CKM PHYSICS FROM CLEO

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Between 1990 and 1999 CLEO II/II.5 accumulated a data sample of ~2 x 10^7 B decays. This has been the premier data sample for B physics in the pre-B Factory era. I will present pre-Osaka determinations of V_{cb} ,V_{ub} and searches for direct CP violation in the B system I will also discuss the future of these measurements at B Factories.

1 Introduction

The parameters of the Standard Electroweak Model (SM) are α, $\sin^2\theta_W$, M_H and the fermion masses and mixings. Four parameters reside in the CKM matrix which relates the quark mass eigenstates to the weak eigenstates:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \quad (1)$$

There are three reasons to determine the CKM matrix with high precision. (1) Within the SM, λ, A, ρ and η are fundamental parameters. (2) The CKM phase is the source of CP violation in the SM. (3) To detect new physics in the flavor changing sector of the SM we must know the CKM matrix well. Currently only the u,d,s,c sub matrix is well known, experiments in B physics are a unique laboratory to determine the remainder of the CKM matrix through measurements of V_{cb} ,V_{ub} and γ, the phase of V_{ub}. The unitarity of the matrix implies:

$$V_{ub}^* + V_{td} = \lambda V_{cb}^* \quad (2)$$

Which is a triangle in the ρ-η plane, shown in Fig. 1

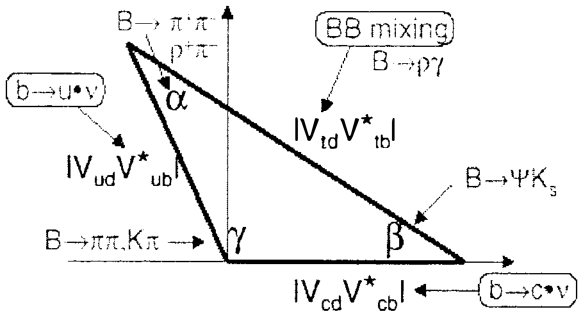


Figure 1. The non-CP triangle of the CKM matrix. A variety of B physics measurements that can be used to measure the triangle are shown.

2 Semileptonic Decays of beauty and V_{cb}

Semileptonic decays are used to determine the quark couplings as the strong interaction is confined to the lower vertex. Since of necessity we must work with hadrons rather than quarks, theory is needed to relate the underlying quark decay to hadronic reality

$$\Gamma = \Gamma_{theory} |V_{cb}|^2 = \frac{Br}{\tau} \qquad (3)$$

The width is proportional to V_{cb} for final states with charm and proportional to for V_{ub} final states without charm.

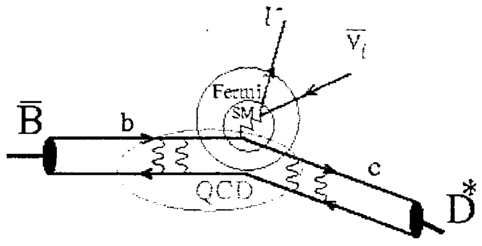


Figure2 The diagram shows the semileptonic decay of a B meson to a charm meson final state. This transition is proportional to V_{cb}. If a $\rho/\pi/\eta/\varpi$ is substituted for the D* the transition is proportional to V_{ub}

The inclusive semileptonic branching ratio B_{sl} can be used to determine V_{cb}. This measurement is systematics limited at CLEO. CLEO expects a new number with x5 the statistics and a reduced systematic error soon. Currently the most precise measurement is from LEP [1]. The error on B_{sl} is 2%, therefore the experimental error on V_{cb}. is 1% while Γ_{theory} is known to 5%. The value of V_{cb} is given in Table 1.

There is a second promising way to obtain V_{cb} with inclusive b→clv. In Heavy Quark Effective Theory (HQET) a controlled QCD expansion in $1/M_Q$, finite mass effects are described by three parameters. λ_1 measures the average kinetic energy of the b quark in the B meson, λ_2 measures the spin energy and Λ converts from m_b to m_B, In principle a fit to the mean and rms of the hadronic and leptonic spectrum in inclusive semileptonic decays determines these parameters with an experimental precision that implies a theoretical error on V_{cb} of 2%, However, currently hadronic and leptonic spectra do not yield consistent results [2], this may be an experimental or theoretical problem and a new analysis is eagerly awaited.

V_{cb} may also be determined in exclusive transitions. in the limit that b and c quarks are infinitely heavy, a beauty or charm hadron becomes similar to a hydrogen atom with the heavy quark playing the role of the proton and the light degrees of freedom playing the role of the electron. The heavy quark is nearly at rest and the heavy quark spin has little effect on the energy. In a b→c transition at q^2_{max} the c quark is at rest and the light degrees of freedom are unaware of the flavor change. The form factor, F(1), describing this transition is unity. Corrections for finite quark mass are second order for B→D*lv and calculable. In addition Br(.B→D*lv) is large near q^2_{max} (w=1) and the D* is relatively easy to reconstruct with low background. For these reasons both CLEO [3}and LEP [1] have measured the differential rate in this decay to extract V_{cb}.

$$\frac{d\Gamma}{dw} = \frac{G_F^2}{48\pi^2} V_{cb}^2 F_{D^*}(w)^2 G(w) \qquad w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}} \qquad m_Q \to \infty,\ F(q^2_{max}) = 1 \qquad (4)$$

CLEO has attempted the same measurement with B⟶Dlv. The result is less precise but provides a useful consistency check. Good agreement between results from both methods and between CLEO and LEP (DELPHI) is shown in Figure 2

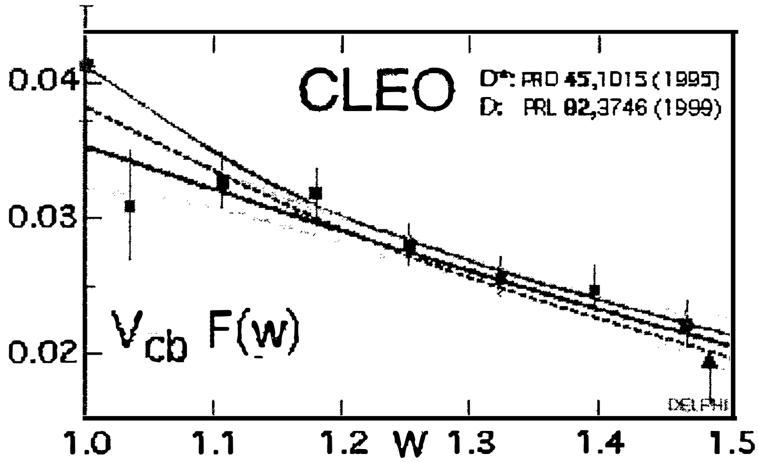
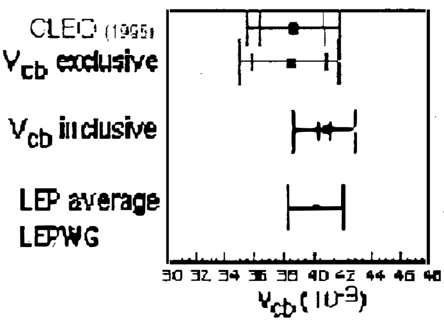


Figure 3. The differential decay rate as function of w. Squares with errors bars B⟶D*lv date (CLEO) Circle with error bar B⟶Dlv (CLEO). Lines are results of log likelhod fits and not fits to the data points. The dark dashed line is the result of a DELPHI analysis of B⟶D*lv.

Table 1. V_{cb} in units of 10^{-3}. Exclusive values are for FD*(1)=0.88±0.5



39.8 ± 3.0 ± 2.3*

39.8 ± 1.8 ± 2.2*

40.7 ± 0.5 ± 2.0

40.4 ± 1.8

From Table 1 V_{cb} from B⟶Xlυ has a small statistical error but the theoretical error is 5%. The theoretical error will improve once the moments analyses are better understood. The exclusive mode B⟶D*lv has a larger statistical error, but the theoretical error on the form factor FD*(1) is about 5%. How will data from the B factories improve this? After several years of running at a B Factory about 60 x 10^6 BB pairs will have been accumulated. Determining V_{cb} from inclusive semileptonic decays the statistical error is negligible, the experimental systematic error may be reducible to ~1%. If HQET parameters in the hadronic and leptonic spectra of inclusive semileptonic decays are consistent, the theoretical error will be 2-3%[4]. The increased data sample will reduce the errors on V_{cb} in exclusive decays as well. In $B \to D^* l \nu$ the statistical error will be 1%, I estimate the systematic error will be 3%. To take advantage of this improvement requires that the error on the form factor, FD*(1), be reduced to $\delta FD^* < 2\%$. This should be achievable with the lattice. The exclusive modes can yield a competitive and precise number, however is the theoretical interpretation correct? So far the data is consistent with the HQET picture of exclusive semileptonic B decay, but there has been insufficient data for precision tests. One example is the ratio of the form factors in $B \to D^* l \nu$, where current data is consistent with the Heavy Quark Symmetry limit itself. This measurement and many others will be performed with the B factory data samples.

3 Determination of V_{ub}

In the Standard model V_{ub} must be non-zero and complex for CP violation to exist. It is important to know both the magnitude of V_{ub} which governs the length of the left side of the unitarity triangle and the phase of V_{ub}, γ, which is the source of CP violation in the Standard Model.. The phase of V_{ub} can only be reliably measured with the very large B data samples expected at the upgraded PEP-II, and KEK-B, at a new high luminosity e+e- collider or at the LHC or with BTeV. The magnitude of V_{ub} is, fortunately, directly accessible in current experiments. Ultimately, if new physics is present in the B system, for example in B_d mixing, identification will come through a careful comparison of the value of sin2β and the magnitude of V_{ub}

Although the quark process $b \to u l \upsilon$ is simple it is very difficult to calculate the strong interaction effects when a heavy B meson becomes a light $\rho/\pi/\eta/\varpi$ meson. Theoretical uncertainties enter twice: first the shape of the form factor determines the acceptance and hence branching ratio. Second the absolute normalization is needed to get V_{ub}. As a $b \to c l \nu$ transition is about 100 times more probable than a $b \to u l \upsilon$ transition, the semileptonic charm final states constitute a severe background., and force experimentalists to measure V_{ub} in small regions of phase space.

CLEO was the first experiment to determine that the magnitude of V_{ub} was non-zero by detection of inclusive leptons from semileptonic B meson decay beyond the kinematic end-point for final states containing a charm meson. Experimentally this is a clean measurement but only 5-20% of the leptons of interest populate the endpoint region a large theoretical extrapolation is required to obtain V_{ub}, therefore, the result is highly model dependent.

More recently CLEO was able to reconstruct exclusive transitions using several analysis techniques that exploit the hermiticity of the CLEO detector to reconstruct the neutrino four vector [5]. Due to large backgrounds it has so far been found necessary to continue to work mostly in the lepton endpoint region. The theoretical error is still large as the form factors governing the transitions are not derived from first principles, and the transitions are measured in only part of the phase space. In consequence model dependence dominates. The recent CLEO study of $B \to \rho l \upsilon$ yields the value below. When this result is averaged with a previous CLEO analysis [6] which employs a slightly different analysis technique, the combined value of V_{ub} is:

$$BR(B \to \rho^- l^+ \nu) = (2.57 \pm 0.29^{+0.33}_{-0.46} \pm 0.41) \times 10^{-4}$$
$$|V_{ub}| = (3.25 \pm 0.14 \pm^{0.21}_{0.29} \pm 0.55) \times 10^{-3} \qquad (5)$$

For LEP results see [7].

Neutrino reconstruction dominates the systematic uncertainty. The combined experimental error is 10% the theoretical error is 20%. To reduce the theory error by a factor of two we need to know how much of the rate is in the acceptance to about 10% and the overall normaliztion to 15%. This is extremely difficult to achieve. The alternative is to minimize the extrapolation experimentally by maximizing the acceptance to test the theory. Working in the endpoint will not suffice. Fig. 5 shows the problems inherent in trying to choose between models when only high momentum leptons are observed, and the improvement in discriminating power to be gained when leptons of all momenta are used in an analysis.

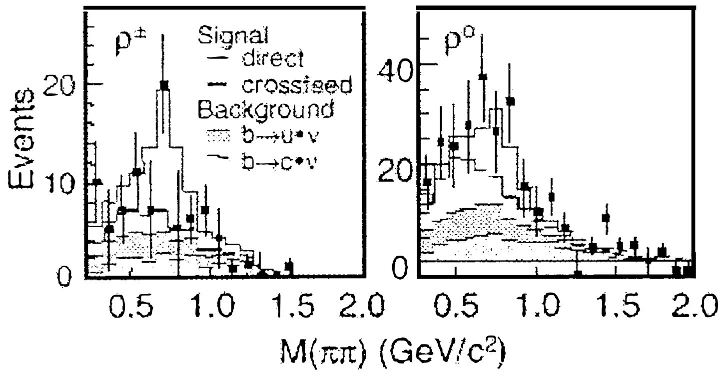


Figure 4. The $\pi\pi$ invariant mass spectrum in events with a lepton near the endpoint, from the CLEO $B \to \rho l \upsilon$ analysis.

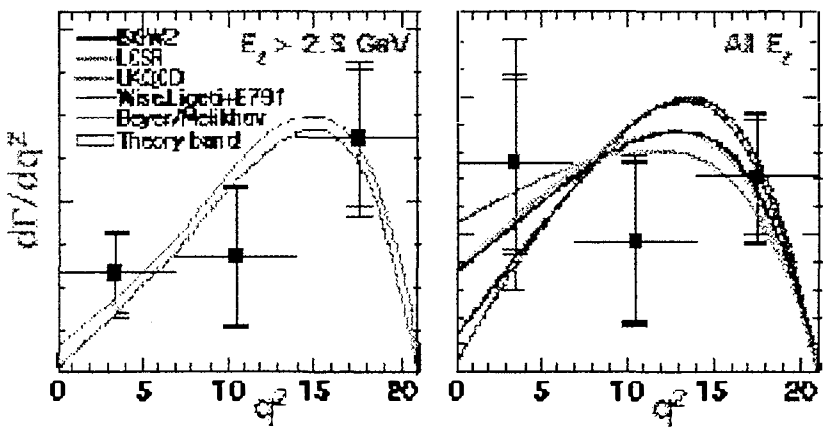


Figure 5 The differential decay rate as a function of the momentum transfer squared in $B \to \rho l \upsilon$. Left: for leptons in the endpoint region, the yellow band is the range of theory predictions. Right: for all leptons, at low momentum transfer there is a relatively large difference between models.

One part of increasing the experimental acceptance is to work to lower the lepton momentum cut for the modes that have already been observed. A second approach is to increase the number of b →ulυ transitions observed to provide a second constraint on the theoretical models.The decay B →ηlυ is an example of a transition that has never been observed that can provide new experimental constraints on the models.

Some of these approaches are being attempted with the CLEO data. How will the B Factories change the situation? The exclusive approach will remain the most precise way to determine. V_{ub} with data samples of order 60 x 10^6 BB decays the statistical and systematic errors should be of the order 5%-7%. It will be possible to measure the form factors of the exclusive modes directly and hence eliminate, or greatly reduce, the model dependence. In addition Heavy Quark Symmetry and SU(3) will be used to relate the form factors in D→ρlυ to B→ulυ

As the data samples grow inclusive methods become competitive. While the endpoint of the lepton spectrum represents only a small fraction of phase space, a very large fraction of phase space satisfies $m_x^2<m_D^2$. If these events can be isolated, the theoretical uncertainty associated with V_{ub} can be reduced, The technique is to use B tagging, i.e. full reconstruction of the other B in the event. The remainder of the event is then required to have only one lepton, and missing mass consistent with a neutrino. Since B tagging has an efficiency below 1% a large data sample is required. For 60 x 10^6 BB only 240 events would be reconstructed, however for a sample of 240 x 10^6 BB the statistical error on V_{ub} is 1.5%, and the experimental systematic error, which arises from charm leakage into the signal region and high m_x signal loss, is estimated to be 3-6%.With even larger data samples, of order 3 x 10^9 BB, the inclusive q^2 endpoint can be used to measure V_{ub} .The experimental errors are estimated to be <1% (stat) and 1.5-2.5% (sys).This method is currently believed to have the least theoretical uncertainty (5%) [4] and is one of the motivations to build a new high luminosity e+e- B Factory [8].

4 CP Violation

The origin of CP violation is one of the outstanding questions of particle physics. In the Standard Model CP violation is accommodated by the presence of a complex phase in the CKM matrix and CP asymmetries are related to the three interior angles of the triangle $\beta = \arg(V_{td}^*), \gamma = \arg(V_{ub}^*), \alpha = \pi - \beta - \gamma$ For CP violation to be permitted in the SM, the triangle must have non-zero area, i.e. V_{ub} is non-zero. In the SM a precision measurement of the sides of the triangle would completely determine the triangle, including the phase, and measurements of the angles would not be required. However the SM is incomplete, any extension of the SM that explains the mass of the W and Z involves, for example, extra Higgs bosons or SUSY partners that could change the CP asymmetric phase of B_d mixing and/or the phase of penguin diagrams from their SM expectations. Additional quark generations would also introduce new CP-violating phases. Finally, and most importantly, if the origin of the matter anti-matter asymmetry of the Universe did not arise at the GUT scale it is widely believed that the small size of CP violation in the SM implies that new and accessible physics gives rise to the net baryon number of the Universe

The study of rare decays of B mesons plays a key role in understanding the phenomenon of CP violation within the Standard Model. Large CP asymmetries are predicted for some exclusive final states, and although the relatively small branching fractions of order 10^{-5} currently limit the experimental reach for such studies, the sensitivity of the CLEO II detector allows measurements of branching fractions for many decay modes. Many of these processes proceed via loop diagrams which are uniquely sensitive to new, massive particles such as SUSY or Higgs. The very small rate for the primary decay process allows for competition by these new physics processes.

Using B →Kπ as an example, the method of reconstruction of a B meson decay is as follows. A beam constrained B mass $M = (E_b^2 - p_B^2)^{1/2}$ is calculated where p_B is the B candidate momentum and E_b is the beam energy. The resolution in M is about 2.5-3 MeV , where the larger resolution corresponds to modes with a pizero in the final state. We define $\Delta E = E_1 + E_2 - E_b$ where E_1 and E_2 are the energies of the daughters of the B meson candidate. The resolution in ΔE is mode dependent. For final states without photons the resolution in ΔE = 20-26 MeV.

A critical aspect of isolating rare B decays is the suppression of background.The large background from continuum quark-anti-quark production is reduced with event shape cuts. Because B mesons are produced almost at rest, the decay products of the B B pair tend to be isotropically distributed, while particles from continuum production have a more jet-like distribution.

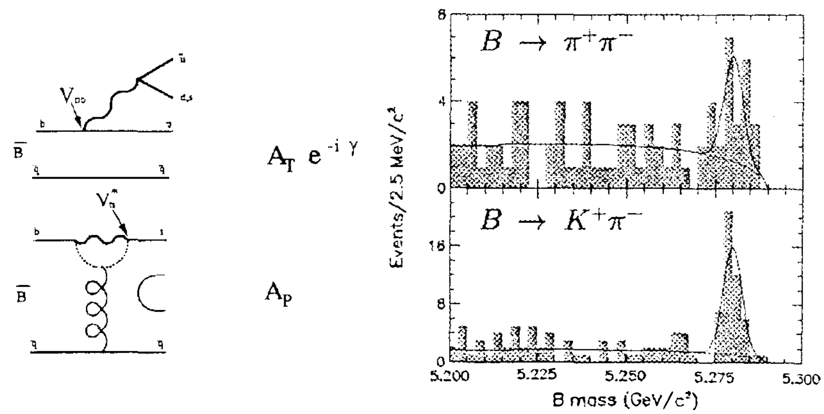


Figure 6. Left: Quark level diagrams for the B →Kπ/ππ family of decays. Right: beam constrained mass for B →ππ and B→Kπ.

Using this technique all four of the B →Kπ/ππ family of decays have been measured by CLEO[9]. In Figure 6 the beam constrained mass for B→Kπ and B →ππ are shown. A summary of the results of this analysis are given in Table 2.

The decays B →Kπ/ππ are of interest as they provide a relatively low statistics way to bound γ. The quark level decay diagrams for B →Kπ and B →ππ are shown in Figure 6. From CKM counting we expect: B →Kπ to be mostly penguin and B →ππ to be tree dominated. A bound on γ can be obtained in two ways: measure rates or CP asymmetry, Acp, both contain information on the product of γ and the (unknown) strong phase difference Δφ, between contributing amplitudes.

$$(BR+\overline{BR})/2=|A_T|^2+|A_P|^2+2|A_T A_P|\cos\gamma\cos\Delta_{strong} \quad (6)$$

$$A_{CP}=\frac{B(b\to f)-B(\bar{b}\to \bar{f})}{B(b\to f)+B(\bar{b}\to \bar{f})}=\frac{2|A_T A_P|\sin\gamma\sin\Delta\phi}{|A_T|^2+|A_P|^2+2|A_T A_P|\cos\gamma\cos\Delta\phi} \quad (7)$$

Where A_T and A_P are tree and penguin amplitudes respectively. The results in Table 2 are in general agreement with theoretical expectations. $B\to\pi\pi$ has finally been observed but the branching ratio is small. Gluonic penguin modes are large, this implies severe penguin pollution will complicate the extraction of α at BaBar/Belle

Table 2. A summary of event yields and branching ratios for rare two-body B decays in the $K\pi/\pi\pi$ family

Mode	N	$\mathcal{B}\times10^6$
$\pi^\pm\pi^\mp$	$20.0^{+7.6}_{-6.5}$	$4.3^{+1.6}_{-1.4}\pm0.5$
$\pi^\pm\pi^0$	$21.3^{+9.7}_{-8.5}$	<12.7
$K^\pm\pi^\mp$	$80.2^{+11.8}_{-11.0}$	$17.2^{+2.5}_{-2.4}\pm1.2$
$K^\pm\pi^0$	$42.1^{+10.9}_{-9.9}$	$11.6^{+3.0}_{-2.7}{}^{+1.4}_{-1.3}$
$K^0\pi^\pm$	$25.2^{+6.4}_{-5.6}$	$18.2^{+4.6}_{-4.0}\pm1.6$
$K^0\pi^0$	$16.1^{+5.9}_{-5.0}$	$14.6^{+5.9}_{-5.1}{}^{+2.4}_{-3.3}$

CLEO has searched for CP violation in all the decay modes listed in Table 3 [10]. These decays are selected because they have well-measured branching ratios and significant signal yields in our data. In addition these decays are self-tagging: the flavor of the parent b quark is tagged simply by the sign of the high momentum charged hadron. It is not possible to calculate the absolute value of the amplitudes and the phases from first principles, factorization models predict Acp($K\pi$): 4-11% FSI (large $\sin\Delta\phi$) predict Acp($K\pi$): 20-40% New Physics, i.e. additional phases predicts Acp($K\pi$): 40-60%. With current statistics (80 events) a ~3σ result is possible in the SM.

Table 3. Summary of results. Signal yields are taken from [9]. SM theory predictions are from [11]. The 90% C.L. interval includes both statistical and systematic errors, the former dominate.

	Events	$\mathcal{A}_{CP}^{\rm Theory}$ (Ali *et al.*)	$\mathcal{A}_{CP}$	90% CL Region
$K^\pm\pi^\mp$	$80.2^{+11.8}_{-11.0}$	$[+0.037,+0.106]$	-0.04 ± 0.16	$[-0.30,0.22]$
$K^\pm\pi^0$	$42.1^{+10.9}_{-9.9}$	$[+0.026,+0.092]$	-0.29 ± 0.23	$[-0.67,0.09]$
$K^0_S\pi^\pm$	$25.2^{+6.4}_{-5.6}$	$+0.015$	$+0.18\pm0.24$	$[-0.22,0.56]$
$K^\pm\eta'$	100.0^{+13}_{-12}	$[+0.020,+0.061]$	-0.03 ± 0.12	$[-0.17,0.23]$
$\omega\pi^\pm$	$28.5^{+8.2}_{-7.3}$	$[-0.120,+0.024]$	-0.34 ± 0.25	$[-0.75,0.07]$

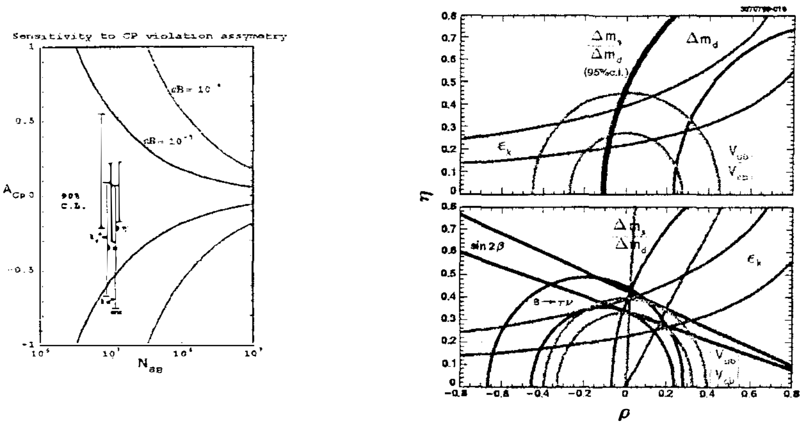


Figure 7. Left: curves of constant efficiency branching ratio product as a function of the data sample size required for a four sigma measurements of Acp. Right: constraints on the ρ-η plane from the measurements indicated in 2000 (upper) and 2003 after the initial operation of the B factories and Run IIa of the Tevatron. The area of the region of overlap is exepcted to be reduced by about a factor of six in the next three years.

No evidence for direct CP violation is found in the five modes. The results are statistics limited Our ability to distinguish between charge conjugate states depends on particle identification using dE/dx. No charge dependencies were found in the dE/dx and a conservative systematic error of 0.02 is assigned. The results exclude a large part of the parameter space. Clearly precision measurements of Acp will require very large data sets!

Outlook

B physics is a unique probe of the quark mixing sector of the standard model, and beyond The CLEO experiment has been a pioneer in this field. The B factories, CDF, and D0 will qualitatively transform the field in the next 5 years. Hadron and e+e- colliders will contribute in complementary ways. Undoubtedly new and un-anticipated discoveries will be made. Small branching ratios and rich phenomena challenge theory, but need very large datasets. The B factories will likely have a 10 year life span. In the second half of their life the LHC will turn on. BTeV, LHC-B, ATLAS and CMS are expected to make significant contributions to B physics during that time. Second generation extremely high luminosity B factories are also under consideration. Together this arsenal of accelerators and experiments will be make the definitive measurements of CP violation in the B system.

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