# The Allure of Luminosity

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2003 年 5 月 20 日

Luminosity to an experimental physicist is like mother's milk to a new-born baby. Given enough, they are cheerful, content, and full of smiles; deprive them, and they are ill-tempered and very apt to cry. At KEK these days, there are lots of smiling and contented physicists from Belle. Without any additional information, you can be confident that KEKB must be reaching excellent levels of luminosity.

Last October, the total integrated luminosity collected by the Belle detector passed 100 *inverse femtobarns*, and the total number of B-meson/antiB-meson pair events accumulated during the two years of KEKB/Belle operation exceeded 100 millions. For an old-timer in this field, these numbers are staggering. It was only twenty years ago that we were digging for the first evidence for B mesons with the CLEO detector at the Cornell Electron Storage Ring (CESR). Then, after months of running, we accumulated a grand total of one single inverse *picobarn* ( 0.001 inverse femtobarns ) of integrated luminosity. With this, we were just barely able to make out the Upsilon(4S) resonance (see Fig. 1). The small excess events that made up the first evidence for the Upsilon(4S) signal contained only a few hundred B-meson pair events.

Now that Belle has a hundred inverse *femtobarns*, we have 100,000 times as much data as we had in those early days at CLEO. In those simpler times, in our very best days we accumulated 60 inverse *nanobarns*, an amount of data that Belle collects every 10 seconds. The results of a few hours of scanning across the Upsilon(4S) resonance at KEKB gives the results of Fig. 2, which the reader can compare to the first CLEO signal in Fig. 1, which was accumulated over many months. This is unbelievable progress for only two decades.

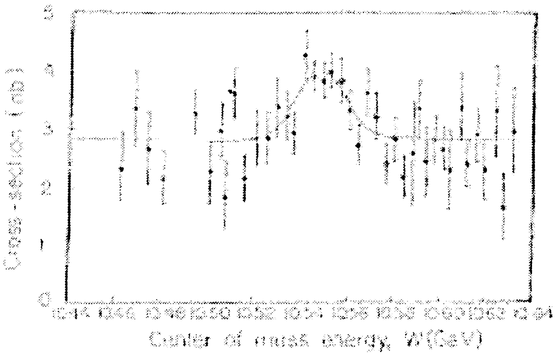

図 1: Energy scan at $\Upsilon(4S)$ for CLEO in 1980. It took many months to accumulate these data.

Also impressive, but perhaps not on such a grand scale, has been the improvements in detector capabilities. In the original CLEO detector, charged-particle tracking was done inside of a large solenoidal electromagnetic coil, and all other measurements were done outside of the coil. As a result, only those particles that penetrated the coil cleanly — i.e. without interacting or scattering in the coil's material — and entered the limited coverage of our external detection devices could be identified as leptons, pions, kaons or protons. Because of this, we only knew what about 10% of the particles in an event were. Gamma detection was primitive. The gamma-ray energy resolution was about 30%, and that was achieved only for the small fraction of gamma rays that made it cleanly through the coil. Now Belle routinely identifies 90% of the produced particles and detects gammas with

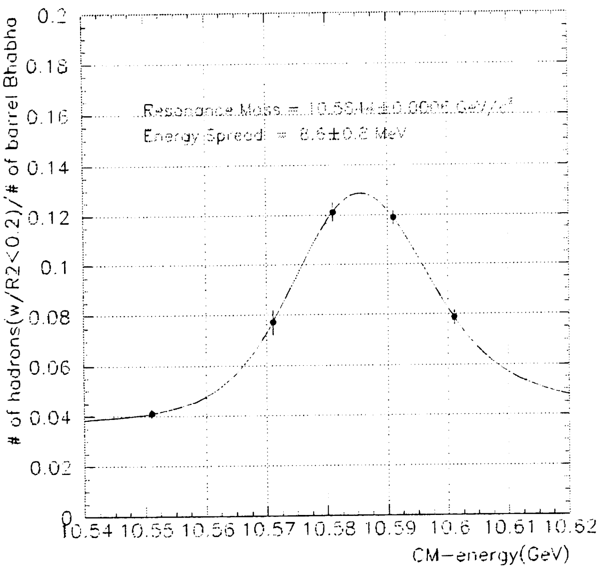

図 2: Energy scan at $\Upsilon(4S)$ for Belle. These measurements were made in a few hours.

exquisite ( 2%) energy resolution.

What drove such extraordinary progress? The answer is simple: the Physics.

In the early days at CLEO, we were carefully watched by a visitor from Rockefeller University — a theorist named Tony Sanda — who was relentless in his encouragement (and his criticism). While we were struggling to see indirect traces of B mesons — we didn't fully reconstruct a B meson decay for another three years — Sanda was urging us to look for B-meson oscillations to antiB-meson and CP violations. Even an optimist like Sanda knew that these measurements would require thousands of times the data samples we were accustomed to and detectors with ten times better performance than we knew how to build.

As we learned more about B mesons, their allure became intoxicating, even to thick-headed experimentalists. We knew well that in the decades of the 1950's and 60's, the neutral K mesons provided the most important keys to the weak interactions: strangeness (our first sign of the existence of flavors); parity violation; $K^0$-$\bar{K}^0$ mixing; CP-violation; and the absence of flavor-changing neutral currents. The B meson system promised similar opportunities — if only we could make them in sufficient number and detect them with good efficiency.

Progress was rapid. Luminosities increased and detectors improved. By 1987, CESR and the Doris storage ring (at DESY) had learned to use multiple bunches and smaller beam sizes, thereby increasing the luminosity by nearly a factor of a hundred. The ARGUS group at DESY devised a detector that did particle identification and gamma detection inside their magnetic coil, thereby greatly improving the quality of the recorded data. These improvements quickly paid off: ARGUS discovered B-antiB oscillations in 1987. Also around that time, CLEO observed the first example of the "golden mode" decay $B \to KJ/\psi$ that Sanda had identified as the key to understanding CP violation. However, at the luminosities available then, only a handful of golden mode decays were observed per year; serious CP studies requires thousands of these events. Thus, SLAC and KEK started developing plans for the very high luminosity PEPII/BaBar and KEKB/Belle "B-factory" facilities.

Sure enough, with data samples another factor of a hundred larger and with high quality detectors, both BaBar and Belle were able to detect the strong signals for CP violation in the B meson system that Sanda predicted some twenty years earlier. The first conclusive measurements of particle-antiparticle asymmetries in the decays of neutral B mesons, reported by both groups in Summer 2001 (see Fig. 3), was the first successful observation of CP violation outside of the neutral Kaon system after forty years of intensive searches, and a dramatic confirmation of the Kobayashi-Maskawa theory. Belle has now even seen CP violations in the very rare decay channel $B \to \pi^+\pi^-$ (see Fig. 4); these decays, which only occur about once in a million B meson decays, provide detailed checks of the KM theory.

Thanks to the very high luminosity provided by KEKB, Belle has been able to isolate small samples of B decays that proceed via the flavor-changing-neutral-current quark level process $b$-quark $\to$ $s$-quark + $\mu^+$ + $\mu^-$. This process, which is forbidden in standard decay processes, can occur when the b-quark spontaneously fluctuates into a W boson and a t-quark via the Quantum Mechanical process illustrated in Fig. 5. Since the W boson and the t-quark are much more massive than the b-quark (by factors of 20 and 40, respectively) such fluctuations strongly violate the conservation of energy and, according to the Heisenberg Uncertainty Principle, can only exist for very, very short times. As a result,

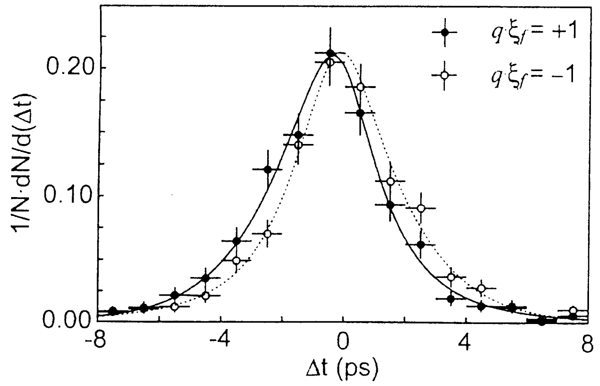

図 3: Decay time distributions for $B \to J/\psi K_S$ (○) and $\bar{B} \to J/\psi K_S$ (●). The difference between the two distributions is evidence for CP violation.

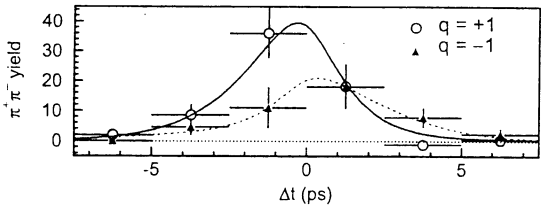

図 4: $B^0 \to \pi^+\pi^-$ yields with $B^0$-tag (▲) and $\bar{B}^0$-tag (○). Here again differences appear between B and anti-B meson decays.

these decays are extremely rare.

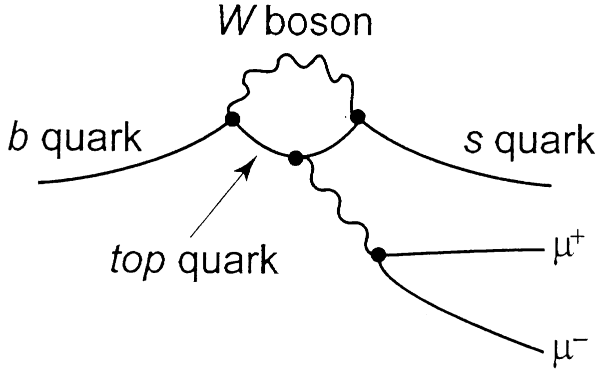

図 5: The $b \to s\mu^+\mu^-$ process occurs via the quantum mechanical fluctuation shown in this figure. (Physicists refer to this as a "Penguin Process.")

However, the same thing that makes these "platinum-mode" decays very rare, also makes them very interesting. Many theories predict new particles with masses comparable to those of the t-quark and W boson. Such particles would have to contribute to $b \to s\, \mu^+\mu^-$ decays and, if their masses are of the same scale as the t-quark, as many theorists believe, their effects will be large and clearly observable. So, just as a few thousand golden mode $B \to J/\psi K_S$ events allowed us to establish matter-antimatter asymmetries, a few thousand of these platinum decays would clearly show effects of new physics if it exists.

Now, however, even with KEKB's world record luminosity, we only find a handful of these events per year. This is enough to establish that these decays exist, but not enough for the detailed studies that could indicate the existence of new particles. To really exploit the physics opportunities provided by B mesons, we need even larger data samples and, so, the luminosity frontier has to be pushed forward by another factor of a hundred or so — i.e. a Super KEKB, and a detector with greatly improved performance — a Super Belle. This is a huge challenge for the KEKB/Belle team. But, like before, the physics case is compelling and, so, I'm sure that somehow we'll find a way to do it.