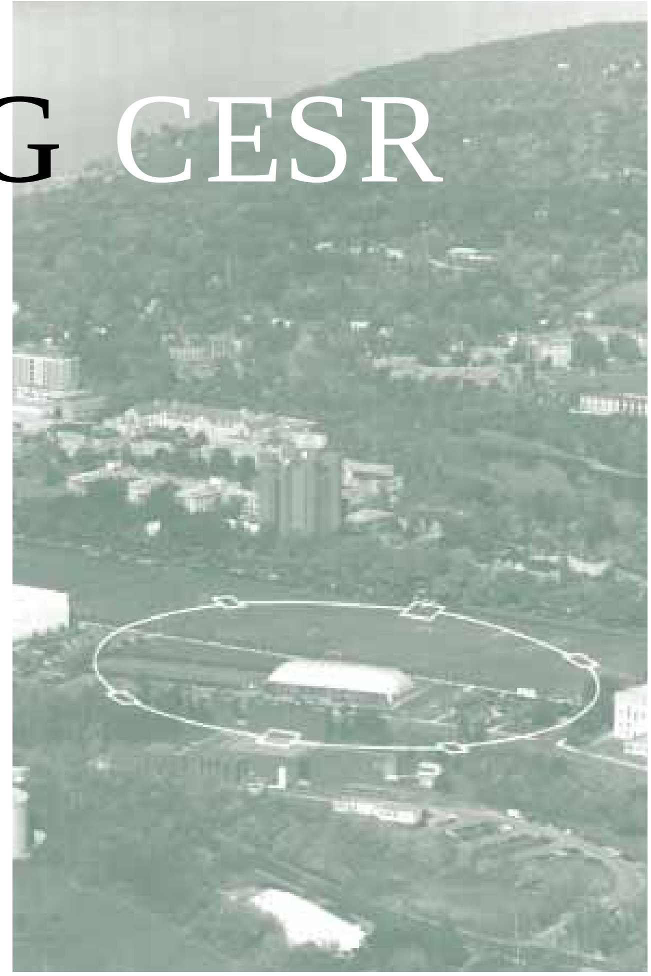
UPGRADING CESR

by KARL BERKELMAN



Experimental sensitivity to rare decay processes will be greatly increased by the upgrade of the Cornell Electron Storage Ring and its detector facility.

The Two Frontiers

OUR PRESENT PARTIAL UNDERSTANDING of the physical world is embodied in the Standard Model. It relates the behavior of matter in all its forms to the properties of a few fundamental constituents—the six kinds of quarks and six kinds of leptons. It unifies the phenomena of electromagnetism, weak decays, and the strong interaction that binds hadrons and nuclei, and explains them in terms of the exchange of several kinds of intermediate vector bosons—the photon, the *W* and *Z*, and the gluon. It successfully correlates the results of many experiments. But it is widely recognized as being incomplete.

How do the elementary constituents get their masses, and why do they have those particular masses? How does gravity relate to the other forces? Why are there six flavors of quarks and leptons, and are the quarks and leptons really fundamental or are they composites? What is the mechanism for the small violation of particle-antiparticle symmetry (*CP* violation) observed in *K* meson decays, and how did matter win out over antimatter in the Universe?

To answer these questions theorists have suggested various extensions to the Standard Model. These typically involve hypothetical particles that have not yet been discovered: heavier quarks and leptons, heavier copies of the *W* and *Z* intermediate bosons, Higgs bosons, supersymmetric partners of the known particles—squarks, sleptons, and so on.

Aerial view of the Cornell University campus, indicating the location of CESR, forty feet below the intramural athletic fields.

Why haven't we seen any of these particles? Maybe it is because they are unstable and decay too rapidly. So instead of looking for such a particle in the wild, we can try to create it at an accelerator. For the direct production of such new particles, the energy of the collision has to be far enough above the Mc^2 threshold for the creation of the new mass M. New particle production has historically been a successful route to exploration of new physics as frontier accelerator facilities have opened up new energy ranges. Here are a few examples, involving the discovery of the antiproton and of some particles containing heavy quarks.

$pp \rightarrow ppp\bar{p}$	Bevatron	1956
$e^+e^- \rightarrow \psi$	SPEAR	1974
$e^+e^- \rightarrow B\bar{B}$	CESR	1980
$pp \rightarrow t\bar{t}N^*\bar{N}^*$	Tevatron	1995

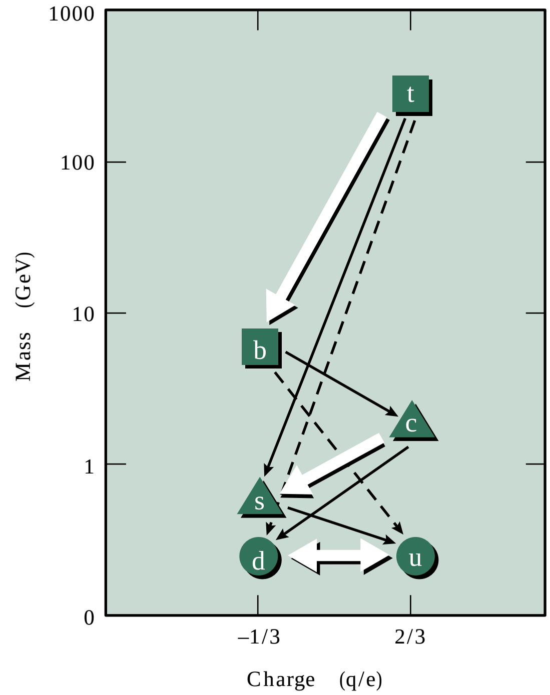
This is in fact the prime motivation for the next generation of accelerators—the Large Hadron Collider at CERN in Geneva, Switzerland, and the next linear e^+e^- collider wherever it may be built. But exploring new physics at the energy frontier is expensive, requiring billions of dollars for the accelerator and for the experiments.

But there is another way. The Heisenberg Uncertainty Principle allows the momentary occurrence of an unstable high-mass particle in an intermediate stage of a multistep process even when the total energy available is less than the Mc^2 of the free particle. A familiar example is the evidence for the Z that came from mu-pair production experiments at the PETRA e^+e^- collider in Hamburg, Germany. Although the total energy was 45 GeV, the effect of the 91 GeV Z could be seen clearly in the forward/backward asymmetry caused by the interference of the usual $e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-$ amplitude and the $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$ amplitude. In this way the Z mass was estimated before the Z was first produced and detected in the UA1 experiment at the CERN proton-antiproton collider.

Exploring high masses with lower energies gets you early access to new phenomena. But that doesn't make it easy. You have to understand the Standard Model prediction well, and your experiment has to be sensitive to small rates or accurate enough to detect small deviations from the predictions. Instead of the *energy frontier*, we might call this the *sensitivity frontier*. They are complementary. The sensitivity frontier is where you can get the first indication of new physics, and the energy frontier is where you make the more definitive explorations of the new phenomena.

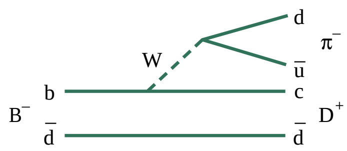
RARE *B* MESON DECAYS

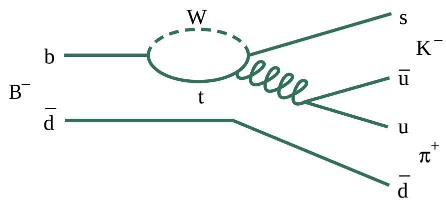
B mesons are made of one b quark and one ordinary $\bar{u}$ or $\bar{d}$ antiquark. The rates for their decays are sensitive to the presence of high mass particles in intermediate states. To see why this is so, I first have to explain how quarks decay.



The masses and charges of the six quarks. The arrows show the allowed flavor changing direct weak decay transitions with the relative probablilities indicated.

The illustration above shows the six quarks in mass versus charge. They are paired in three doublets of charge $(-\frac{1}{3}, \frac{2}{3})$: (d,u), (s,c), and (b,t). In the weak decay process a heavier quark can transform into its lighter partner by emitting a W boson that can subsequently materialize as a lepton pair or quark pair. There is also a smaller probability for decay to a quark in a different doublet.





Feynman diagrams for two B meson decay processes. A diagram represents the propagation and interactions of particles in space and time, with time plotted horizontally and a space coordinate vertically. The diagram on the top shows an example of a favored direct decay of the B meson, $B \rightarrow D\pi$, in which the b quark emits a W boson and becomes a c quark. The W becomes a quark-antiquark pair. The diagram on the bottom shows an example of a rare two-step decay, $B \rightarrow K\pi$, in which the b quark first becomes a t quark by emitting a W boson and then reabsorbs the W to become an s quark. Another quark-antiquark pair is produced through an intermediate gluon.

These relative probabilities are suggested by the widths of the arrows in the figure on the previous page. They are called the "flavor-changing charged-current" decays.

Consider the case of the b quark. A decay to its heavier partner, the t, would violate energy conservation. The other two possiblilities, decay to c or u, have low rates because c and u are outside of the (b,t) doublet. As an alternative to these direct processes involving a change in the charge of the quark, the Standard Model also predicts a two-step process that results in a quark transition with no charge change, that is b-to-s (or $-d$) (see diagrams on the left). In these effective "flavor-changing neutral-current" decays the b makes two successive charge changing transitions, becoming a quark of the other charge (u or c or t) in the intermediate stage. The W boson that is emitted in the first step is reabsorbed in the second. The momentary violation of energy conservation in the intermediate stage considerably depresses the transition rate, but since the direct rate is also suppressed, the two-step b-to-s (or $-d$) decays have a chance to compete with the direct b-to-c (or $-u$) modes. The two-step flavor-changing neutral-current decays have been called "loop" or "penguin" decays. The latter name was invented by John Ellis of CERN, who had to pay off a debt by getting the word "penguin" published in *Phyical Review Letters*.

An analogous two-step process is responsible for the transition that can convert a $b\bar{d}$ neutral B meson into its $\bar{b}d$ antiparticle. The intermediate stage again involves the W and a quark of the other charge. When two of these processes—direct decay, penguin, particle-antiparticle oscillation—produce the same final state, the interference of the two amplitudes can lead to a violation of the particle-antiparticle symmetry called *CP*. *CP* violation has been seen in K decays and it is expected in B decays. One must either measure an asymmetry between the rates for some B meson decay mode and its corresponding antiparticle mode, arising from interference between the direct and two-step decays, or one must observe an asymmetry in the time evolution of of the decays of originally produced B^0 and $\bar{B}^0$, arising from an inteference between the $B^0 \leftrightarrow \bar{B}^0$ oscillation and the direct decay (see the article by Michael Riordan and Natalie Roe in the *Beam Line*, Vol. 26, No. 1, Spring/Summer 1996).

The first clear evidence for a penguin decay, $B \rightarrow K^*\gamma$, was reported by the CLEO experiment at CESR in 1993 (see the figure at the top of the next page). The quantitive comparison with theory had to wait until the next year's publication of the CLEO measurement of the inclusive branching fraction $(2.3\pm0.7)\times10^{-4}$ for the radiative B to any single- or multiparticle strange meson state $B \rightarrow X_s\gamma$, and for the recently completed Standard Model calculation, which predicts a compatible $(3.3\pm0.4)\times10^{-4}$.

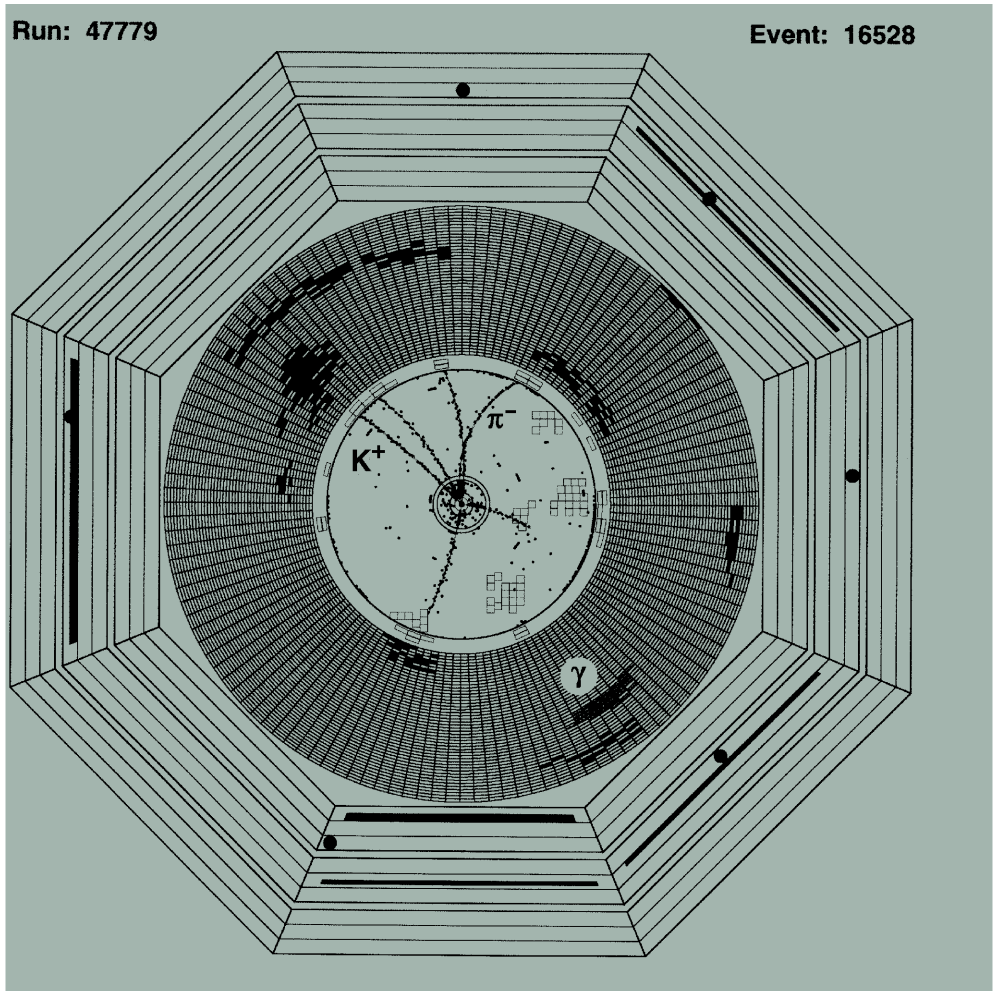
Why all this interest in penguins? It is because some hypothetical massive particle representing a new extension of the Standard Model could replace one of the particles in the intermediate loop stage. The agreement between the CLEO data and the Standard Model prediction already places strict limits on possible new physics. For instance, if you added just a charged Higgs boson to the Standard Model, $M_{Higgs}c^2$ would have to be greater than 260 GeV to keep the $B \rightarrow X_s\gamma$ prediction compatible with the data. It is remarkable that the limit set by a *sensitivity* frontier experiment at the CESR 5 GeV storage ring can be very much more stringent than the limits of around 70 GeV set by the searches for charged Higgs production at the LEP *energy* frontier.

CLEO has seen evidence for other possibly penguin-dominated decays: $B^0 \rightarrow K^+\pi^-$ or $\pi^+\pi^-$, $B^- \rightarrow \omega K^-$ or $\omega\pi^-$, and similar final states without c quarks. The $K^+\pi^-$ mode is especially interesting, because of a possible *CP*-violating asymmetry between this rate and the $K^-\pi^+$ rate. So far, measurements of rare B meson processes—penguin decay rates as well as particle-antiparticle asymmetries—have not shown any deviation from the predictions of the Standard Model at the levels of accuracy implied by the rather sparse data samples available. Maybe they will, once we are able to produce more B mesons and reliably identify the rarest decay processes. These are the main motivations for the CESR/CLEO upgrade.

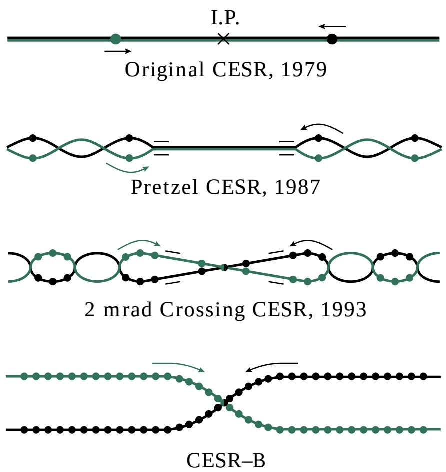
THE CESR UPGRADE

Our ability to observe rare events in CESR depends on its luminosity. If we think of colliding particles in terms of the cross-sectional area each presents to the other, then the rate for a particular collision reaction is the product of the cross section, measured in cm^2, and the luminosity of the storage ring facility, measured in units of cm^{-2} seconds^{-1}. You might expect the luminosity of CESR to vary as the product of the e^+ and e^- beam currents and inversely as the transverse area of the interaction region, but because the beam-beam interaction tends to increase the beam overlap area, the luminosity is proportional to only one power of beam current. For flat beams the other important factors are the vertical "depth of focus" β^* at the interaction point and the vertical beam-beam tuneshift parameter ξ, a measure of the beam density.

Over the 17 years that CESR has been operating, the accelerator physicists at Cornell have brought the β^* and ξ parameters pretty close to their limiting values. The only opportunity for major gains in luminosity is storing larger beam currents. In the original CESR design there was just one circulating bunch of particles in each beam. Instabilities, however, limit the amount of charge that one can stuff into a single bunch,



A computer reconstruction of a rare B decay event in the pre-upgrade CLEO-2 detector. The beam axis is in the center, perpendicular to the page. The cylindrical cesium iodide scintillation counter array is represented in a tunnel view to display the hit counters (in black). This event was one of 13 such events that heralded the discovery of penguin decays. It is interpreted as $e^+e^- \rightarrow B^0\bar{B}^0$ followed by $B^0 \rightarrow K^{*0}\gamma$ (the penguin decay) and $\bar{B}^0 \rightarrow D^+\rho^-$ (a more conventional kind of B decay). The K^*, D, and ρ mesons are also unstable and decayed immediately, as indicated.



Electron and positron beam orbits in the vicinity of the collision point in four configurations. From the top down they are the original CESR single-bunch configuration; the pretzel scheme with head on collisions; the upgrade pretzel with collisions at an angle; and a two-ring configuration. The drawings are not to scale.

so we had to find a way of circulating many bunches. In 1982 we considered a two-ring setup but opted instead for Raphael Littauer's single-ring scheme, in which the beams are separated by electric fields into two "pretzel" orbits that weave back and forth across each other. Multiple beam bunches can be cleverly spaced so that opposing bunches always miss each other except at the desired collision point. By 1991 the pretzel had produced a record luminosity of 2×10^{32} with seven bunches of particles in each beam.

We then revived the old two-ring plan as a way of storing even larger beam currents, but with the additional idea from Pier Oddone of Lawrence Berkeley National Laboratory that separate rings would allow one to store electrons and positrons with different energies. The asymmetric collision would boost the produced *B* mesons in the direction along the more energetic of the two beams. As Riordan and Roe explain in their *Beam Line* article, this would make it easier to see the time evolution of the decays, thus facilitating the observation of *CP* violation with neutral *B*'s. But CESR lost out to PEP2 in the competition for Department of Energy support, so the asymmetric *B* Factory is being built at SLAC (also at KEK), and the Cornell collider will remain a single ring with both beams at the same energy.

The Cornell accelerator physicists got to work immediately on their alternate plan, suggested by Robert Meller. In this scheme the two beams collide at a 0.23 degree angle to each other instead of head on, thus allowing up to 45 bunches to circulate in each pretzel orbit without interference. The bunches are not uniformly spaced but travel in nine trains, with up to five bunches per train. The bunches in a train are separated by 4.7 meters, while the trains repeat every 86 meters. Several modifications of CESR are necessary.

Electrostatic separators. The charged deflection plates that direct the electrons and positrons into their separate orbits had to be reconfigured in order to make the beams collide at an angle.

Final focus. The array of quadrupole focusing magnets on both sides of the crossing point had to be shortened and strengthened in order to accomplish the focusing in a distance less than the spacing between successive beam bunches. The first stage of this has been completed, to allow a bunch spacing of 9.3 meters. Superconducting magnets are now being constructed to permit 4.7 meter spacing.

Multibunch feedback. Wake fields trailing an intense electron or positron bunch can deflect the following bunches. Pickups sense the horizontal and vertical transverse motion of each bunch. High-power wide-band amplifiers feed the appropriately phased signals to deflection plates to restore the bunches to their correct orbits. This system is now operational. A future system will also damp longitudinal bunch excursions.

Vacuum system. Electrons and positrons traveling in magnetic fields emit X rays. This synchrotron radiation liberates gases from the vacuum chamber walls and causes severe heating. Chambers, pumps, valves, and other components have to be upgraded in order to keep the residual gas pressure low for good beam lifetime and low experiment backgrounds.

Radiofrequency system. The radiated energy must be replaced in microwave cavities. These have traditionally been copper cells with shapes optimized to give the maximum accelerating electric field with minimum power dissipated in the walls. Unfortunately this optimization helps the cavity to resonate at frequencies higher than the fundamental accelerating mode. The wake fields of intense beam bunches passing through the cavities excite these higher modes, wasting power and destabilizing the beam. Although feedback can increase the stable beam current limit, we can raise the limit much more effectively by eliminating the higher modes in the cavities. This is done by making them out of superconducting niobium cooled to liquid helium temperature. Since practically no power is dissipated in the walls, one has the freedom to optimize the shape to suppress higher modes. Moreover, since less power is wasted, fewer cavities are needed. Replacing the present 20 cells of copper cavities in CESR with 4 new supeconducting cells will greatly increase the maximum stable beam current. The prototype cavity performed successfully in CESR; the first production cavity will be installed in 1997; three more will follow later.

The table at the top of the page lists the performance goals for the upgrade. The components already installed permit the ring to operate routinely now with 18 bunches per beam and a peak luminosity 4×10^{32}. If all goes well, the remaining upgrade modifications for 45 bunches per beam will be ready for installation in 1998.

THE CLEO UPGRADE

The CLEO collaboration comprises 209 members from 24 universities, from Harvard to Hawaii. The present CLEO-2 detector started operating in 1989. The illustration on page 24 shows the layout of components, including silicon and multiwire drift chambers for charged particle tracking, scintillation counters to measure time-of-flight, a cesium iodide scintillation counter array for photon shower detection, a 1.5 Tesla superconducting solenoid coil, and a muon detector interleaved with magnet iron. CLEO-2 represents the state of the art in detection efficiency and energy resolution for charged particles and photons.

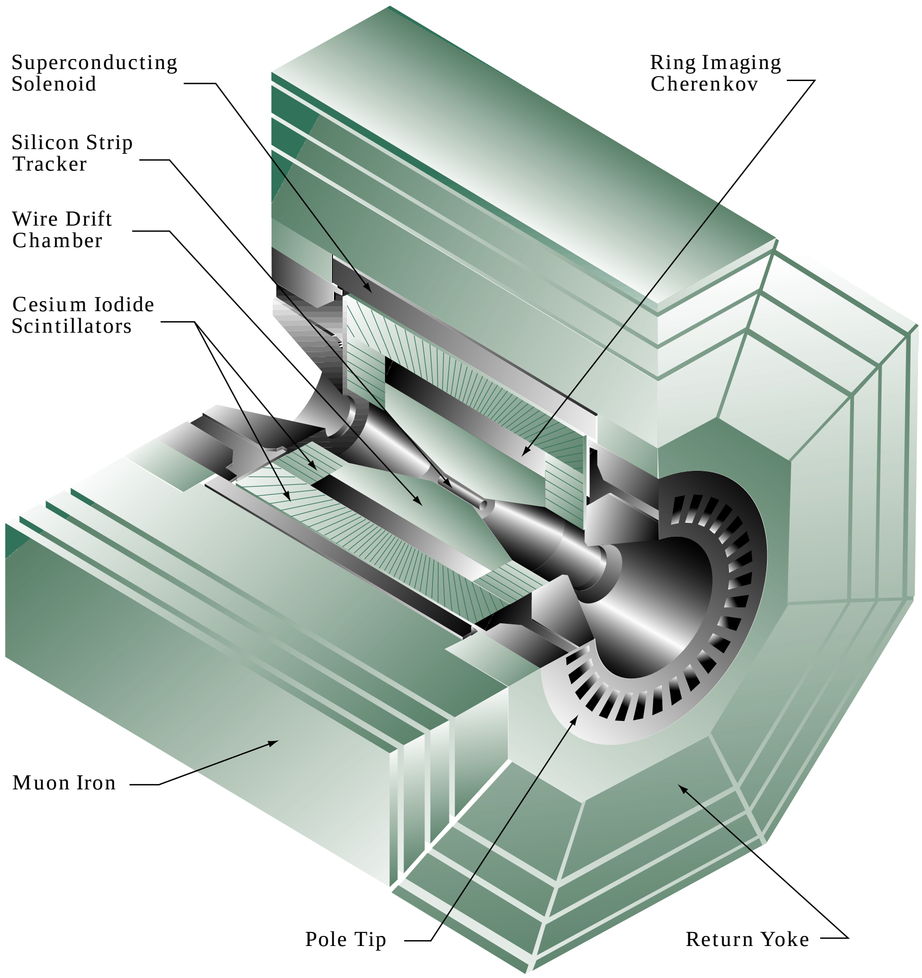
Although electrons and muons of all momenta are distinguished by interactions and penetration, the identification of pions, kaons, and protons has to rely on velocity measurements, combined with the momentum determined by the track curvature in the magnetic field. The velocity-dependent drift chamber ionization and the time-of-flight measurement suffice for particles with momenta below about 0.8 GeV/c, but at the higher momenta the ionization is only slightly dependent on particle velocity, and the flight times are indistinguishable. However, the rare *B* processes of interest produce kaons and pions with momenta up to 2.6 GeV/c, and to cover this momentum range we will have to use the velocity dependence

Goals for the Upgraded CESR

Beam energy	E = 5.3 GeV
Circumference	C = 768 m
Luminosity	L > $1.7 \times 10^{33}/cm^2 s$
Number of bunches per beam	n_b = 45
Current per beam	I beam > 0.5 Amp
Vertical beam-beam tune shift	$\xi > 0.03$
Vertical depth of focus at IP	β^* = 1 cm
Number of rf cells in ring	n_c = 4
Total accelerating voltage	V_c = 7.2 MV
Total rf power	P_{tot} = 1.4 MW

The CLEO Collaboration

SUNY Albany	Cal Tech	Carleton
Colorado	Cornell	Florida
Harvard	Hawaii	Illinois
Kansas	McGill	Minnesota
Ohio State	Oklahoma	Purdue
Rochester	UC San Diego	UC Santa Barbara
SLAC	Southern Methodist	Syracuse
Vanderbilt	Virginia Tech	Wayne State



A cut-away view of the upgraded CLEO-3 detector. The axis of symmetry in the middle is the electron-positron beam line.

The Upgraded CLEO-3 Detector

Tracking		
double-sided silicon layers		4
drift chamber layers:	axial	16
	stereo	31
r.m.s. $\delta p_T/p_T$ at $p_T = 2.5$ GeV/c		0.5%
r.m.s. resolution in dE/dx per track		6%
acceptance solid angle		95%
High momentum π, K, p identification		
average photoelectrons per track		>12
K/π separation, standard deviations		>3.5
acceptance solid angle		80%
Electromagnetic calorimetry		
number of CsI scintillators		7800
r.m.s. $\delta E/E$ at $E = 2.5$ GeV		2%
acceptance solid angle		98%
Muon identification		
iron & proportional tubes		

of the angle of emision of Cherenkov light by the particles.

Adding a Cherenkov light detector to the CLEO detector without rebuilding the very expensive cesium iodide array and solenoid magnet means giving up some of the space now used for tracking. What's more, the present drift chamber occupies some of the space needed for the upgraded CESR quadrupole focusing magnets. To recover the resolution lost by downsizing the tracking chamber, we decrease its mass, thereby reducing the scattering of the particles, and we supplement the drift chamber by a more extensive silicon multistrip tracker near the beam pipe.

The CLEO-3 upgrade therefore consists of the following major new components: a ring-imaging Cherenkov detector using a lithium-fluorine radiator and a TEA photon converter with wire-and-pad readout; a downsized multiwire drift chamber with helium-based gas and thin end plates; a four-layer double-sided silicon microstrip detector, and faster trigger and data acquisition electronics.

Construction is proceeding on each of these systems with the goal of being ready for 1998 installation. The table at the left shows some specifications and projected performance figures for the upgraded detector.

The three rival detectors, CLEO, BaBar, and Belle, at the CESR, SLAC, and KEK colliders respectively, will have many similarities, but each will have its own advantages. In the CLEO detector the unboosted *B* decay products all have momenta below 2.6 GeV/c, thus making energy measurements more precise and the velocities of the different particle species more easily distinguishable. Since the *B*'s will not be boosted along the beam line, fewer decay products will be lost in the undetectable low-angle cone near the beam direction. On the other hand, since the *B*'s are produced almost at rest in the symmetric CESR collisions, the observation of the time evolution of the decays, while not impossible, will not be as straightforward as in the asymmetric B Factories. But that is just one of the potentially crucial experiments that might expose the shortcomings of the Standard Model. CLEO will have a good chance at other CP violation measurements and will contribute to the measurement of rare decay rates. No one knows where the payoff in new physics will come.

As CLEO has benefited from the rivalry with the ARGUS experiment at DESY, experimenters now look forward to friendly competition with the asymmetric B Factories.