for this information. In a few years, tapes capable of holding more than 100 Gigabytes should be available. The full cold storage could then be kept on ~ 800 such tapes. We would need to purchase a sufficient number of robots to store these tapes.

7.2 Analysis Issues

CLEO-c analysis projects undertaken with the J/ψ data will consist of the more traditional “bump hunting” and partial wave analyses. We must be set up to allow both to continue.

The ideal target is an analysis system allowing users to work within only one analysis environment, freeing them from having to code in, for instance, both C++ and PAW. This analysis system is envisioned to appear interactive like an enhanced PAW session connected to the data. The underlying code will have to be smart enough to optimize caching for iterative calculations, making storage and memory issues transparent to the physicist.

A partial wave analysis will require two steps: 1) identification of interesting events, and 2) iterative minimization to identify the correct partial waves. Typical decay modes of the J/ψ occur with a branching ratio of 10^{-3} , meaning that a fully identified decay sample will typically contain 10^6 events of interest. However the number of events with the same number of final particles reached through difference resonances will undoubtedly be large, and we should plan on being able to handle some 20×10^6 events in any user’s analysis.

With so many events in the original sample, and assuming a 1 millisecond access time per event (somewhat faster than at present) in the data set, a first pass through the full data to create an interesting event list will typically take 12 days on one machine, assuming that the disk access is the limiting factor.

The next step in a typical partial wave analysis will require iterative minimization, with perhaps 100 passes through the data to complete the minimization. At 1 millisecond access

time per event in the 20 million event skim sample, one such minimization step will take 5 hours on one computer, and the full 100 steps will take 23 days on one computer for one analysis! Because the above has assumed that the disk access time is the limiting factor and not the CPU power, it is clear that caching management and disk allocation will have to be optimized. Since the typical analysis can be broken up as shown above into an identification and a fitting step, and the fitting step requires access to only the four-vectors of the handful of particles in the final decay mode, much can be gained by locally storing only the interesting four-vectors and not the detector response. In the alternate scheme of RAM storage, each minimization step could be done much faster than in the disk based scheme. But in either case, a non trivial effort will be required to set up the optimal analysis environment. Caching of event information in a convenient and transparent way for the user will require significant development effort, including more personnel devoted to this development.

If a typical turn around time of 1 day is required for analysis, and CLEO will have perhaps three such analyses being conducted simultaneously, an analysis farm of approximately 100 CPUs will be necessary. This also makes it clear that tools allowing real time monitoring of analyses will be essential. The size of this farm, the amount of data that it must be able to look at, and the analysis style will all influence the most appropriate network hardware and topology. This issue will have to be addressed in conjunction with the analysis software design.

7.3 Monte Carlo Issues

The aspect of simulation requires careful review. We certainly need to be able to generate fully simulated J/ψ signal events in large numbers, which alone requires a farm of CPUs. A much larger farm will be needed if we also must generate statistically significant generic J/ψ and uds decays that are fully simulated in the CLEO III detector. A simulation package that uses functional parameterizations of detector response would be much faster to generate and easier to store; however this will require having a very detailed knowledge of the CLEO III detector performance.

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