CESR and CLEO

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1 Introduction

Most of us have looked at the spectacular pictures taken by the Hubble Space Telescope. Galaxies, nebulae, super novae—but there is something peculiar about these images. Where ever we look in space we only see matter. No significant quantities of anti-matter have been found. Because we believe equal amounts of matter and anti-matter have been produced originally, we must conclude that there is an asymmetry between particle and anti-particle decays. Or, in quantum mechanical terms, we say that the CP symmetry is broken.

While it was observed in the laboratory more than 30 years ago, understanding CP violation has been hard on both theorists and experimentalists. For years, there has been great hope in our community that the B meson system will offer a cleaner environment to study this phenomenon. Accelerators have been upgraded and new detectors have been constructed. If you are willing to stretch it a bit, this conference marks the beginning of the Golden Age of B physics. The next generation of experiments is coming online, and a new window to study CP violation is opening up.

The overall effect we are looking for is rather small. Large data samples will be required and so the first question to ask is: Where to "B"? In order to set the scale, we will consider measuring CP violation to 10% accuracy. It turns out that for a certain parameter—$\sin(2\beta)$—this requires a few hundred $B \to \psi K_s$ events. However, these have to be fully reconstructed and the flavor of the decaying b quark has to be tagged. If we fold in branching fractions, efficiencies, *etc.* we find that about 3×10^7 $B\overline{B}$ events will be needed. Such data samples can be generated in different ways, for example, in e^+e^- annihilations on the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ is the first $b\overline{b}$ bound state heavy enough to decay to a pair of B mesons. CLEO, BaBar, and Belle are using this mechanism, which offers a fairly clean environment with a signal to noise ratio of 1 to 3. At design luminosities, 2 to 3 $B\overline{B}$ pairs are generated per second, so it will take about a year of running to accumulate sufficient data to perform a 10% measurement of CP violation—assuming for the moment that the Standard Model predictions are correct.

Orders of magnitude more *B* mesons are produced in hadronic interactions at the Tevatron and at HERA. At the Tevatron, the production rate is as high as 20 KHz, but the interesting events are hidden in 10 MHz of background. In either scenario, there is also substantial background from real but less interesting $b\bar{b}$ events.

2 The CESR storage ring

For the rest of the talk I will focus on CESR and CLEO—the grandparents of all *B* factories. CESR is the Cornell electron positron storage ring. Operations started more than two decades ago, and over the years we have enjoyed a steady increase

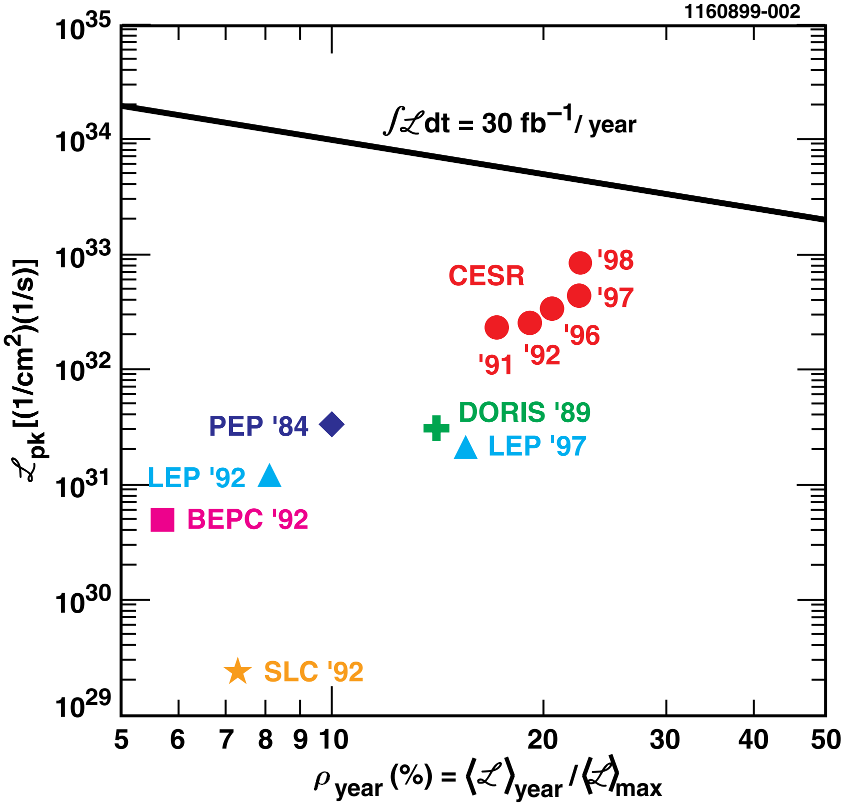

Figure 1: Peak performance versus the ratio of integrated luminosity delivered per year to the maximum luminosity.

in peak luminosity. This year an instantaneous luminosity of 8.5×10^{32} cm^{-2}s^{-1} was reached. The CLEO experiment tries to collect as much of this data as possible. The current data sample is just shy of 14 fb^{-1} and contains $\approx 10^7$ $B\overline{B}$ events. We are excited about CESR's peak performance, but more important than that is integrated luminosity which in the end is what generates physics results. Efficiency and stability of operations contribute to the integrated luminosity just as much as the peak performance. As shown in Fig. 1, this is another area where CESR shines. The figure shows the ratio of integrated luminosity delivered per year to the maximum luminosity one would get by running the entire year at peak instantaneous luminosity. Year after year CESR has the highest scores. The line shown in Fig. 1 has to be reached to perform the 10% CP violation measurement mentioned earlier in just one year. Nobody said that this would be easy.

CESR is constantly upgraded to further increase its performance and reliability. Most notably, we have replaced all RF cavities with 4 single cell super conducting cavities. This not only allows us to increase the beam current to 1 A and eventually to shorten the bunch length, but it also reduces the impedance, which is important to avoid beam instabilities. Early next year, we plan to install a pair of new super conducting quadrupoles near the interaction point that will allow us to reduce β^* from 18 mm to 12 mm. With this configuration, we are confident that we will reach an instantaneous luminosity of 2×10^{33} cm^{-2}s^{-1} some time during the next year.

3 The CLEO III detector

In order to take advantage of the increased luminosity delivered by CESR, we had to rebuild the CLEO experiment. Figure 2 shows a schematic view of the new CLEO III detector. The magnet, the muon system, and the CsI calorimeter are basically the same as in CLEO II. The readout electronics has been upgraded to support higher data rates. The entire inner detector is new. Starting from the center, we have a beryllium beampipe of 2.2 cm radius, a four layer silicon vertex detector, a drift chamber, and a ring imaging Čerenkov detector (RICH). The solid angle coverage is 93%. CLEO operates with a magnetic field of 1.5 T. In the following sections, I will discuss some of the detector components in greater detail. Wherever possible, I will try to motivate our design choices with some physics results obtained by the CLEO II experiment.

3.1 Charged particle tracking

Even in the next generation of detectors, charged particle tracking will remain the most important tool in event reconstruction. The average charged multiplicity in

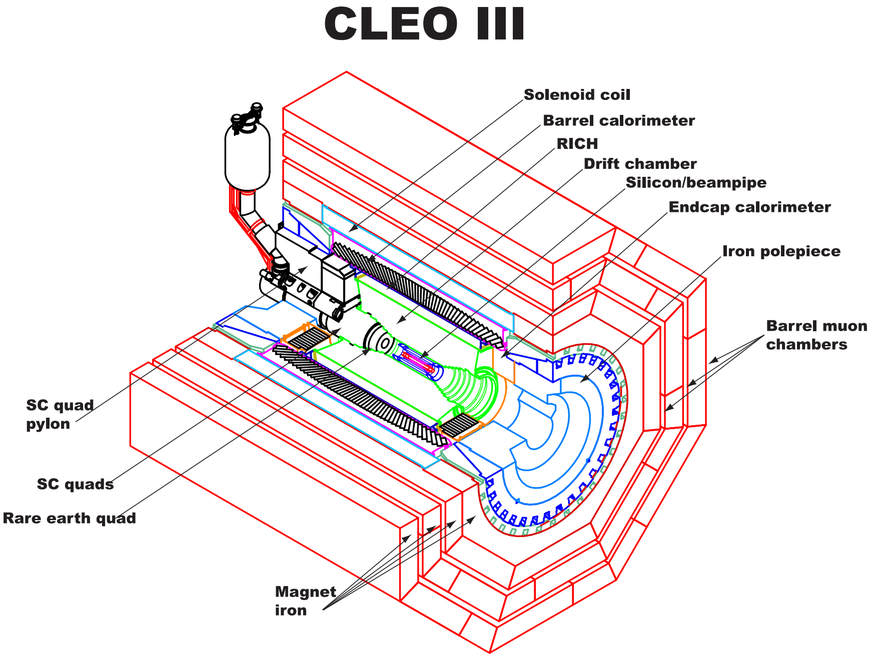

Figure 2: Schematic view of the CLEO III detector.

an $\Upsilon(4S) \to B\overline{B}$ event is not that high, about 10. Typical momenta are around 700 MeV/c, but for several important physics topics we require tracking at 100 MeV/c and below. At these momenta, multiple scattering is an important contributor to the overall resolution. For CLEO III, the challenge is even larger because, compared to the previous detector, the tracking volume is significantly reduced by the RICH.

Drift chamber

In order to maintain sufficient momentum resolution, we focused on reducing multiple scattering. First, we removed any structural support from the inner skin of the drift chamber. A 2.5 mm Rohacell cylinder with $X_o < 0.15\%$ provides the gas seal. Further improvements were obtained by replacing the standard CLEO chamber gas—Ar-Ethane (50:50)—with a lighter, helium based mixture. By switching to He-Propane (60:40) we could double the radiation length of the chamber gas. We operated the CLEO II drift chamber with this mixture for more than 3 years, and the results were excellent. Most notably, due to the reduced Lorentz angle, single wire efficiencies improved significantly near the edge of the drift cells.

At smaller radius, the chamber design has to be compatible with the final focus quadrupoles of the storage ring that are now closer to the interaction point than ever before. The CLEO III drift chamber accommodates the machine elements with a staggered inner section of 16 axial layers followed by 31 stereo layers. The end plates have a conical shape and are made of 0.6” aluminum. The chamber includes 9796 drift cells in total.

Silicon vertex detector

Reducing multiple scattering recovered some, but not all of the momentum resolution lost due to the smaller tracking length. Adding a silicon vertex detector insures that the CLEO III momentum resolution is as good or better than CLEO II. With symmetric beam energies, it will be a challenge for CLEO to see the *B* vertex, but *B* factories are also excellent charm factories. At this conference, CLEO presented some exciting new results on $D^0 - \overline{D}^0$ mixing that were only made possible by the use of vertex information provided by a silicon detector.

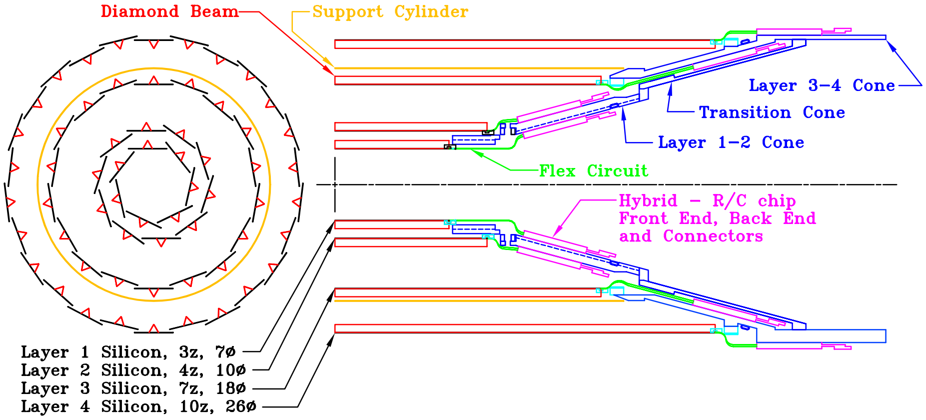

Figure 3: Schematic view of the CLEO III silicon vertex detector.

The CLEO III vertex detector consists of 4 layers of double sided silicon strip detectors. The mechanical structure is shown in Fig. 3. Much effort was spent to keep the amount of material at a minimum. Inside the fiducial volume we have only active elements and minimal support, consisting of a carbon fiber tube between the outer two layers and support beams made out of CVD diamond for each ladder. There are no support structures outside of layer 4, which greatly simplifies track matching between the vertex detector and the drift chamber. In order to simplify design and construction, all 447 silicon sensors are identical. The wafers are 300 μm thick and measure 27.0 by 53.2 mm^2. Up to five sensors are bonded together to form half-ladders. A complete ladder in the outermost layer is more than 50 cm long.

The readout electronics is mounted on beryllium oxide hybrids mounted on copper cones which also provide cooling. The entire device generates about 400 W. The transitions between the sensors and the electronics are provided by flex cables wire-bonded at each end. The readout electronics itself is radiation hard up to 100 kRad. We use a custom designed preamplifier chip that is based on the Viking design. The ADC, sparsification and I/O logic are derived from the SVX II chip. Bias voltages are applied through special RC chips. The readout chain is operated with a rather long shaping time of 2 μs. Even in the worst case, the noise is less than 1000 enc resulting in an excellent signal to noise ratio of better than 20:1 even for the z-readout of the outermost layer.

3.2 Neutral particle reconstruction

So far, we have focused on charged particles, but for many interesting questions neutral particles like photons and π^0's are just as important. One of our goals is the determination of the CKM matrix elements. One of these elements, V_{cb}, describes the transitions between a b and a c quark. It has been reasonably well measured, but the results are model dependent. There is, however, a special case where the theory is deemed reliable. In semileptonic $B \to D^*$ transitions at maximum momentum transfer, the D^* meson moves with the same velocity as the B. If you now consider the light degrees of freedom, the quarks and gluons whirling around the heavy quark, you realize that for them nothing has changed when the b quark turned into a c quark. One source of a color field has been replaced with another. The form factor describing this transition is absolutely normalized to 1 and V_{cb} can be extracted from the differential decay rate.

While the theoretical predictions are clean at maximum momentum transfer, we have to overcome serious experimental difficulties. At CLEO, the B mesons are produced almost at rest and hence the interesting D^* mesons are at rest as well. The momenta of the pions from the $D^{*+} \to D^0\pi^+$ decays is therefore very small. It is very difficult to track charged pions that do not move, so this method of determining V_{cb} usually requires an extrapolation to maximum momentum transfer. This causes additional systematic uncertainties. With an electro-magnetic calorimeter of sufficient energy resolution and granularity, it should be possible to try the same analysis with π^0's instead of charged pions. As proof of the principle, Fig. 4 shows a CLEO analysis of $B \to D^{*0}\ell\nu$ transitions with the neutral pion decaying at rest.

Aside from a few minor modifications, the CLEO calorimeter has not been changed. It contains 7800 CsI crystals, and at 1 GeV, achieves an energy resolution of 2% with an angular resolution of 4 mr. In approximately 10 years of

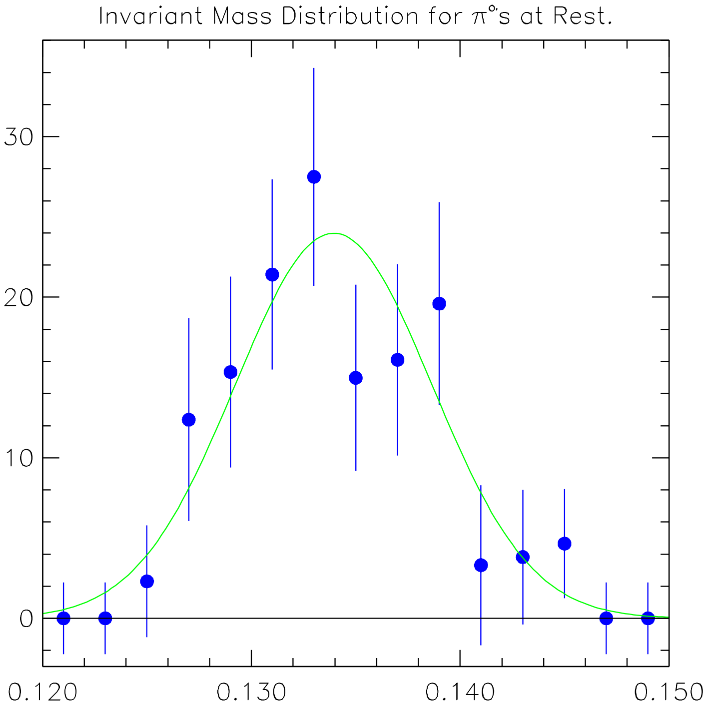

Figure 4: Invariant mass of neutral pions decaying at rest.

operation, no significant radiation damage has been observed. CLEO pioneered the use of high resolution CsI calorimeters, which are now in use in all *B* factory experiments.

3.3 Particle identification

Good particle identification, in particular pion-kaon separation is very important for the next generation of *B* physics experiments. All three collaborations made significant investments in elaborate particle identification systems. CLEO chose a ring imaging Cherenkov detector (RICH). The basic principle of a RICH detector is shown in Fig. 5. A charged particle traverses a radiator and—if fast enough—produces Čerenkov photons. Through an expansion volume, these photons travel along a cone to a photon detector. With a sufficient number of photons registering in the detector, the Čerenkov angle, θ_C, and hence the particle's velocity can be reconstructed. For the photon detector, CLEO uses a TEA/CH_4 based proportional chamber with pad read-out. TEA is only sensitive to photons in the ultra violet (135 - 165 nm) forcing us to use UV transparent CaF_2 windows and LiF

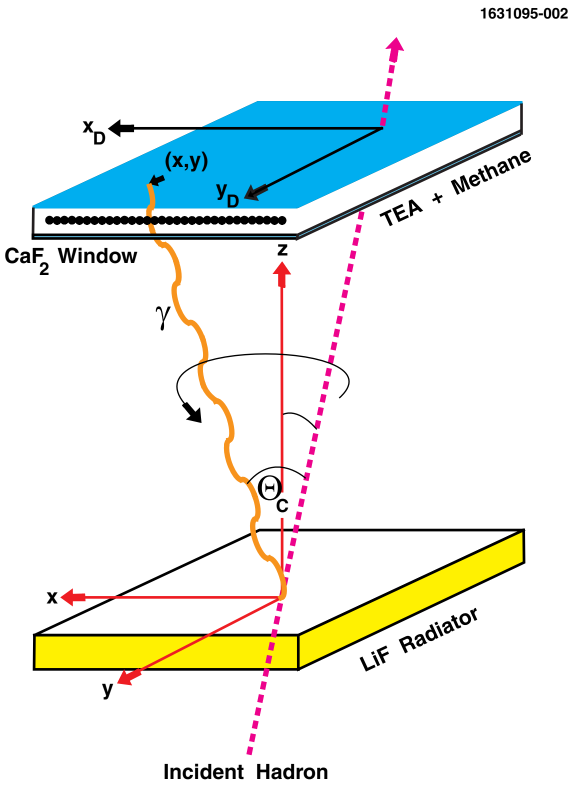

Figure 5: Principle of a RICH detector.

radiators. Each of the 420 radiators is $17.5 \times 17 \times 1$ cm^3 in size. While most of them have a planar surface, 120 radiators use a saw-tooth pattern to avoid losses due to total internal reflection in the central part of the detector. The expansion volume between the radiators and the photon detectors is 16 cm wide and filled with pure nitrogen. Photons are detected by 230,000 pads, each with an area of 8×7.5 mm^2. Custom designed pre-amplifiers based on the Viking design are mounted directly on the detector chambers. Based on preliminary results, we detect on average 14 Čerenkov photons per track, which leads to a Čerenkov angle resolution of 4 mr.

4 Summary and outlook

I would like to conclude this talk about CLEO's and CESR's future with a look back at our long history. The CLEO experiment started more than 20 years ago. It is probably the longest-lived collaboration in the history of high energy physics. As shown by the time line in Fig. 6, these have been exciting years with many im-

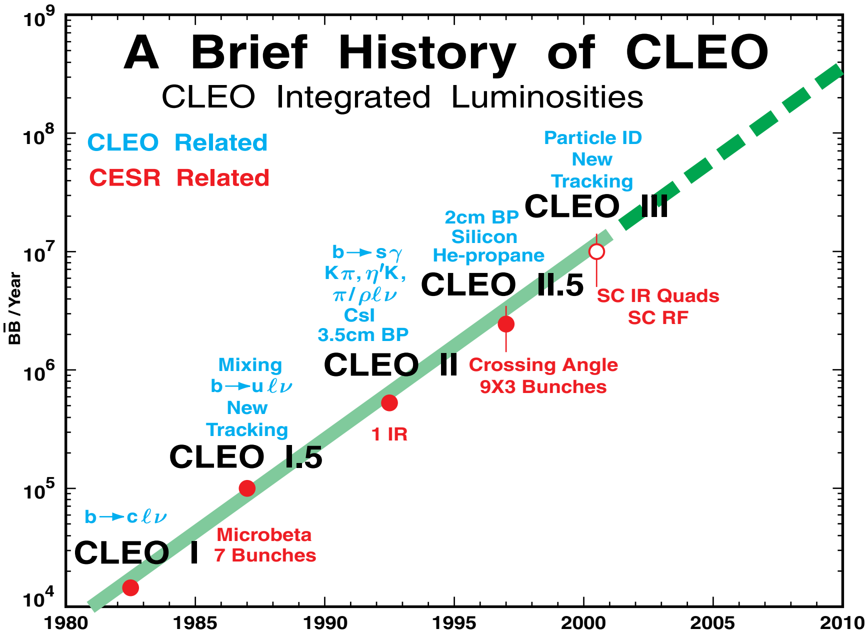

Figure 6: History of the CLEO experiment.

portant physics results. Major upgrades of both the detector and the accelerator allowed us to remain competitive throughout the years. With the storage ring achieving even higher luminosities and with the improved detector, we are confident that we can maintain this position for years to come, and we are looking forward to the friendly competition with Belle and BaBar. The next years promise to be very interesting for heavy flavor physics.

5 Further reading

More detailed information on CESR, its current status, and our upgrade plans can be found at the CESR web site (http://w4.lns.cornell.edu/public/CESR/), which also provides links to the recent articles by S. Henderson (CBN 99-28) and by S. Peck and D. Rubin (CBN 99-16). More information on the new CLEO III detector can be found at the CLEO collaboration web site (http://w4.lns.cornell.edu/public/CLEO/).