CLEO B Physics

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Active and friendly competition with the ARGUS Collaboration was an important chapter in the history of the CLEO Collaboration. In this talk, I will discuss some of my impressions of the CLEO B physics program, which – not only for the purpose of the ARGUS Symposium – can conveniently be divided into three periods or efforts: before $B^0\bar{B}^0$ mixing, studying $B^0\bar{B}^0$ mixing, and after $B^0\bar{B}^0$ mixing. My emphasis is on CLEO's insights, turning points, interactions with ARGUS, and measurements that are still competitive in the B Factory era.

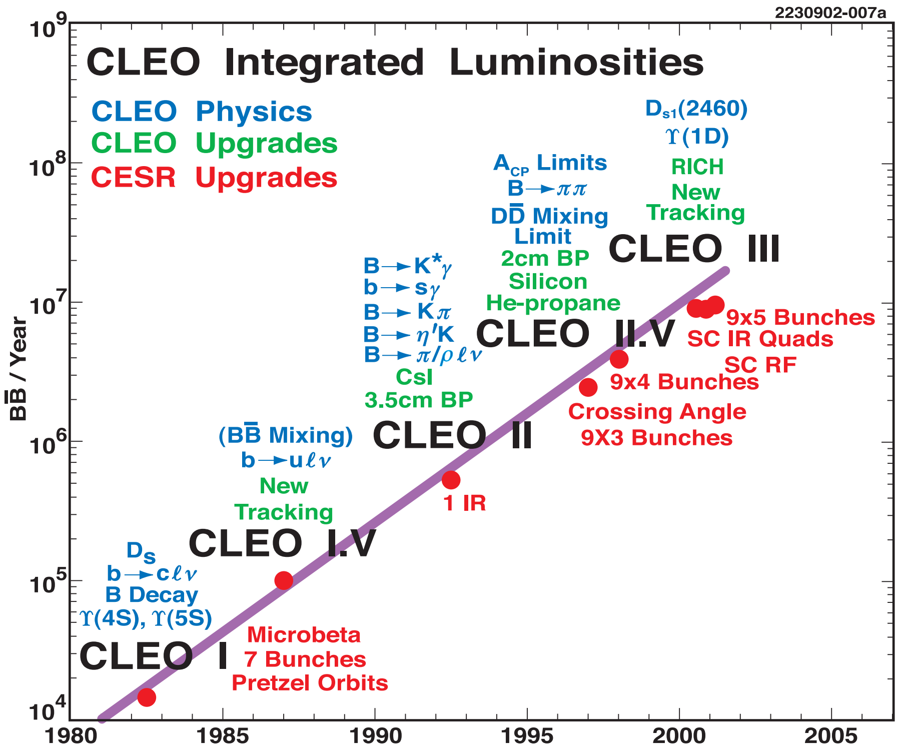

FIGURE 1. Graphical history of CLEO integrated luminosity, detectors, and the results of the CLEO B physics program. The physics results were all discoveries or co-discoveries except for ($B^0\bar{B}^0$ Mixing) which – as everyone at this symposium knows – was a confirmation following the discovery by ARGUS.

1 Overview

The CLEO Collaboration took data in the Υ energy region at the CESR storage ring from 1979 to 2003. Many of the important discoveries and measurements of CLEO during that period are illustrated in Fig. 1, which emphasizes the CLEO B physics program. The CUSB collaboration took data simultaneously with CLEO from the beginning through the early CLEO II period. CUSB published results simultaneously with CLEO for several of the earliest discoveries and measurements. Other important CLEO results from the Υ period include Υ, D, τ, and QCD measurements, as well as the first observation of about 2/3 of the known charmed baryons. From 2003 to 2008, CLEO took data in the charm threshold region. Results of the CLEO-c physics program include: first observations of $h_c(^1P_1)$ and f_{D^+}; confirmations of $\eta_c(2S)$ and $Y(4260)$; and precision measurements of f_{D_s}, M_{D^0}, and M_η; precision absolute hadronic branching fractions of D^0, D^+, and D_s^+; precision measurement of η branching fractions: and precision measurements of D^0 and D^+ semileptonic branching fractions. To date (March 2008) CLEO has published or submitted for publication 468 articles in refereed journals. A total of 211 graduate students completed Ph.D. theses with CLEO data and 30 Cornell graduate students in accelerator physics based their theses on work they did at CESR. Much more information on the history of CLEO and the CLEO physics program is available in a monograph by Karl Berkelman [1].

The CESR storage ring is illustrated in Fig. 2 along with two Cornell accelerator innovations that contributed significantly to the almost exponential increase in integrated luminosity for CLEO illustrated in Fig. 1. These innovations were pretzel orbits, invented by Raphael Littauer (1983), and bunch trains, invented by Robert Meller (1990). These innovations involved separating the electron and positron orbits at the points where parasitic collisions of multiple bunches would otherwise occur and beam-beam interactions would limit luminosity. Electrostatic separators introduced horizontal betatron oscillations that – of course – were of opposite sign for the two beams. LEP and LEP II also utilized these inventions, which contributed to the success of the LEP physics programs.

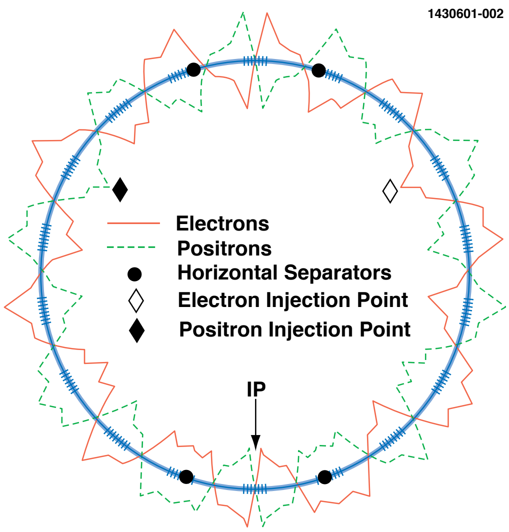

FIGURE 2. (Left) the CESR tunnel with CESR on the right and the 10 GeV synchrotron, which is used as an injector for CESR, on the left. Boyce McDaniel, the director of the Cornell laboratory during the construction and early operation of CESR and CLEO, is standing next to CESR. (Right) an illustration of pretzel orbits and bunch trains in CESR, with betatron oscillations greatly exaggerated. The locations of the bunch trains are illustrated by the small tick marks at the maxima of the betatron oscillations.

The CLEO I [2] and CLEO II [3] detectors are illustrated in Fig. 3. The CLEO I detector was a first-generation detector with particle identification (dE/dx measurements or Cherenkov radiation detectors) and electromagnetic calorimetry outside of the solenoidal magnet coil. The ARGUS detector [4] was superior to the CLEO I detector, which provided several advantages for the ARGUS physics program. With the CLEO II detector, CLEO pioneered the utilization of CsI for electromagnetic calorimetry, a technique that BaBar and BELLE now use.

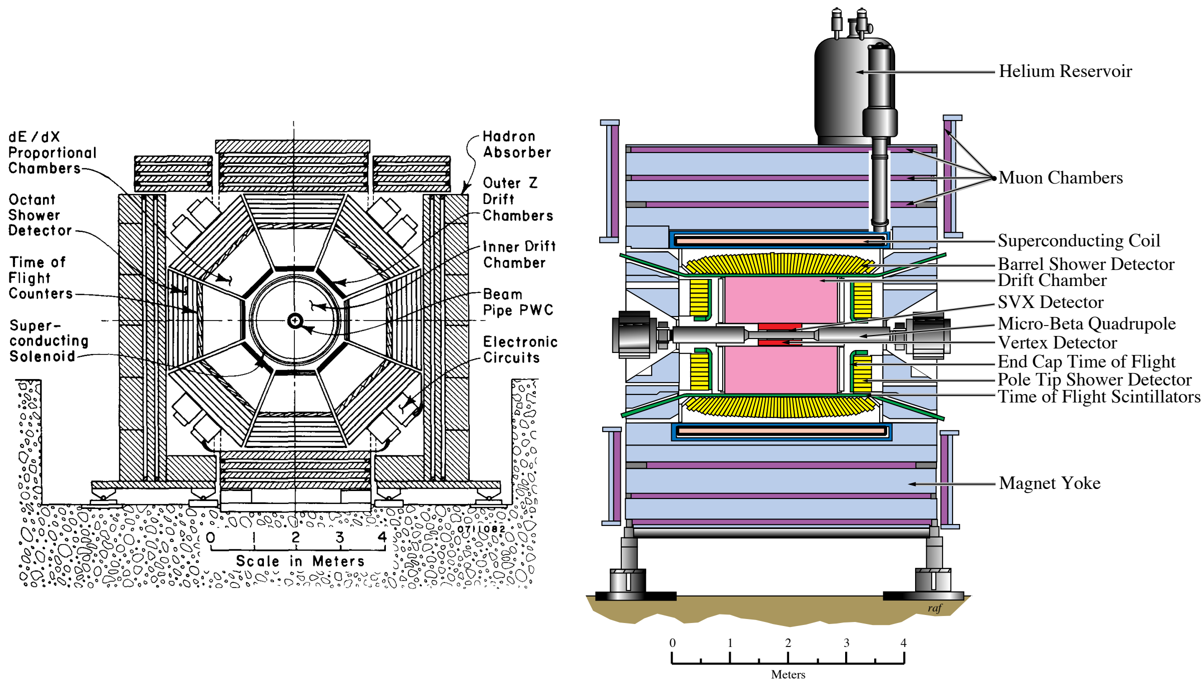

FIGURE 3. (Left) the CLEO I and I.V detectors 1979 – 1989, and (right) the CLEO II and II.V detectors 1989 – 1999. In the CLEO I.V configuration, the CLEO II drift chamber replaced the original CLEO I drift chamber. The CLEO II.V detector included the silicon vertex (SVX) detector indicated in the figure, which was not part of the original CLEO II configuration.

2 Before $B^0\bar{B}^0$ Mixing

The first physics results of the CLEO Collaboration (simultaneously with the CUSB Collaboration) were the confirmation that the $\Upsilon(3S)$ was a narrow resonance [5,6]. DESY contributed significantly to these first CLEO and CUSB observations of Υ states, because the LENA [7] collaboration at DORIS had measured the mass difference, $M_{\Upsilon(2S)} - M_{\Upsilon(1S)}$, accurately. Once CLEO and CUSB found the $\Upsilon(1S)$, finding the $\Upsilon(2S)$ was relatively quick and easy. This is illustrated in Fig. 4, which shows the 1979 holiday card that was sent by Cornell to colleagues and laboratories, and also shows the data that were published by CLEO [5]. These figures show that the $\Upsilon(1S)$ state was found with a few outlying points in the scan. The $\Upsilon(1S)$ position determined the energy scale of CESR relative to that of DORIS. Then using the LENA measurement of the mass difference, $M_{\Upsilon(2S)} - M_{\Upsilon(1S)}$, CLEO and CUSB found the $\Upsilon(2S)$ state with essentially no wasted effort. However, since the DORIS energy was too low to enable LENA to observe the $\Upsilon(3S)$, finding it required more time and effort as illustrated by the many data points taken above that resonance. The energy scan of the $\Upsilon(3S)$ by CLEO and CUSB was the first demonstration that this resonance was narrow. This symposium is a good opportunity to thank members of the LENA collaboration for their contribution to the earliest CLEO and CUSB measurements!

CLEO and CUSB followed their observations of the first three Υ states with the discovery of the $\Upsilon(4S)$ state and the observation that this state is broad, suggesting that it is above the threshold for $B\bar{B}$ production [8,9]. The CLEO data for this discovery are illustrated in Fig. 5. The upper figure on the left illustrates the cross section in the neighborhood of the $\Upsilon(4S)$, while the lower figure on the left illustrates the cross section in that region with a requirement that selects events with relatively spherical shapes. Fig. 5 also illustrates CUSB data for the first four Υ states and CLEO data for the later discovery with CUSB of the $\Upsilon(5S)$ and $\Upsilon(6S)$

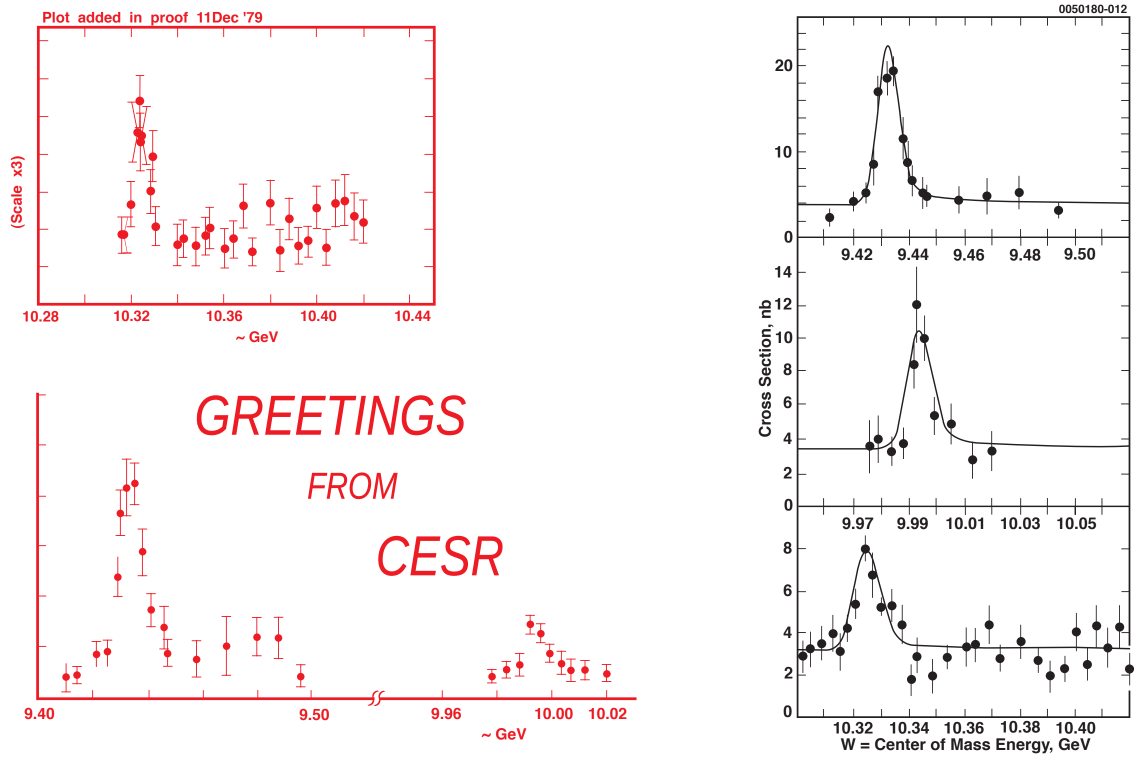

FIGURE 4. (Left) the 1979 Cornell holiday card illustrating the CLEO confirmation of the $\Upsilon(1S)$ and $\Upsilon(2S)$, and demonstration that the $\Upsilon(3S)$ is narrow. (Right) the same data when published. At the time of the holiday card, the analysis of the data was in an early stage, so the horizontal and vertical scales were purposefully left vague.

states [10,11]. These states complete the list of known ${}^3S_1$ Υ states.

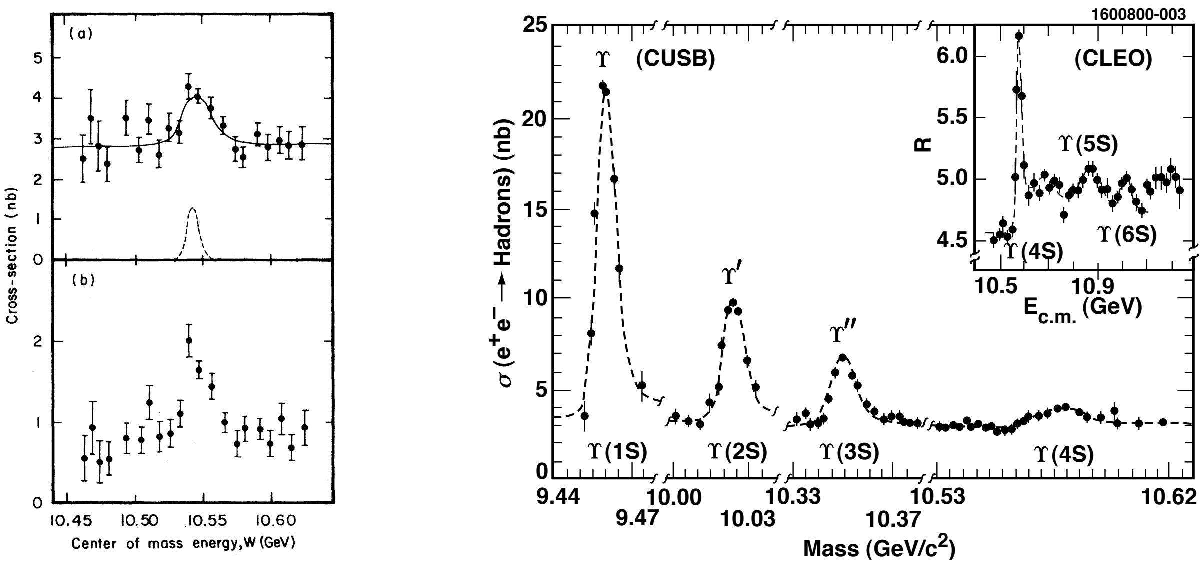

FIGURE 5. (Left) the CLEO observation of the $\Upsilon(4S)$ resonance. The top figure illustrates the measured cross section, while the bottom figure illustrates the cross section with an additional requirement that selects events with a relatively spherical shape. (Right) CUSB data illustrating the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(4S)$ states with an insert of CLEO data illustrating the $\Upsilon(5S)$ and $\Upsilon(6S)$ states.

The discovery of the $\Upsilon(4S)$ was soon followed by convincing, but indirect, evidence for the existence of B mesons and of the decay $\Upsilon(4S) \to B\bar{B}$. It was well known (and indeed verified by the discovery of D mesons) that leptons produced in e^+e^- annihilation experiments can come from two principle sources: from scattering or annihilations, which produce leptons with a cross section that varies smoothly with energy, and from semileptonic decays of mesons containing heavy quarks. The cross sections of leptons from heavy mesons have thresholds at the production of these mesons. As illustrated in Fig. 6, CLEO saw evidence for the enhancement of electron [12] and muon [13] yields at the $\Upsilon(4S)$ state. The leptonic branching fractions measured in these papers $\mathcal{B}(B \to Xe\nu) = (13 \pm 3 \pm 3)\%$ and $\mathcal{B}(B \to X\mu\nu) = (9.4 \pm 3.6)\%$ are consistent with current measurements, which are much more precise.

The period 1981-1986 was an exciting time in B physics; since essentially nothing about B mesons had been known, everything was new. ARGUS [14] entered the arena during this period, so three experiments actively studied B mesons produced at the $\Upsilon(4S)$ and competed with each other. During this period, ARGUS, CLEO, and CUSB discovered many B decay modes and measured their branching fractions; now the 2007 Particle Data Group (PDG) summary [15] lists 347 B^0 and 300 B^+ modes and submodes (including upper limits). Among these many decay modes, it is hard to single out any one hadronic decay as being particularly significant. However, inclusive and exclusive semileptonic decays played a substantial role in measurements of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$ [16]. I will not discuss exclusive semileptonic decays further in this talk, although ARGUS and CLEO were active in measuring branching fractions of these modes and determining the two B decay CKM matrix elements from the measurements.

Progress was impeded by the existence of so many decay modes, which implies that essentially all exclusive branching fractions are rather small. Fully reconstructing B decay modes was further hindered because nearly all B decays lead to D mesons in the final state, and fully reconstructing D meson decays was difficult because D branching fractions are also small. At

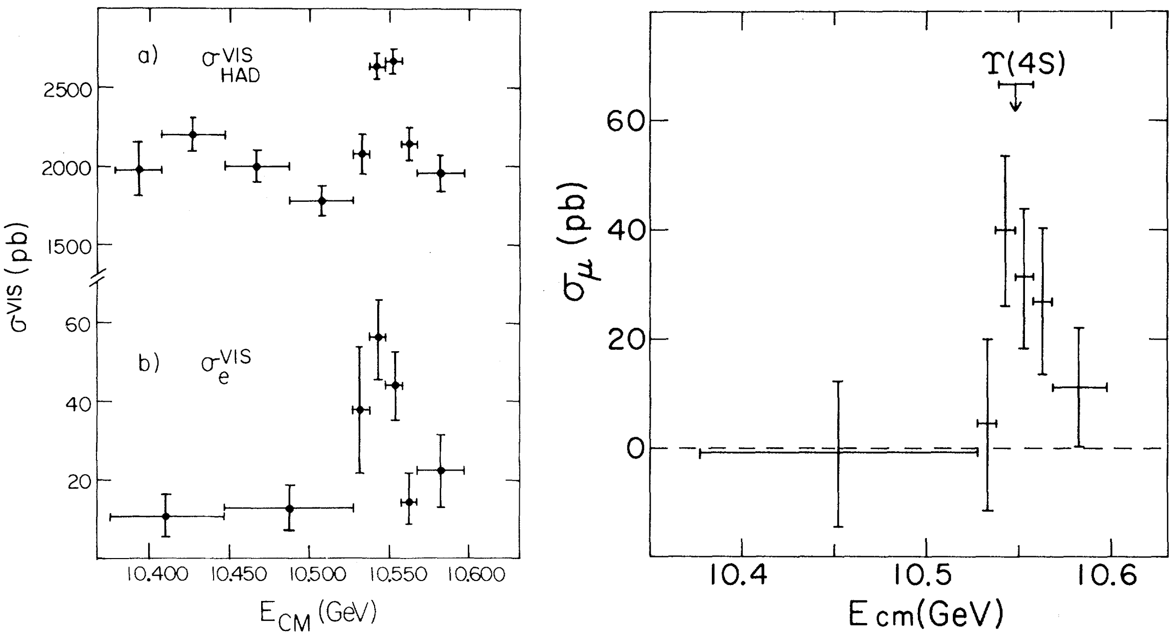

FIGURE 6. Data from CLEO's observation of leptons produced at the $\Upsilon(4S)$ from the semileptonic decays of B mesons. (Left) the visible cross section for production of electrons and (right) the visible cross section for production of muons in the $\Upsilon(4S)$ region. The hadron production cross section included in the figure on the left indicates that the increase in lepton production cross section in both figures is more noticeable than the increase in the hadron production cross section.

least one technique to sidestep the reconstruction of D mesons is worth mentioning. In 1984 CLEO developed a method of partially reconstructing D^{*+} decays to measure $\bar{B}^0 \to D^{*+}\pi^-$ [17]. This technique uses the momentum p_h of the hard π^- from the $\bar{B}^0$ decay and the momentum p_s of the soft π^+ from $D^{*+} \to D^0\pi^+$ decay. With these two momenta, the beam energy, and the known magnitude of the momentum of the B, it is possible to determine the mass of the B reasonably well without reconstructing the D. This technique substantially increases efficiency for reconstructing $\bar{B}^0$ decays because the branching fractions for D^0 decays to a few hadrons are small. Since then many other techniques for partially reconstructing B mesons have been developed and successfully employed.

The large ($\gtrsim$1 ps) lifetime of B mesons [15], observed at PEP and confirmed at Petra, was the big surprise and perhaps the most important single discovery of that era. This large lifetime implied that the CKM parameter $|V_{cb}|$ was small compared to $\sin\theta_C$, and inspired Wolfenstein's [18] parameterization of the CKM matrix. The long B meson lifetime was one of the ingredients that made the ARGUS discovery of $B^0\bar{B}^0$ mixing particularly important.

3 Studying $B^0\bar{B}^0$ Mixing

ARGUS's discovery of $B^0\bar{B}^0$ mixing [19] in 1987 came as a surprise to CLEO and – I dare say – to nearly all of the elementary particle physics community. As we all know, it was a very important result because the large value of $B^0\bar{B}^0$ mixing and the long B^0 meson lifetime opened the door to observation of CP violation in B decay. Study of CP violation is the principal raison d'être for the current very high interest in B physics and the justification for the community and agency support for most B meson programs subsequent to ARGUS's discovery.

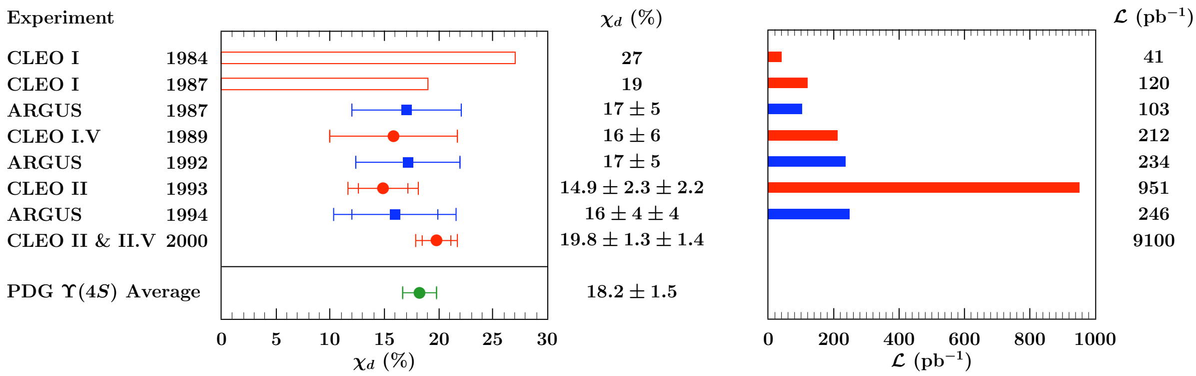

FIGURE 7. (Left) ARGUS and CLEO measurements of the $B^0\bar{B}^0$ mixing parameter χ_d and (right) the luminosities on which these measurements were based. Note that the 9.1 fb^{-1} of luminosity utilized in the CLEO 2000 measurement was much larger than any of the others, going well beyond the scale of the figure, so there is no bar illustrating that luminosity.

CLEO was interested in the possibility of observing $B^0\bar{B}^0$ mixing well before the ARGUS discovery. In fact, CLEO published two upper limits on $B^0\bar{B}^0$ mixing [20,21] before the ARGUS announcement. Although CLEO had slightly more luminosity than ARGUS at that time, the (next generation) ARGUS detector was much better suited for the measurement. Furthermore, CLEO's upper limits were based only on searches for like-sign dilepton events, while ARGUS also utilized leptons in events with one fully reconstructed B meson, and – of course – the well known fully reconstructed event [19]. In fact, CLEO [22] required two more years and a new detector to confirm the ARGUS result. Measurement of $B^0\bar{B}^0$ mixing by ARGUS [19,23,24] and CLEO [20,21,22,25,26] are illustrated in Fig. 7. The χ_d average in the figure is taken from the Heavy Flavor Averaging Group (HFAG) [27]. The values of Δm_d obtained from these measurements of χ_d have been superseded by BaBar and Belle [15].

Since most of the reports in this symposium concern ARGUS's discovery of $B^0\bar{B}^0$ mixing and the consequences of that discovery, I will now turn to a description of some of the other ARGUS and CLEO observations and measurements in B physics.

4 After $B^0\bar{B}^0$ Mixing

For more than a decade following ARGUS's discovery of $B^0\bar{B}^0$ mixing, CLEO enjoyed a rich program of studying B meson physics. Many of the earlier results of this program were obtained in intense and fruitful competition with ARGUS. After ARGUS left the field, CLEO became the source of most results in B physics until BaBar and Belle took over the field. I will describe two measurements from the period of competition between ARGUS and CLEO: measuring $|V_{cb}|$ with inclusive $B \to X_c\ell\nu$ decay and measuring $|V_{ub}|$ with inclusive $B \to X_u\ell\nu$ decay. I will follow this with discussion of CLEO's discovery of $B \to K^*\gamma$ decays, which are dominated by radiative penguin diagrams, and of CLEO's measurements of the branching fraction for $B \to X_s\gamma$ decay, which imposes rather stringent limits on new physics in the heavy quark sector and enables theoretically sound (model-independent) measurements of $|V_{cb}|$ and $|V_{ub}|$.

4.1 Measuring $|V_{cb}|$ with Inclusive $\bar{B} \to X_c\ell\nu$ Decay

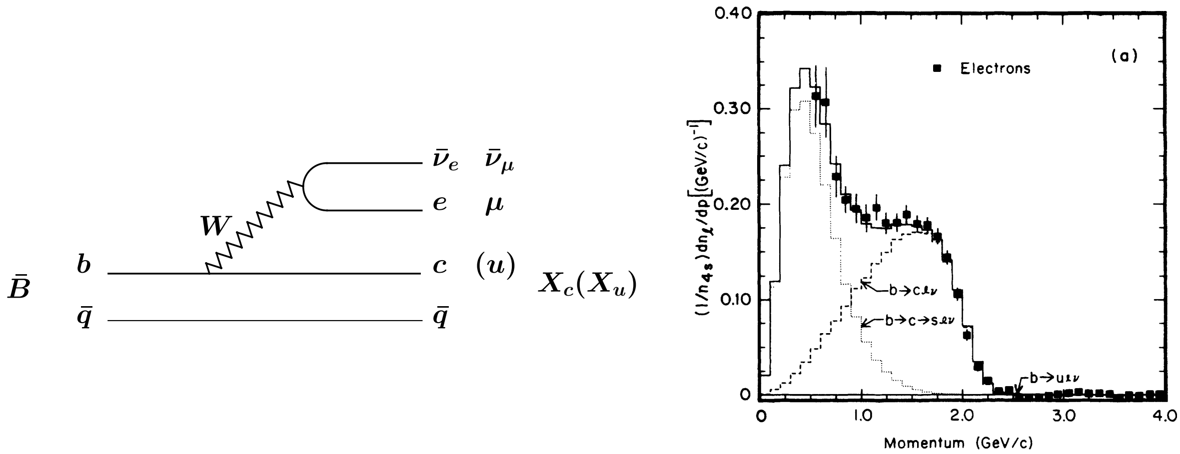

FIGURE 8. (Left) the Feynman diagram for semileptonic B decay to states X_c containing a charm quark or to states X_u without a charm quark. (Right) the inclusive electron momentum spectrum observed from B meson decays. The spectrum labeled $b \to c\ell\nu$ is from semileptonic B decay, while the spectrum labeled $b \to c \to s\ell\nu$ is from the semileptonic decays of D meson daughters produced in B decay.

The Feynman diagram for semileptonic B decay is illustrated in Fig. 8. The CKM matrix $|V_{cb}|$ can be determined from

$$\Gamma_{SL}^c \equiv \Gamma(\bar{B} \to X_c\ell\nu) = \frac{\mathcal{B}(\bar{B} \to X_c\ell\nu)}{\tau_B} = \gamma_c|V_{cb}|^2,$$

where $\mathcal{B}(\bar{B} \to X_c\ell\nu)$ is the branching fraction for $\bar{B} \to X_c\ell\nu$ decay, τ_B is the B meson lifetime, and γ_c is a constant that must be provided by theory. The chief experimental challenge [28] in measuring $\mathcal{B}(\bar{B} \to X_c\ell\nu)$ is also illustrated in Fig. 8. Below $p_\ell \sim 1.2$ GeV/c there is a large contribution from semileptonic decays of D meson daughters produced in B decays. Initially, theoretical models were used to extrapolate the $\bar{B} \to X_c\ell\nu$ momentum spectrum through the region dominated by semileptonic D decay down to $p_\ell = 0$ GeV/c. Hence, theoretical models were required to obtain $\mathcal{B}(\bar{B} \to X_c \ell \nu)$, as well as to obtain $|V_{cb}|$ from $\mathcal{B}(\bar{B} \to X_c \ell \nu)$. The ACCMM [29] and ISGW [30] models were frequently used for both purposes.

ARGUS [31] revolutionized this subject by developing a tagging technique to separate the lepton spectrum quite reliably into a $\bar{B} \to X_c \ell \nu$ component and the sequential decay $\bar{B} \to DX$ followed by $D \to \bar{X}_s \ell \nu$. ARGUS's key idea was to use leptons in the momentum range $1.4 \leq p_\ell \leq 2.3$ GeV/c to tag a B decay. When ARGUS found an electron in the same event, with momentum in the range $0.6 \leq p_\ell \leq 2.3$ GeV/c, they attributed the electron to $\bar{B} \to X_c \ell \nu$ decay if the leptons had opposite sign, or attributed it to sequential semileptonic D decay if the leptons had the same sign.

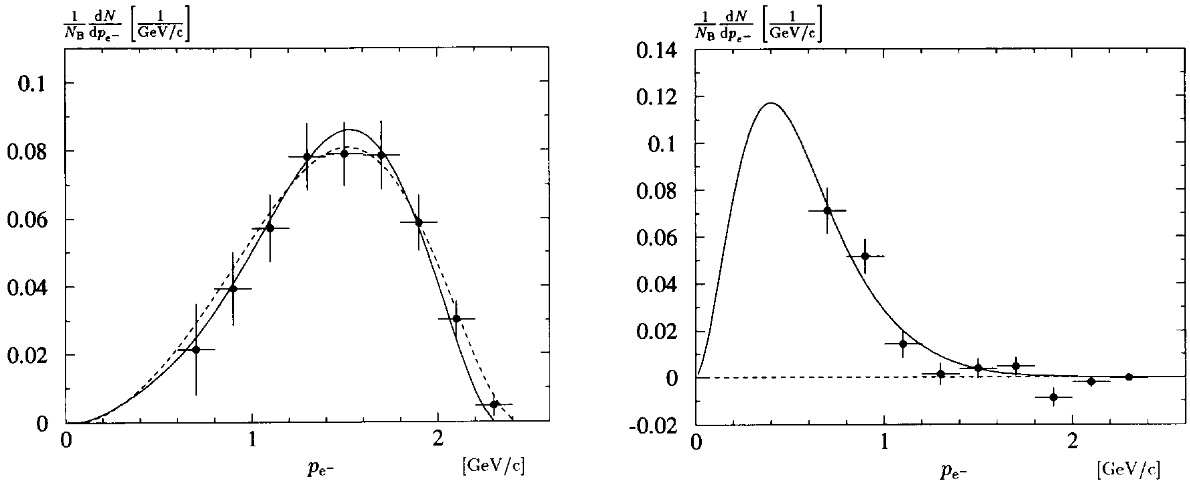

FIGURE 9. (Left) the electron spectrum from $\bar{B} \to X_c \ell \nu$ decay that ARGUS obtained with the tagging technique. (Right) the corresponding electron spectrum that ARGUS obtained for sequential semileptonic D decay.

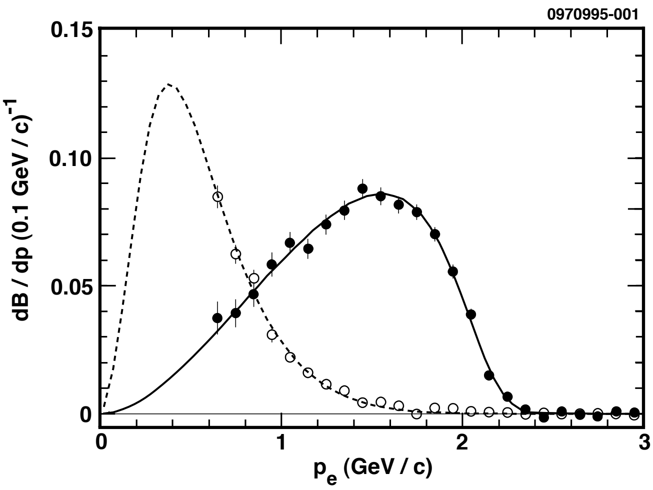

FIGURE 10. The p_ℓ spectra that CLEO obtained for $\bar{B} \to X_c \ell \nu$ decay (solid circles) and sequential semileptonic D decay (open circles), by using a tag technique similar to the ARGUS tag technique.

Figure 9 illustrates the success of ARGUS's tagging technique in separating the two components in the lepton momentum spectrum. This technique was used down to lepton momenta $p_\ell \approx 0.6$ GeV/c. Extrapolating the p_ℓ spectrum the rest of the way to $p_\ell = 0$ GeV/c can be accomplished with relatively little model dependence, making the measurement of the branching fraction $\bar{B} \to X_c \ell \nu$ almost independent of models. Model calculations were still required to determine $|V_{cb}|$ from the branching fraction, but the overall model dependence was substantially reduced by this method. CLEO [32] refined and successfully employed the ARGUS tagging technique to measure the lepton momentum spectrum from $\bar{B} \to X_c \ell \nu$ decay; the resulting spectra are illustrated in Fig. 10.

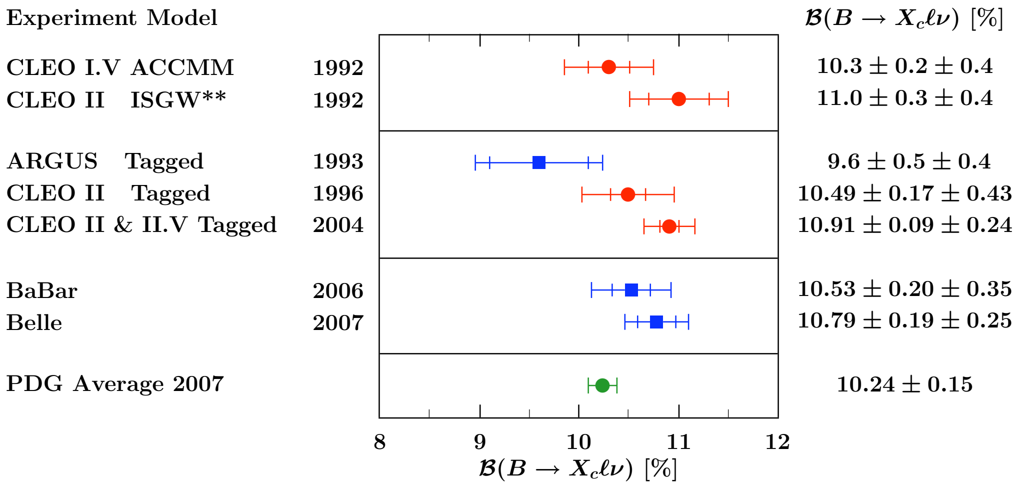

FIGURE 11. Measurements of $\mathcal{B}(\bar{B} \to X_c \ell \nu)$ by ARGUS, CLEO, BaBar, and Belle. The 1992 measurements utilized the ACCMM and ISGW** theoretical models to separate the $\bar{B} \to X_c \ell \nu$ component in the lepton momentum spectrum from the leptons from sequential semileptonic D decay. The rest of the measurements utilized tagging techniques based on the original ARGUS tagged measurement.

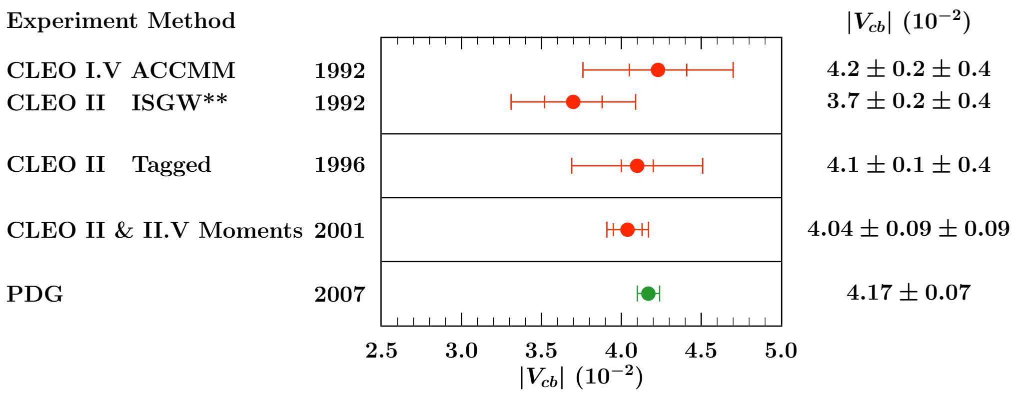

FIGURE 12. CLEO measurements of $|V_{cb}|$. The 1992 and 1996 measurements used the parameter γ_c from the ACCMM and ISGW** theoretical models to determine $|V_{cb}|$ from $\mathcal{B}(\bar{B} \to X_c \ell \nu)$. The theoretical basis for the 2001 measurement is substantially more sound.

The results of ARGUS [31] and CLEO [32,33] measurements of $\mathcal{B}(\bar{B} \to X_c \ell \nu)$ are illustrated in Fig. 11. The CLEO measurements [28] labeled ACCMM [29] and ISGW** [30] are model-dependent untagged measurements, in which the shapes of the momenta spectra were determined using these models. (The ** in ISGW** indicates that one component of the ISGW spectrum was allowed to float in order to obtain a better fit in the crossover region between the electrons from semileptonic B decay and those from semileptonic D decay.) More recent measurements from BaBar [34] and Belle [35] (corrected for the portion of the $\bar{B} \to X_c \ell \nu$ spectrum below $p_\ell = 0.6$ GeV/c using the correction factor 1.0495 given in HFAG 2007 [27]) and the PDG 2007 average [15] are included for comparison. BaBar and Belle used fully reconstructed B decays for their tags, rather than the lepton tags used by ARGUS and CLEO, so the experimental errors are larger than they might otherwise be, given the huge luminosities obtained by these two collaborations. In any event, this method is a descendent of the ARGUS technique.

Values of $|V_{cb}|$ obtained from the CLEO measurements [28,32,36] of $\bar{B} \to X_c \ell \nu$ are illustrated in Fig. 12. The measurement labeled CLEO II & II.V Moments 2001 utilized measurements of the moments of hadronic mass distributions to eliminate the model-dependence in the earlier measurements. The moment technique, based on Heavy Quark Effective Theory (HQET) has a much more secure theoretical foundation, resulting in the substantial reduction of the theory error compared to the other measurements. Recent measurements utilize HQET moments to extract $|V_{cb}|$ from the $\bar{B} \to X_c \ell \nu$ decays [16].

4.2 Measuring $|V_{ub}|$ with Inclusive $\bar{B} \to X_u \ell \nu$ Decay

CLEO and ARGUS detected inclusive $\bar{B} \to X_u \ell \nu$ decays in the p_ℓ spectrum above the endpoint for $\bar{B} \to X_c \ell \nu$ decays. Observing and measuring inclusive $\bar{B} \to X_u \ell \nu$ decays is even more challenging than measuring $\bar{B} \to X_c \ell \nu$ decays because: the branching fraction is very small $\mathcal{O}(10^{-4})$, only a very narrow window in p_ℓ is useful, the background from $\bar{B} \to X_c \ell \nu$ decays is significant, and continuum events can produce charged particles in this narrow p_ℓ range. These challenges are illustrated in Fig. 13, where the contribution of $\bar{B} \to X_u \ell \nu$ decays to the p_ℓ spectrum is increased by a factor of 10 to make it visible. Despite these difficulties, CLEO [37] and ARGUS [38] both reported $\bar{B} \to X_u \ell \nu$ signals in 1990. Fig. 14 illustrates measurements of the $\bar{B} \to X_u \ell \nu$ spectrum from ARGUS [39] in 1991 and later from CLEO [40] in 2002 with much larger luminosity. ARGUS [39] also fully reconstructed two events with $\bar{B} \to X_u \ell \nu$ decays, providing convincing evidence that there were actually $\bar{B} \to X_u \ell \nu$ decays in the endpoint region of the p_ℓ spectrum.

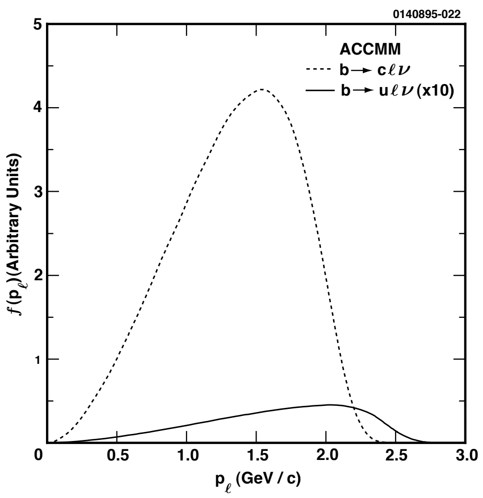

FIGURE 13. The ACCMM prediction for the lepton momentum spectrum for $\bar{B} \to X_c \ell \nu$ decays and the spectrum for $\bar{B} \to X_u \ell \nu$ decays. The height of the latter spectrum is increased by a factor of 10 to make it visible.

The $|V_{ub}|$ measurements from ARGUS [38] and CLEO [37,40,41] are illustrated in Fig. 15,

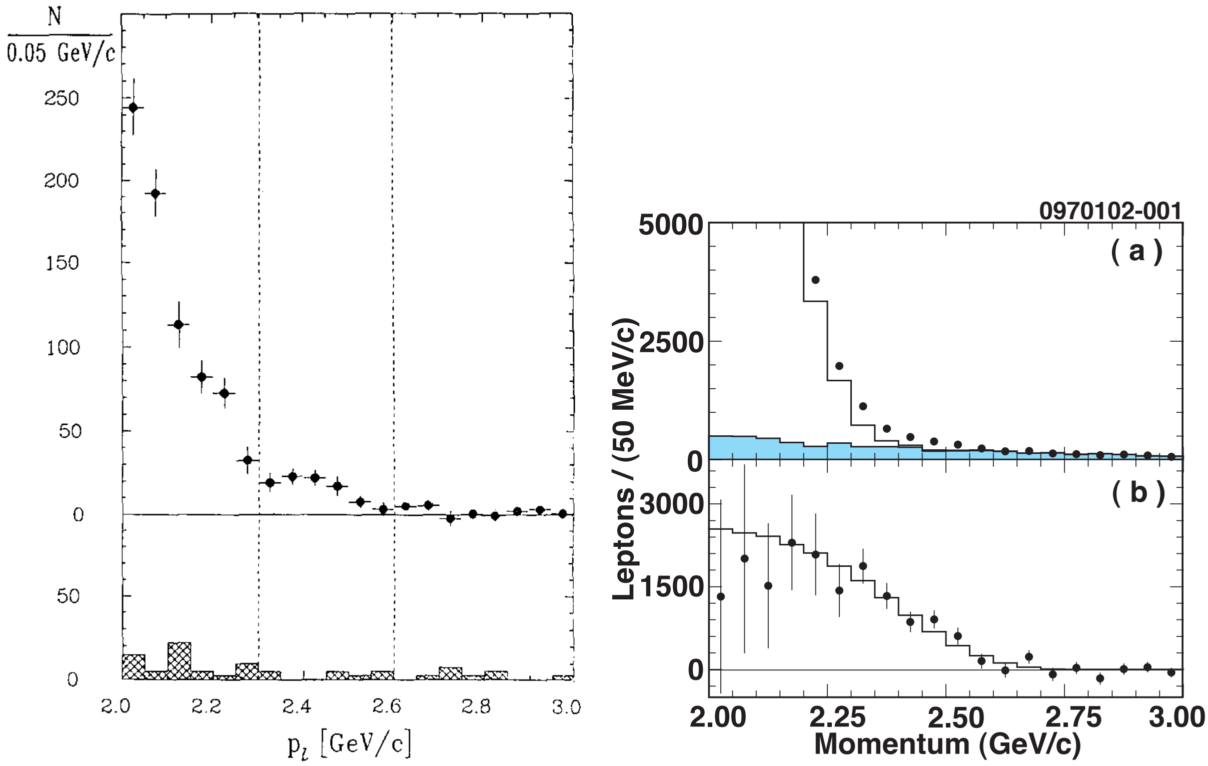

FIGURE 14. (Left) the ARGUS p_ℓ spectrum for charmless semileptonic B decay from 1991 and (right) the corresponding CLEO spectrum from 2002. ARGUS illustrates the spectrum observed at the $\Upsilon(4S)$ (points) and the scaled spectrum from the continuum (hatched histogram), which must be subtracted. CLEO illustrates the observed $\Upsilon(4S)$ spectrum along with the continuum spectrum (shaded histogram), and the net $\bar{B} \to X_u \ell \nu$ spectrum (points with error bars) with the prediction (histogram) from the measured value of $|V_{ub}|$.

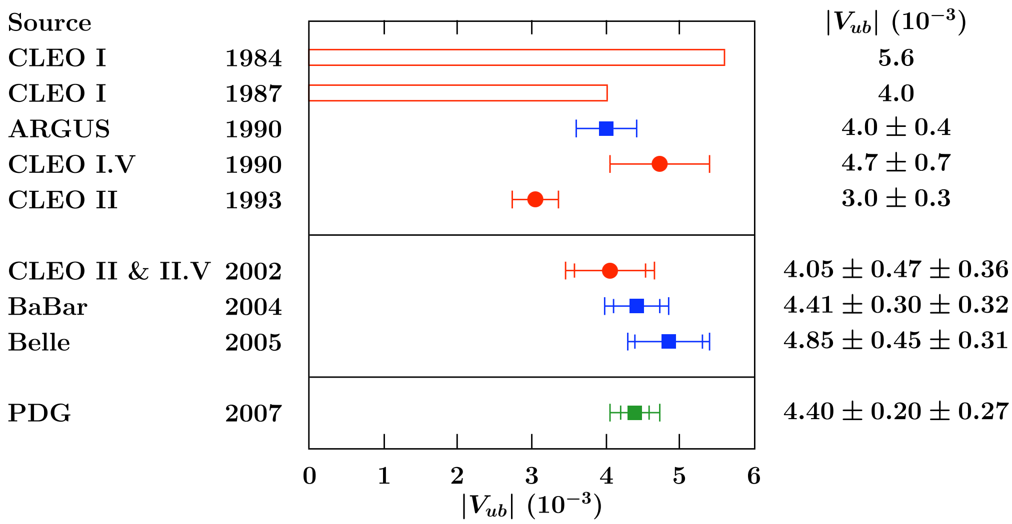

FIGURE 15. Measurements of $|V_{ub}|$ from ARGUS, CLEO, BaBar, and Belle and the PDG 2007 average.

along with two earlier upper limits from CLEO [42,43] and more recent measurements from BaBar [44] and Belle [45]. CLEO used the ACCMM [29] model to obtain the upper limits and values of $|V_{ub}|$ in the 1984 to 1993 analyses. However, this use of models is even less satisfactory than it is for measurements of $|V_{cb}|$ because model dependence for $|V_{ub}|$ is much more serious than it is for $|V_{cb}|$. For the CLEO 2002, BaBar, and Belle results, these collaborations utilized more rigorous HQET techniques to extract $|V_{ub}|$ from moments of the $\bar{B} \to X_u \ell \nu$ and $B \to X_s \gamma$ spectra. The results given in Fig. 15 are rescaled from the original measurements to a common value of τ_B and – in the case of the more recent measurements – derived from a common HQET analysis [16].

Many of us in CLEO noticed that the two upper limits had not decreased much even though the 1987 limit was based on substantially more luminosity than the 1984 limit. Due to our experience with upper limits for $B^0\bar{B}^0$ mixing, we felt that we were near an observation of $\bar{B} \to X_u \ell \nu$ decays, and this hunch turned out to be correct.

4.3 Discovery of Radiative Penguin Processes

The discovery of exclusive radiative penguin processes and measurements of the corresponding inclusive processes were the most challenging and important CLEO results that were not shared with ARGUS or other collaborations until Belle and BaBar entered the field.

Penguin diagrams, illustrated in Fig. 16, were initially proposed to explain the $\Delta I = \frac{1}{2}$ rule in K decay (see Ref. [46] for references to the early theoretical literature). The penguin diagram introduces a large $\Delta I = \frac{1}{2}$ enhancement, in contrast to a picture in which the $\Delta I = \frac{3}{2}$ is suppressed somehow. However, there was no incontrovertible experimental evidence for the existence of penguin decays for nearly 20 years, until CLEO observed $B \to K^* \gamma$ decays [46].

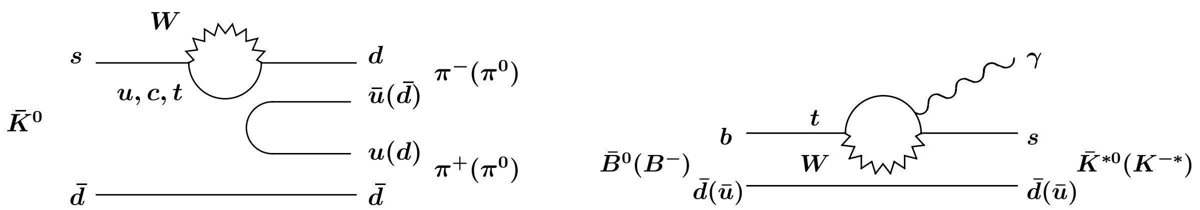

FIGURE 16. (Left) the penguin diagram proposed to explain the $\Delta I = \frac{1}{2}$ rule in K decay and (right) the diagram for exclusive radiative penguin decays.

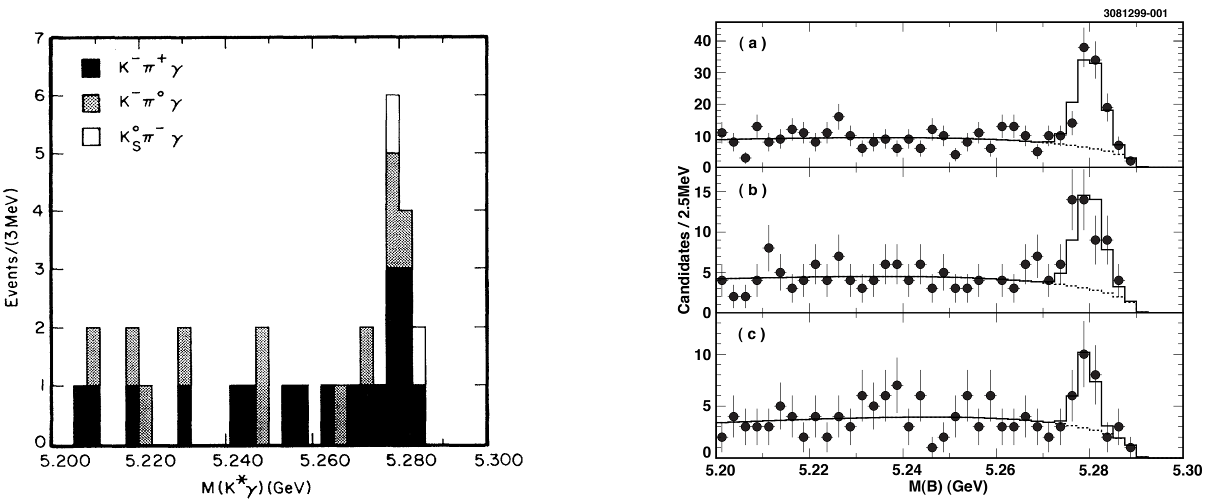

FIGURE 17. The B mass distributions for $B \to K^* \gamma$ candidates from the CLEO 1993 (left) and CLEO 2000 (right) analyses. For the CLEO 2000 analysis, the K^* candidates are (a) $K^{*+}(892)$, (b) $K^{*0}(892)$, and (c) $K_2^*(1430)$ candidates.

CLEO searched for the decay modes $\bar{B}^0 \to \bar{K}^{*0}\gamma$ with $\bar{K}^{*0} \to K^-\pi^+$, and $B^- \to K^{*-}$ with $K^{*-} \to K^-\pi^0$ or $K^{*-} \to K^0_S\pi^-$. Reducing the backgrounds, particularly the backgrounds from continuum events, was the principal experimental challenge. CLEO had devoted approximately $\frac{1}{3}$ of its luminosity to taking data on the continuum below the $\Upsilon(4S)$, and these data were crucial for exclusive and inclusive $B \to X_s\gamma$ analyses. Figure 17 illustrates the B mass distributions for $\bar{B} \to \bar{K}^*\gamma$ candidates from discovery of these decays in 1993 [46] and from the 2000 [47] analysis with a significantly larger data sample.

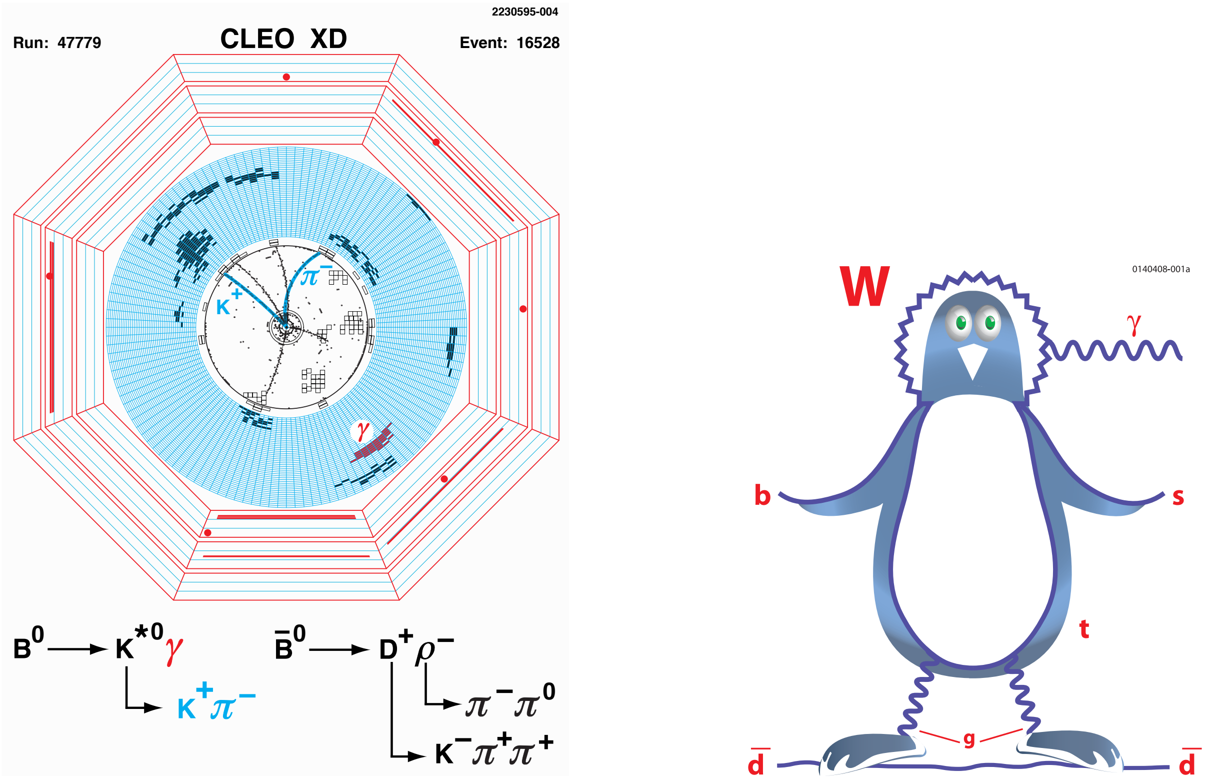

FIGURE 18. (Left) a fully reconstructed $B^0\bar{B}^0$ event with the decays $\bar{B}^0 \to D^+\rho^-$ and $B^0 \to K^{*0}\gamma$. (Right) an artist's view of the radiative penguin diagram.

Following ARGUS's lead in presenting fully reconstructed events, CLEO displays a fully reconstructed $B^0\bar{B}^0$ event with the decays $\bar{B}^0 \to D^+\rho^-$ and $B^0 \to K^{*0}\gamma$. Figure 18 illustrates this event along with an artist's view of the penguin Feynman diagram. All decay daughters (except one soft photon from π^0 decay) in the event were detected and measured. Figure 19 illustrates the branching fractions for $B \to K^*\gamma$ decays measured by CLEO [46,47], BaBar [48,49] and Belle [50]. Since individual $B \to K^*\gamma$ branching fractions depend on how the X_s final state hadronizes, there are no secure theoretical predictions with which to compare these experimental results.

4.4 Measurement of $\mathcal{B}(B \to X_s\gamma)$

The inclusive branching fraction $\mathcal{B}(B \to X_s\gamma)$ is much more important than the exclusive branching fractions $\mathcal{B}(B^0 \to K^*(890)\gamma)$ described in the previous section, because the Standard Model (SM) rate for the inclusive decays can be calculated with some precision. Furthermore, the SM rate is sensitive to Beyond SM effects in the loop.

The experimental challenges involved in measuring the inclusive branching fraction are much more severe than they are for measuring exclusive branching fractions, because reconstruction of K^* candidates and imposition of a K^* mass cut are very useful in reducing background in exclusive analyses. Figure 20 illustrates the expected signal and backgrounds. The backgrounds from photons in continuum events are approximately a factor of 100 above the SM signal.

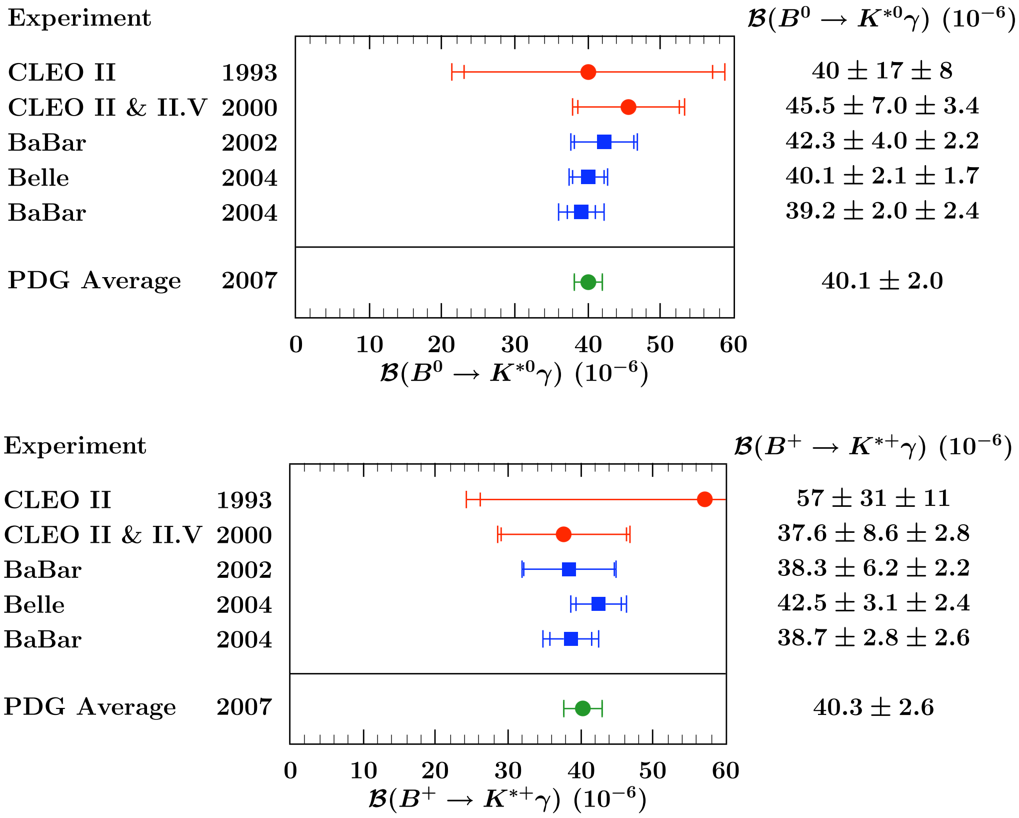

FIGURE 19. (Top) branching fractions for $B^0 \to K^{*0}\gamma$ and (bottom) $B^+ \to K^{*+}\gamma$ decays measured by CLEO, BaBar, and Belle. The PDG 2007 average utilizes the CLEO 2000, BaBar 2004, and Belle 2004 measurements only.

In an 1995 analysis, CLEO eliminated photons that could be paired with any other photon to produce a $\gamma\gamma$ pair with an invariant mass consistent with either the π^0 or η mass. CLEO also developed a neural network that utilized several event-shape variables and the energies detected in cones parallel and antiparallel to the candidate photon direction. CLEO's large sample of continuum events was crucial for training the neural net and demonstrating that it was effective in picking out continuum background. CLEO also reconstructed events that were consistent with $B \to X_s\gamma$ decays with $0.6 < M(X_s) < 1.8$ GeV/c^2. The results of the two techniques are consistent and only mildly correlated. CLEO's publication of this 1995 result [51] was based on 2.0 fb^{-1} of $\Upsilon(4S)$ data. The photon energy spectrum from an updated analysis in 2001 [52] that utilized 9.1 fb^{-1} of $\Upsilon(4S)$ data is illustrated in Fig. 20.

Measurements of $B \to X_s\gamma$ from CLEO [51,52], Belle [53,54], and Babar [55,56], are illustrated in Fig. 21, along with the PDG 2007 [15] average and a recent theoretical calculation of the branching fraction in next-to-next-to-leading order (NNLO) [57]. It is clear that there is not much room for physics beyond the SM between this theoretical calculation and the experimental average. The fact that the CLEO result remains competitive (so far) with results from BaBar and Belle is due, in part, to CLEO's enormous investment in continuum data.

The importance of these measurements of $B \to X_s\gamma$ decay go well beyond the search for new physics. Moments of the photon energy spectrum are sensitive to HQET parameters that also appear in moments of the electron energy or hadronic mass spectrum in $\bar{B} \to X_c\ell\nu$ and

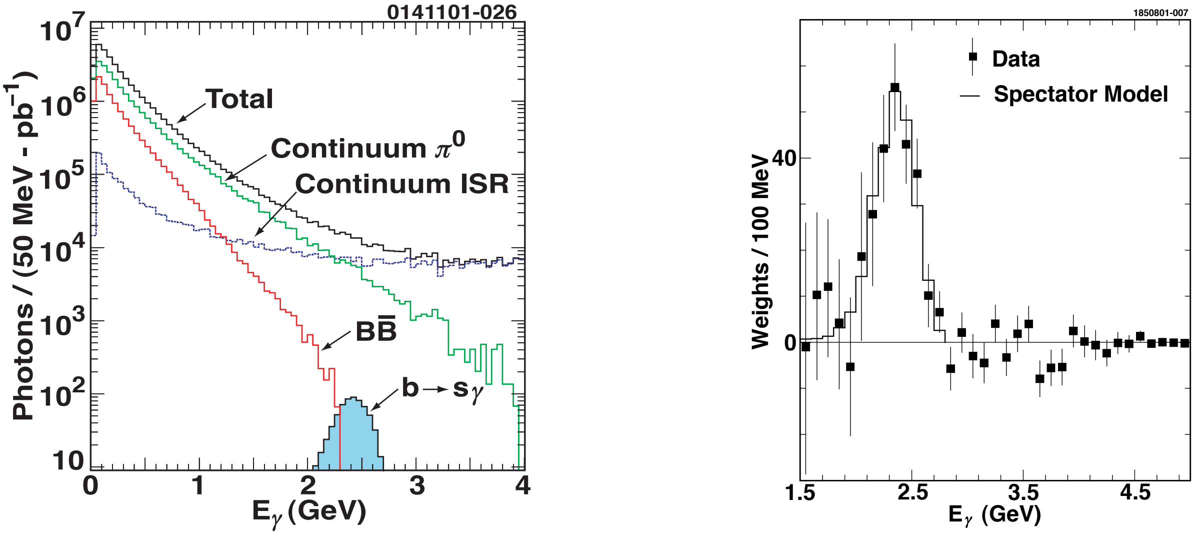

FIGURE 20. (Left) the $B \to X_s\gamma$ signal expected from SM predictions and the backgrounds anticipated from photons and π^0s in continuum events, and from photons in other $B\bar{B}$ decays. Note the logarithmic scale on the vertical axis. (Right) CLEO's 2001 photon energy spectrum for $B \to X_s\gamma$ decays.

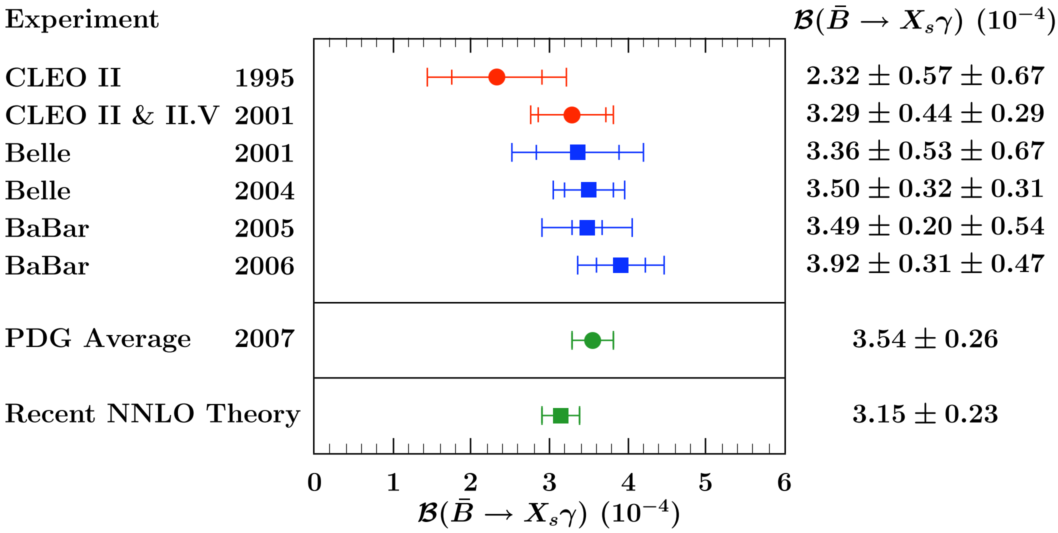

FIGURE 21. A summary of measurements of the inclusive $B \to X_s\gamma$ branching fraction and a recent SM theoretical calculation in next-to-next-to-leading order. The PDG 2007 average utilizes the CLEO 2001, Belle 2004, and BaBar 2005 and 2006 measurements.

$\bar{B} \to X_u\ell\nu$ decays. In fact, the most precise inclusive semileptonic measurements of $|V_{cb}|$ and $|V_{ub}|$ with the least theoretical uncertainty are obtained from these moments [16].

5 Concluding Remarks

First, I am delighted to congratulate ARGUS for discovering $B^0\bar{B}^0$ mixing! Obviously I would have been pleased if this had been a CLEO discovery, but ARGUS was definitely first with a better detector and a better method of analyzing the data.

Beyond this, I wish to express a few personal thoughts about ARGUS, CLEO, and my experience in CLEO. It is clear that large $B^0\bar{B}^0$ mixing and the resulting promise of observable CP violation in B meson decay were crucial for mustering the community and agency support necessary for the last 20 years of the CLEO program! I believe that the competition between ARGUS and CLEO was very healthy for both collaborations and for the advancement of elementary particle physics. This competition kept all of us on our toes and (as I have described in this report) we often learned something from each other.

Our experience in CLEO with $B^0\bar{B}^0$ mixing and $B \to X_u \ell \nu$ decays taught me that converging upper limits may indicate that a discovery is near. On the other hand, in some instances we also learned that the first observation of a phenomenon may be an upward fluctuation. We found that developing a new field requires substantial time and creative effort because even experienced physicists have a lot to learn if the field is largely unexplored. Furthermore, sustaining an experiment over several decades requires frequent detector and/or luminosity upgrades. This lesson is also understood by other collaborations, including the LHC collaborations, which have not even taken data so far. These upgrades are expensive and disruptive because they require substantial time and effort, but they are necessary.

Finally, heavy quark physics with CLEO was (and still is) a wonderful experience! Now it's time for CLEO members to finish CLEO-c and move on to other experiments.

Acknowledgements

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