B Physics at e^+e^- Machines

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Abstract. A review of present successes and future prospects for B physics at e^+e^- machines is undertaken. Existing measurements are briefly examined to lay the groundwork for extrapolating results for the future of threshold experiments, before considering the capabilities of Z^0 experiments. Proposals for new facilities are also discussed.

Although the first evidence for the b-quark was found some 10 years ago [1] with the discovery of the $\Upsilon(1S)$, the lightest $b\bar{b}$ bound state, progress in determining the properties of the b-quark has been painfully slow. Most of what we do know, with the exception of lifetimes, has been the work of e^+e^- experiments running on the $\Upsilon(4S)$ at the threshold for B production. The dominant $b \to c$ modes have been explored, including the reconstruction of a few exclusive channels. B^0-$\overline{B}^0$ mixing has been observed, and first evidence for a finite $b \to u$ coupling obtained. However, these measurements are only sufficient to whet one's appetite.

A future program should aim for precision determinations of:

- V_{ub} and V_{cb}
- lifetimes and semi-leptonic branching ratios
- B^0-$\overline{B}^0$ and B^0_S-$\overline{B}^0_S$ mixing rates and properties

Observation of rare decay modes, in particular of radiative B decays via the penguin diagram, would help clarify our picture of weak decays. When seen, the leptonic B decay to $\tau\nu_\tau$ will provide a much needed measurement of the B form factor. Ultimately, of course, the rich realm of CP violation in the b-system beckons. These goals will be considered as benchmarks for this review.

A survey of existing experimental techniques and results will shed some light on the difficulties and future prospects. The Z^0 as a prolific source of b-quarks will soon be available, with possible new and complementary approaches to the experimental problems. Reflecting the active interest of the community and the successes achieved at e^+e^- machines, proposals for new e^+e^- facilities are under consideration and will be examined.

1 Present Situation

1.1 B Reconstruction

Both ARGUS [2] and CLEO [3,4] have succeeded in reconstructing B mesons. Starting with data samples containing 1 to 2×10^5 B decays, they each have been able to identify about one hundred B mesons in the cleanest hadronic decay channels. This low reconstruction efficiency is the major impediment to progress in probing the b-system. Hence, it is instructive to examine the techniques used by these groups. Not all of the difficulties encountered are applicable to continuum experiments above threshold. However, a common factor is certainly the typically small exclusive branching ratios for hadronic modes. For two-body decays, presumably the most accessible, these are approximately an order of magnitude smaller for B mesons than for charm.

The $\Upsilon(4S)$ is in many ways an attractive source of B mesons: the large cross section implies both a high rate of B production and a favourable signal-to-background ratio. Moreover, the $\Upsilon(4S)$ is a pure source of B^- and B^0; there are no complications due to production of heavier b-flavoured hadrons. This also implies that the energy of a B candidate is the beam energy, which provides an often invaluable constraint, as we will see shortly.

However, there are also disadvantages. Working at threshold means the B mesons are produced nearly at rest, with at least two detrimental consequences. First, the decay products of the B and $\overline{B}$ are completely intermixed, resulting in formidable combinatorial backgrounds. Second, detectors must cover a large solid angle, since geometry contributes to the acceptance losses with a power corresponding to the number of final state particles in the decay. The combinatorial background can, in part, be reduced by particle identification. Even so, searches are in general confined to channels with intermediate charm states, more readily identified in the detector, or low multiplicity. Unfortunately, the use of intermediate states implies yet another substantial efficiency reduction, since only a small fraction of charm decays will be available.

As a specific example, consider the reconstruction by ARGUS of the decays:

$$\begin{aligned} \overline{B}^0 \quad \rightarrow \quad & D^{*+}\pi^- \\ & D^{*+}\pi^-\pi^0 \\ & D^{*+}\pi^-\pi^-\pi^+ \end{aligned}$$

and

$$\begin{aligned} B^- \quad \rightarrow \quad & D^{*+}\pi^-\pi^- \\ & D^{*+}\pi^-\pi^-\pi^0 \end{aligned}$$

where the D^{*+} is detected via its decay into $D^0\pi^+$, and the D^0 is seen in any of the following channels:

$$\begin{aligned} D^0 \quad \rightarrow \quad & K^-\pi^+ \\ & K^0_S\pi^+\pi^- \\ & K^-\pi^+\pi^0 \\ & K^-\pi^+\pi^+\pi^- \end{aligned}$$

In all, five B decay channels were studied, comprising, with the four D^0 decay modes, a total of 20 decay chains. Up to 9 particles observed in the detector are combined to form a B candidate.

In the search for B candidates, two principal requirements were made:

- the probability for the sum of χ^2 from particle identification and kinematic fits must exceed 1%
- the candidate must have an energy within 3σ of the beam energy

Through particle identification and good mass resolution for short-lived intermediate states, particularly for the D^{*+}-D^0 mass difference, a sharp reduction in combinatorial background is achieved. Candidates satisfying these cuts were subject to an energy constraint fit. Thereby, the mass difference between m(B) and a fixed value for $m[\Upsilon(4S)]/2$ is effectively measured, for which the experimental resolution is about 4 MeV/c^2.

The resulting mass plot for 59 pb^{-1} on the $\Upsilon(4S)$ is shown in Figure 1a. A signal of about 71 events can be seen above a falling background, parameterized by:

$$\frac{dN}{dm} \sim m\sqrt{1 - m^2/E^2_{beam}}$$

This is the expected shape if the background is uniformly distributed in phase space, a reasonable assumption for the continuum contribution. Backgrounds from $\Upsilon(4S)$ events with incomplete or incorrect reconstruction problems, e.g. missing soft particles or particle misidentification, lead to correlated background components and nearby reflections. Such difficulties should receive serious consideration in the planning of future experiments.

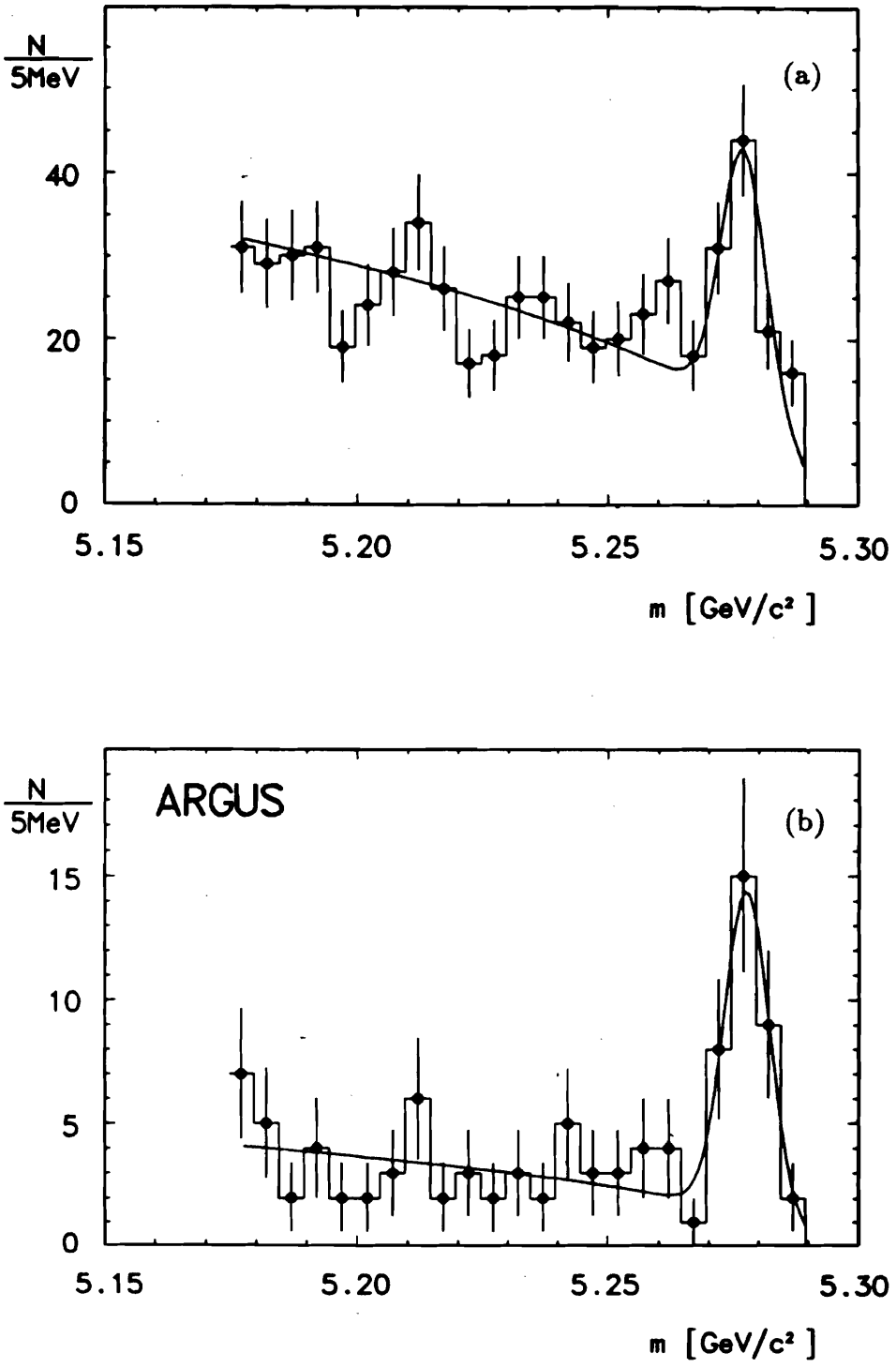

Figure 1. Mass distribution for combined B^- and $\overline{B}^0$ channels [2], (a) for all 20 considered decay chains, and (b) with the 6 highest-background decay chains removed.

Typically, Monte Carlo studies implicitly ignore such possibilities. If the six channels with large combinatorial background are removed, a clean sample of 29 events is obtained (Figure 1b), suitable for tagging experiments. However, an efficiency of 3×10^{-5} is far too small to be useful with present luminosities.

The same kind of approach has been successfully applied to other exclusive modes involving the D^0, D^+ and J/ψ. A summary of branching ratios for the known B decay modes is given in Table 1. The smallness of hadronic branching ratios is not very encouraging.

Channel	Branching Ratio [%]	
	CLEO	ARGUS
$\overline{B}^0 \to D^+\pi^-$	$0.60 \pm 0.30 \pm 0.14$	
$\overline{B}^0 \to D^{*+}\pi^-$	$0.32^{+0.17+0.11}_{-0.13-0.07}$	$0.35 \pm 0.18 \pm 0.13$
$\overline{B}^0 \to D^{*+}\pi^-\pi^+\pi^-$	< 4.8 (90% CL)	$4.3 \pm 1.2 \pm 2.0$
$\overline{B}^0 \to D^{*+}\pi^-\pi^0$		$2.0 \pm 1.0 \pm 1.0$
$\overline{B}^0 \to J/\psi\overline{K}^{*0}$	0.41 ± 0.19	0.33 ± 0.18
$B^- \to D^0\pi^-$	$0.48^{+0.16+0.11}_{-0.13-0.07}$	
$B^- \to D^+\pi^-\pi^-$	$0.25^{+0.41+0.24}_{-0.23-0.07}$	
$B^- \to D^{*+}\pi^-\pi^-$	$0.21^{+0.15+0.08}_{-0.13-0.05}$	$0.60 \pm 0.30 \pm 0.40$
$B^- \to D^{*+}\pi^-\pi^-\pi^0$		$5.6 \pm 1.7 \pm 3.4$
$B^- \to J/\psi K^-$	0.09 ± 0.06	0.07 ± 0.04
$B^- \to J/\psi K^-\pi^+\pi^-$		0.11 ± 0.07
$B^- \to \psi' K^-$		0.22 ± 0.17

Table 1. Branching ratios for exclusive B decays [5].

More promising are the semi-leptonic modes. ARGUS has used a recoil-mass technique [6] to extract a signal for the decay $B^0 \to D^{*-}\ell^+\nu$, expected to be the dominant semi-leptonic channel. The approach depends on small B^0 momentum, as is the case for $\Upsilon(4S)$ decays. The neutrino is unobserved, but can be inferred if the recoil mass against the $D^{*-}\ell^+$ system, m^2_{recoil}, is consistent with zero. The recoil mass is defined by:

$$m^2_{recoil} = [E_{beam} - (E_{D^{*-}} + E_{l^+})]^2 - [\vec{p}_{D^{*-}} + \vec{p}_{l^+}]^2$$

The D^{*-} was reconstructed in the $\overline{D}^0\pi^-$ decay mode, where the $\overline{D}^0 \to K^+\pi^-$ was kinematically constrained to the known $\overline{D}^0$ mass. Lepton identification was based on the coherent use of information from all detector components, implemented by constructing a combined likelihood ratio. The e^+ or μ^+ hypothesis was accepted if the likelihood ratio exceeded 80%.

If the D^{*-} candidates are required to have $x_p < 0.5$ and the lepton momentum above 1.0 GeV/c, the recoil mass spectrum shown in Figure 2 is obtained from the full 103 pb^{-1} of available $\Upsilon(4S)$ data. Visible is a prominent peak at $m^2_{recoil} = 0$ with little background. A fit to the recoil-mass spectrum yields a signal of 46 ± 7 events at $m^2_{recoil} = 0$. The data are consistent with electron-muon universality, which is assumed in obtaining:

$$Br(B^0 \rightarrow D^{*-}\ell^+\nu) = (7.0 \pm 1.2 \pm 1.9)\%$$

where the first error is statistical and the second systematic. Employing all four D^0 decay channels previously used for the hadronic B decays, ARGUS obtains a tagged sample of over 200 B^0 decays, a substantial improvement in efficiency over the hadronic modes.

1.2 Determination of V_{cb}

One of the primary interests in studying B decays is the determination of the Kobayashi-Maskawa matrix elements [7]. The decay width of the b-quark is calculated from the sum of spectator contributions from $b \rightarrow c$ and $b \rightarrow u$ transitions [8]. The theoretical uncertainties in non-spectator effects and QCD corrections are minimal for the semi-leptonic width:

$$\Gamma_{SL} = \frac{{G_F}^2 m_b^5}{192\pi^3}\left(|V_{ub}|^2 + 0.48|V_{cb}|^2\right)$$

Since $\Gamma_{SL} = \hbar Br_{SL}/\tau_b$, the experimental inputs are measurements of the B inclusive semi-leptonic branching ratio and the b-quark lifetime.

The inclusive semi-leptonic branching ratios for b-flavoured hadrons have been determined with good precision. On the $\Upsilon(4S)$, measurements [9,10] of the branching ratio for $B \rightarrow X\ell^+\nu$ give an average value of $(11.8 \pm 0.3 \pm 0.6)\%$ [11], where B represents a mixture of B^0 and B^+ mesons. A similar result, $(12.0 \pm 0.6 \pm 1.5)\%$ [11], is obtained by continuum e^+e^- experiments [12,13], operating well above the open beauty threshold where a mixture of b-flavoured mesons and baryons is produced. Unless fortuitous, these measurements are remarkably alike, implying that stable b-flavoured hadrons have similar lifetimes. This is, in fact, the expectation if the spectator model provides a correct description of B decays.

Measurements of the B lifetime have been made in continuum e^+e^- production at PEP and PETRA. These results are based on non-zero average impact parameters for enriched b-samples. Varying degrees of enrichment are obtained, for example, by requiring a high-p_T lepton. The results rely on Monte Carlo simulation to estimate the b-content of the sample, and, of course, represent an average lifetime for b-flavoured hadrons. The present world average is (1.18 ± 0.14) ps [14].

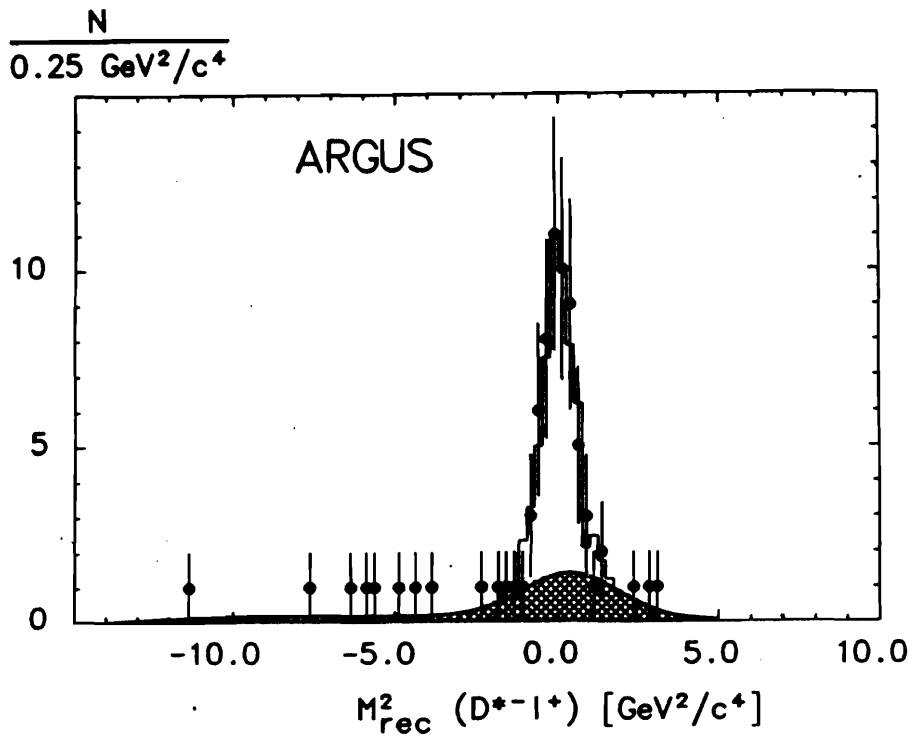

Figure 2. Recoil mass squared, M^2_{Recoil}, for events containing a D^{*-} and one positive lepton with $p > 1.0$ GeV/c [6]. The hatched curve is the estimated background from all sources, and the histogram the Monte Carlo prediction for the decay $B^0 \to D^{*-}\ell^+\nu$.

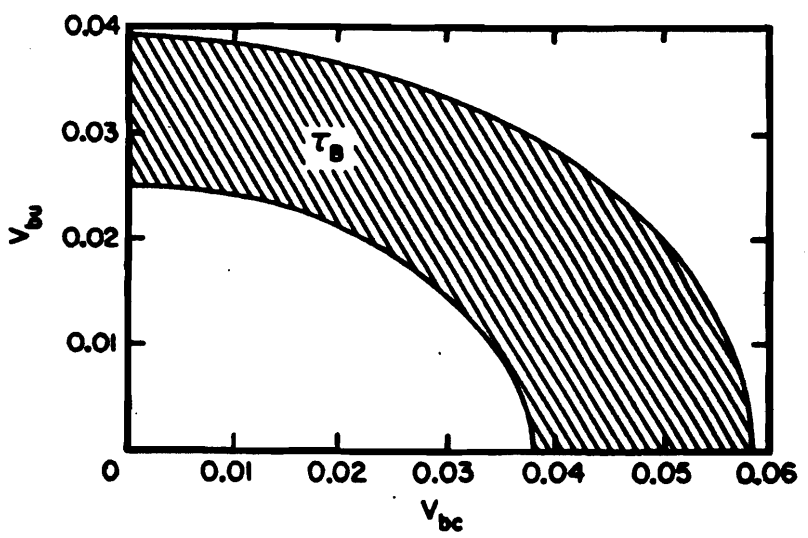

Figure 3. Allowed region (hatched area) for V_{cb} versus V_{ub} from measurements of the b-lifetime and semi-leptonic branching ratio.

These results restrict the allowed values of V_{ub} and V_{cb} to the shaded region in Figure 3. However, it can easily be demonstrated that the $b \to c$ coupling dominates the decay width, simply by summing the observed number of charmed quarks produced per B decay. A charmed quark will be manifested by the observation of one of the stable charmed meson or baryon states, D^0, D^+, D_S^+, J/ψ or Λ_C^+, as a decay product. Direct measurements of the inclusive production rates for the first four of these have been made, while the baryon yield can be inferred from proton and Λ inclusive branching ratios. The latest results are shown in Table 2 [5]. Including a contribution of about 15% for the production of charm in W decays, one expects about 1.15 charm quarks per B decay, if $V_{ub} = 0$. The observed rates are close to this value, although a 30% contribution for $|V_{ub}/V_{cb}|$ could easily be accommodated.

	Branching Ratio [%]	
Channel	ARGUS	CLEO
$B \to D^0X$	63.0 ± 10.0	52.0 ± 8.6
$B \to D^+X$	25.0 ± 6.4	22.0 ± 5.8
$B \to D_S^+X$	12.0 ± 5.0	13.0 ± 4.7
$B \to$ "J/ψ"X	3.5 ± 0.6	3.5 ± 0.6
$B \to$ "Λ_C"X	7.4 ± 2.9	7.4 ± 2.9
Total	$111. \pm 13.2$	97.9 ± 11.8

Table 2. Observed number of charm quarks per B decay.

1.3 Observation of Charmless B Decays

Two approaches have been used in searches for $b \to u$ transitions in B decays. The first exploits the different kinematic limits for the lepton momentum in semi-leptonic $b \to c$ versus $b \to u$ decays. Although conceptually simple, in practice the extracted limits for $|V_{ub}/V_{cb}|$ are dominated by theoretical uncertainties. One can restrict the search to the narrow region beyond the kinematic limit for $b \to c$ transitions, with considerable loss in statistics, and thus eliminate any dependence on assumptions about the exact shape of the $b \to c$ spectrum. However, it still remains necessary to connect such a measurement to the inclusive rate for semi-leptonic $b \to u$ transitions, an extrapolation which embodies large uncertainties. In particular, because of the restricted momentum region of the search, these measurements are sensitive to just a few exclusive semi-leptonic channels. It is necessary to both make the momentum extrapolation, and predict the fraction these channels represent of all $b \to u$ transitions. There are a variety of models [15-19] which propose to do just

this, resulting in limits which vary by a factor of two. The present limit obtained in this manner is $|V_{ub}/V_{cb}| < 0.17$ (90% CL) [20], using a model which gives the least restrictive result [18].

An alternative method is to search for exclusive hadronic B decays with no charm or strangeness in the final state. In order to extract a measurement of V_{ub} from a positive signal, the same difficulty in connecting an exclusive channel to an inclusive rate will arise, perhaps introducing even greater model dependence to any result. However, such a search may be experimentally more accessible, since no phase space restrictions are necessary and backgrounds can be smaller.

Upper limits on channels leading to two or three pions in the final state have been reported by CLEO [4]. These searches are typically restricted to low multiplicity channels, where combinatorial background can be kept to manageable levels, and do not reach an interesting level of sensitivity. If more of the available phase-space were absorbed as mass, it is possible that the sensitivity in low multiplicity channels might be improved. This leads naturally to searches for non-charm final states containing baryons.

Following this line of thought, ARGUS has investigated the channels:

$$\mathrm{B}^- \rightarrow \mathrm{p}\overline{\mathrm{p}}\pi^-$$
$$\overline{\mathrm{B}}^0 \rightarrow \mathrm{p}\overline{\mathrm{p}}\pi^+\pi^-$$

The data for this analysis consists of about 103 pb^{-1} obtained on the $\Upsilon(4S)$, consisting of some 176,000 B decays. For background studies, 42 pb^{-1} in the continuum at centre-of-mass energies just below the $\Upsilon(4S)$ are also used. Particle identification information is incorporated by selecting candidates with a probability of greater than 10% for the sum of χ^2's for the individual mass hypotheses, determined from specific ionization and time-of-flight measurements. As for the reconstruction of B decays through D^{*+} channels [2], an energy constraint fit is applied to those candidates satisfying the requirement: $|\mathrm{E_B} - \mathrm{E_{Beam}}| < 3\sigma$.

The continuum component of combinatorial background is suppressed by taking advantage of the different topologies of $\Upsilon(4S)$ and continuum events. The thrust axes are determined for the candidate, and for the remainder of the event with the candidate removed. For continuum events, which are predominantly two-jet, these axes will tend to align. However, B mesons produced in $\Upsilon(4S)$ decays are essentially at rest, so the signal should exhibit little correlation. The difference in the angle between the two thrust axes is required to satisfy $\cos\alpha_{\mathrm{thrust}} < 0.7$, resulting in a sizable reduction in the continuum background.

The distribution of the opening angle, $\theta_{p\overline{p}}$, between the proton and anti-proton is shown in Figure 4a for candidates which pass these cuts and have an invariant mass in the B mass region ($5.270 < M < 5.285$ GeV/c^2). A strong back-to-back correlation between the baryons is evident. For comparison, the same distribution for the candidates in the sideband below the B mass region ($5.170 < M < 5.260$ GeV/c^2), or in the continuum, is shown in Figure 4b and c, appropriately normalized. There is clearly an excess of about 35 events in the Υ(4S) sample for opening angles greater than 165°. This behavior is readily understood if two-body decay channels, consisting of protons and low-mass baryon resonances, dominate and pions are mainly the product of resonance decays. Exploiting this difference, we require $\cos\theta_{p\overline{p}} < -0.98$.

After this cut, the mass spectrum for the Υ(4S) sample shown in Figure 5a is obtained. The solid line is the result of a fit using a gaussian of free mass and width for the signal, and a one-parameter background of the form noted in section 2.1. The fitted number of events is 32 ± 8, with a mass of $(5279.4 \pm 0.9 \pm 3.0)$ MeV/c^2 and an RMS width, consistent with expectation, of (3.3 ± 0.7) MeV/c^2. The probability that the excess of events at the B mass is just a statistical fluctuation of the background in that region corresponds to six standard deviations. If one instead assumes a more conservative constant background level, the signal still represents more than a five sigma excess.

In general, background can arise from both continuum $q\overline{q}$ and $\Upsilon(4S) \rightarrow B\overline{B}$ events. The level and form of the continuum contribution have been determined by applying identical requirements to a continuum sample taken at centre-of-mass energies below the Υ(4S). The resulting mass distribution (Figure 5b) has no peak at the B mass, and is well described by the one-parameter background function. The fitted curve, scaled by the ratio of luminosities for the Υ(4S) and continuum samples, is shown as the dotted area in Figure 5a. Outside the B mass region, scaled continuum and Υ(4S) samples agree well in magnitude. Thus, the background in the Υ(4S) sample is consistent with originating predominantly from non-resonant $q\overline{q}$ events. Any contribution from $\Upsilon(4S) \rightarrow B\overline{B}$ events, at least outside the B mass region, must be small.

While it is not too surprising that continuum events produce a smooth background, it is far from obvious that the same will be true for background from $B\overline{B}$ pairs. To appreciate the potential difficulty, one should recall the peculiar topology of the signal events. The momentum of the two proton candidates is outside the region where either dE/dx or TOF can provide positive identification. If the tracks were not actually protons, our requirement of consistency with the proton hypothesis would be roughly equivalent to selecting only high-momentum particles. Moreover, after the opening angle cut there

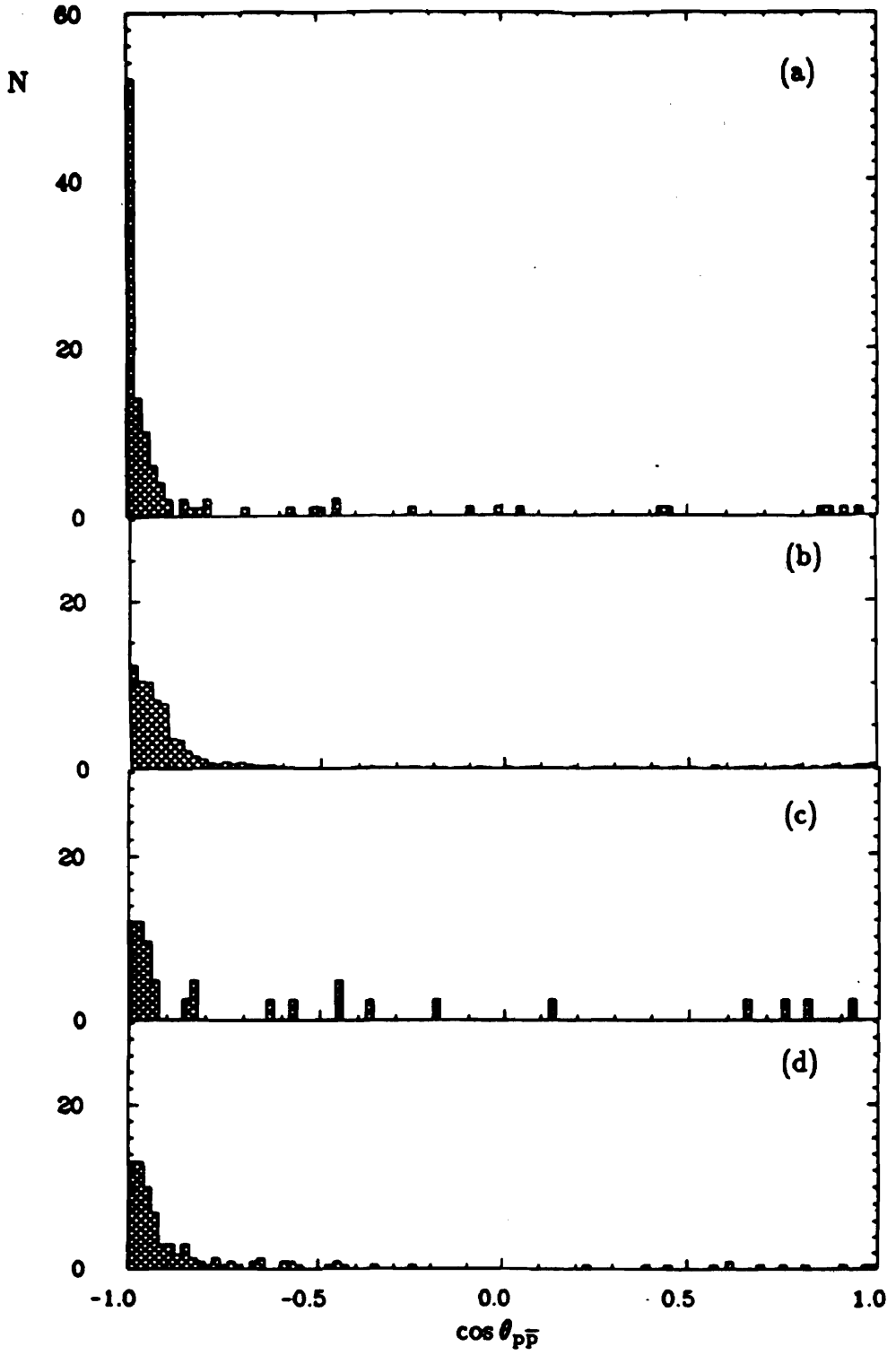

Figure 4. Opening angle, $\theta_{p\bar{p}}$, between the proton and anti-proton for (a) candidates in the B mass region ($5.270 < m < 5.285$ GeV/c^2), (b) a sideband interval below the B mass ($5.170 < m < 5.260$ GeV/c^2), (c) in the continuum and (d) Monte Carlo generated $e^+e^- \to q\bar{q}$.

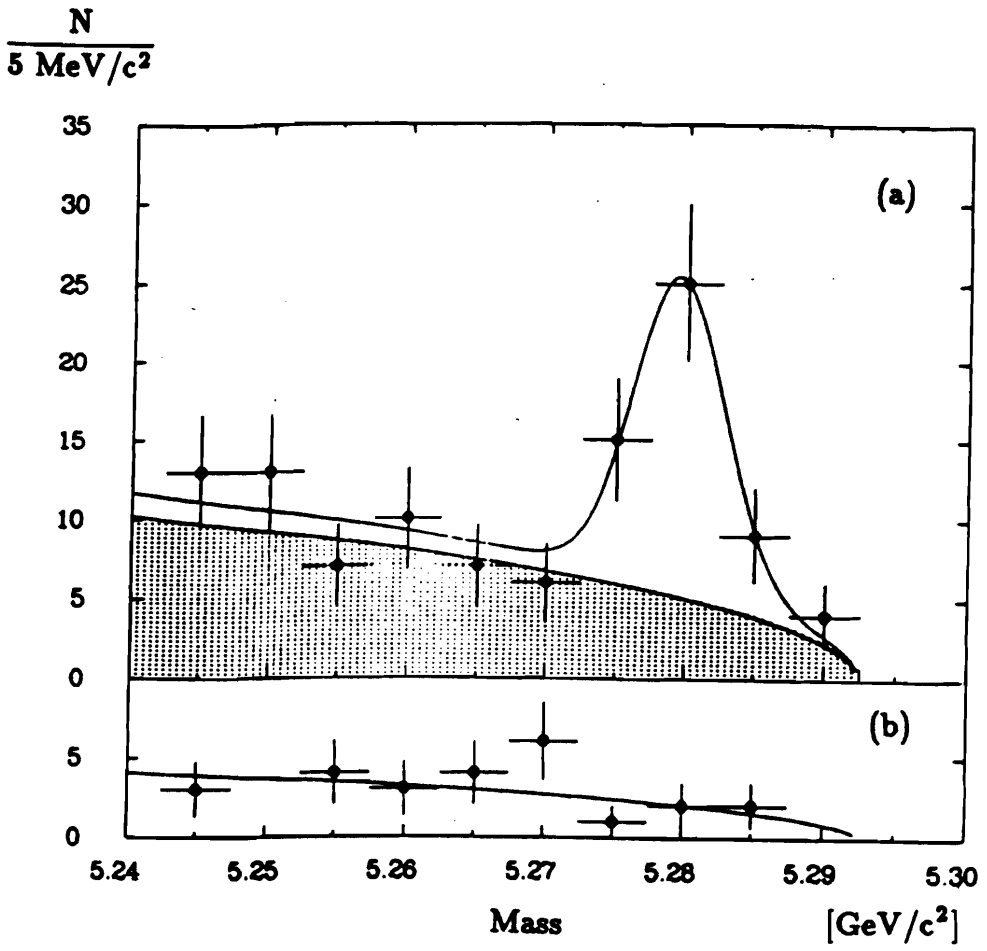

Figure 5. Invariant mass for B candidates (a) in the $\Upsilon(4S)$ and (b) continuum data samples. The fitted background rate in the continuum, scaled by the luminosity ratio, is shown as the dotted area of (a).

would be reasonable acceptance only if the two fast tracks come from a single B decay. It needs to be demonstrated that, despite the implicit correlation introduced by the selection criteria, B decays to charm cannot produce a narrow peak at the observed rate.

There are four logical divisions of these correlated background sources: the candidate tracks are selected from both B decays, or from just one, and for both alternatives the particle mass assignments may or may not be correct. While it is not possible to present the detailed arguments here, the most telling evidence that these backgrounds cannot account for the signals is obtained by (1) explicit searches for charm by using alternative allowed assignments for candidate tracks, (2) event mixing (Figure 6a), (3) repeating the same analysis for wrong-charge combinations (Figure 6b), and (4) Monte Carlo simulation. Figure 6c shows the level and shape of background for 250000 B^0 decays via $b \to c$, obtained by Monte Carlo calculation. There is no indication for any background source which could produce a peak at the B mass. The possibility that these channels are due to a penguin-type loop diagram can be ruled out experimentally. The only viable interpretation is to attribute these decays to $b \to u$ transitions.

The signals can be divided into the separate channels, and preliminary branching ratios determined:

$$\begin{aligned} \mathrm{Br}(\mathrm{B}^- \to \mathrm{p}\overline{\mathrm{p}}\pi^-) &= (3.7 \pm 1.3 \pm 1.4) \times 10^{-4} \\ \mathrm{Br}(\overline{\mathrm{B}}^0 \to \mathrm{p}\overline{\mathrm{p}}\pi^+\pi^-) &= (6.0 \pm 2.0 \pm 2.2) \times 10^{-4} \end{aligned}$$

where the first error is statistical and the second systematic, including a contribution introduced by our assumed background function. It is difficult to translate these measurements into a value for $|V_{ub}/V_{cb}|$. A rough estimation would be:

$$\left|\frac{V_{ub}}{V_{cb}}\right|^2 \cdot \mathrm{f_{PS}} \cdot \mathrm{f_{Baryon}} \cdot \mathrm{f_{Visible}} = \frac{\mathrm{Br}[\mathrm{B} \to \mathrm{p}\overline{\mathrm{p}}\pi^-(\pi^+)]}{\mathrm{Br}[\mathrm{B} \to \mathrm{Baryons}]}$$

where:

$$\begin{aligned} \mathrm{f_{PS}} &= \frac{\text{Phase Space for b} \to \text{u}}{\text{Phase Space for b} \to \text{c}} && \leq 2.2 \\ \mathrm{f_{Baryon}} &= \frac{\mathrm{Br}[\mathrm{B} \to \mathrm{Baryons}] \text{ via } b \to u}{\mathrm{Br}[\mathrm{B} \to \mathrm{Baryons}] \text{ via } b \to c} && \leq 2 \\ \mathrm{f_{Visible}} &= \frac{\mathrm{Br}[\mathrm{B} \to \mathrm{p}\overline{\mathrm{p}}\pi^-(\pi^+)] \text{ via } b \to u}{\mathrm{Br}[\mathrm{B} \to \mathrm{Baryons}] \text{ via } b \to u} && \leq \frac{1}{10} \end{aligned}$$

with plausible limiting values also indicated. Assuming the direct neutron and proton rates in B decays to be equal, and using the measured rates for $\mathrm{B} \to \mathrm{pX}$ and $\mathrm{B} \to \Lambda\mathrm{X}$,

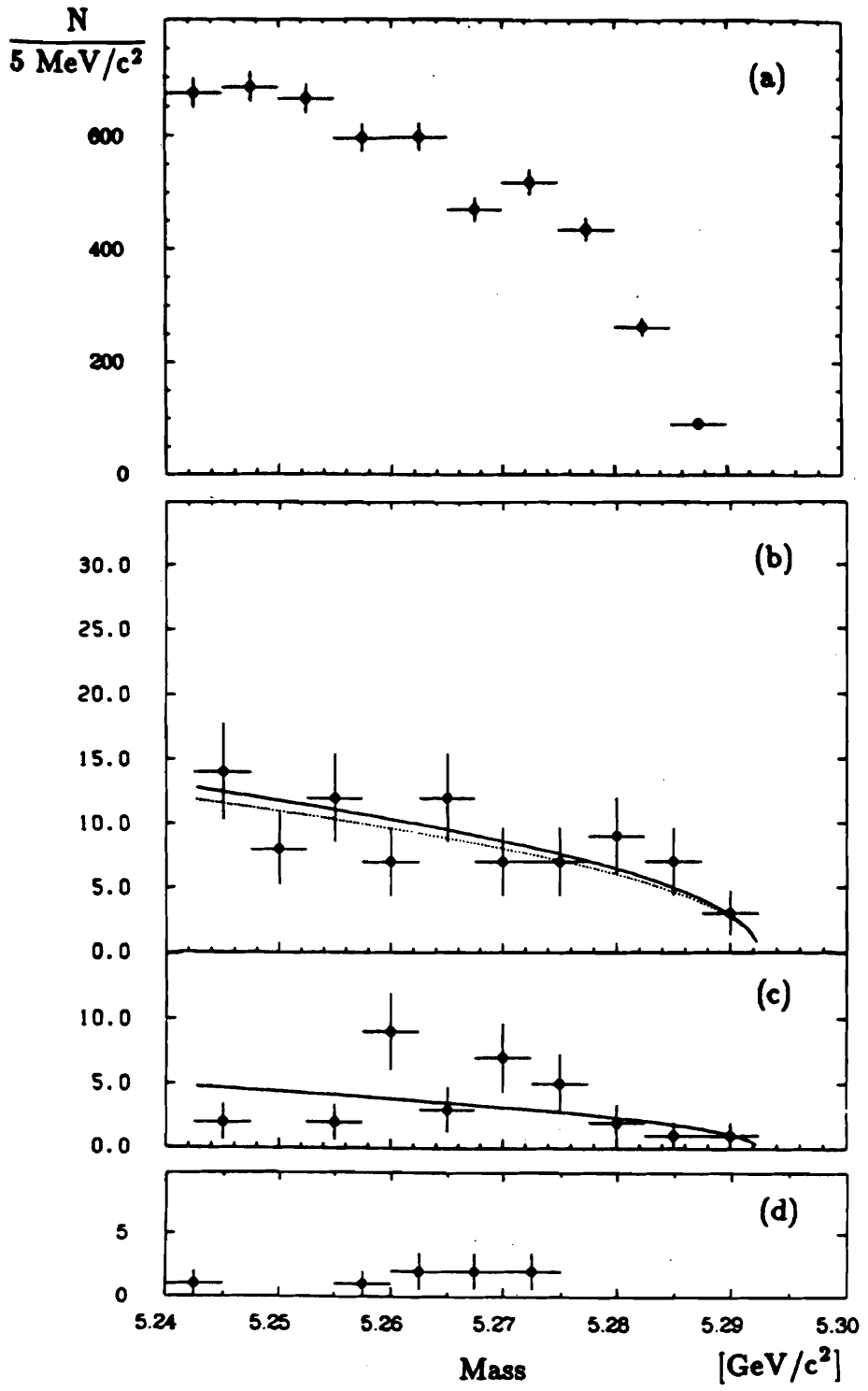

Figure 6. Background studies showing the mass distribution obtained from (a) event mixing, (b) wrong-charge combinations on the $\Upsilon(4S)$, (c) wrong-charge combinations in the continuum and (d) $\Upsilon(4S)$ Monte Carlo containing 250,000 B decays via ($b \rightarrow c$) transitions only.

one obtains: Br[B $\rightarrow$ Baryons] = $(7.4 \pm 2.9)\%$. Recalling the upper limit derived from the lepton momentum spectrum [20], the allowed range of values for V_{ub} is:

$$0.07 < \left|\frac{V_{ub}}{V_{cb}}\right| < 0.17$$

More information about corresponding higher multiplicity channels, as well as a better understanding of the subsystem components contributing to the observed final states, may lead to a better estimate of the ratio. The demonstration that $|V_{ub}| \neq 0$ is in itself quite significant, leaving open the possibility that CP violation originates just from the single non-trivial phase of the Kobayashi-Maskawa matrix.

1.4 Observation of B^0-$\overline{B}^0$ Mixing

The first observation of B^0-$\overline{B}^0$ mixing was reported [21] by ARGUS earlier this year, based on the study of B mesons produced in $\Upsilon(4S)$ decays. Mixing provides basic information on the parameters and validity of the standard model [22] and is potentially a sensitive probe for new physics [23]. A B^0 meson can either decay directly or, through mixing, transform into its anti-particle, the $\overline{B}^0$, before decaying. The ratio of the decay widths [24]:

$$r = \frac{\Gamma(B^0 \rightarrow \overline{B}^0 \rightarrow X')}{\Gamma(B^0 \rightarrow X)}$$

of these two competing reactions describes the strength of mixing. In decays of the $\Upsilon(4S)$, pairs of $B^0\overline{B}^0$ mesons are produced in a p-wave state, so that in this case the experimentally determined ratio:

$$R = \frac{N(B^0B^0) + N(\overline{B}^0\overline{B}^0)}{N(B^0\overline{B}^0)}$$

is related to the mixing parameter r by [25]:

$$R = r$$

Thus, mixing leads to events consisting of B^0B^0 or $\overline{B}^0\overline{B}^0$ pairs, which can be detected experimentally in a number of ways.

1.4.1 Like-sign Dileptons

One way to search for mixing is through study of $\Upsilon(4S)$ decays to lepton pairs, since the charge of leptons from primary b-decays identify whether the parent meson was a B or a $\overline{B}$. Mixing, in this case, results in the production of like-sign lepton pairs. Dilepton

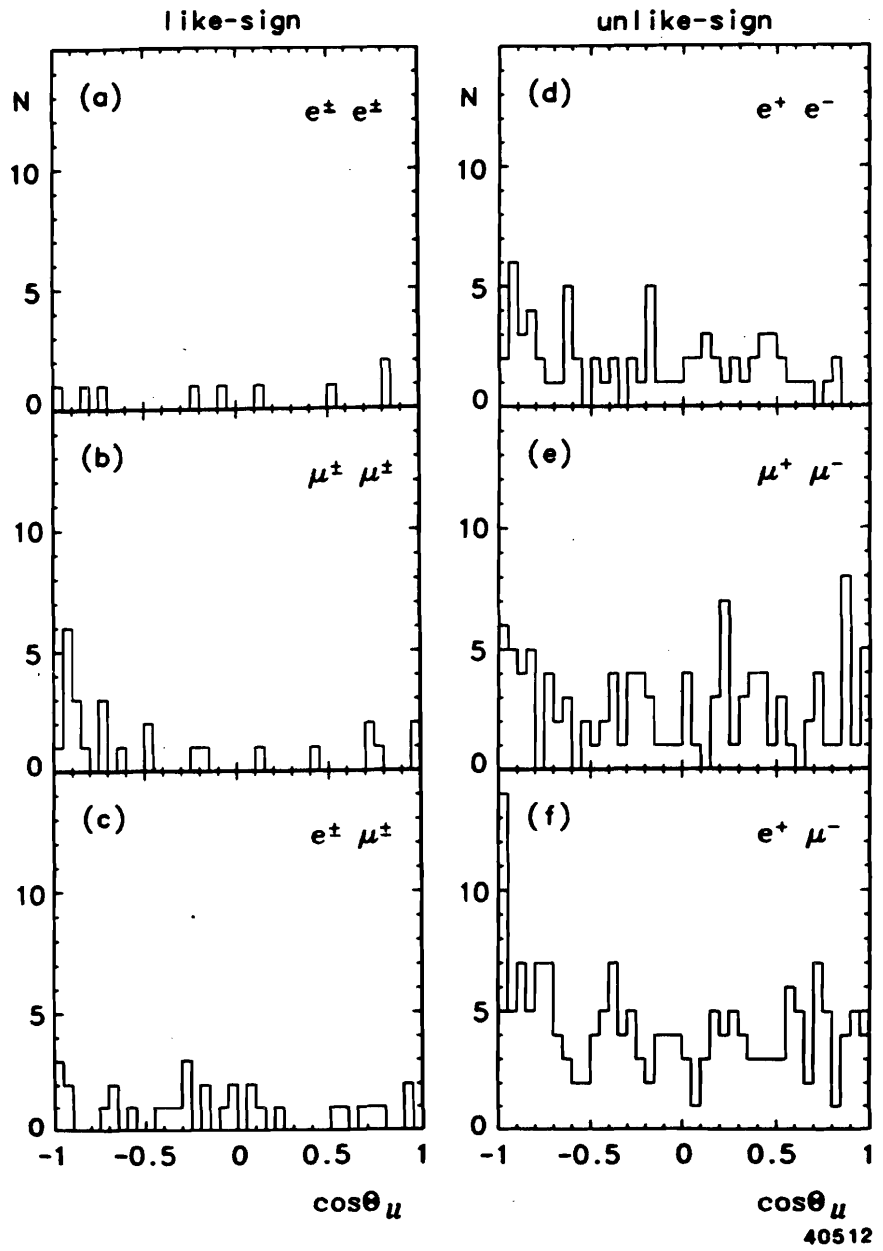

Figure 7. Distribution of the opening angle between leptons for like-sign (a-c) and unlike-sign (d-f) pairs [21].

events were selected by requiring that exactly two particles in the event be well-identified leptons (likelihood ratio for the e^+ or μ^+ hypothesis greater than 80%) with momenta greater than 1.4 GeV/c. The momentum cut suppresses most secondary leptons originating from charmed mesons in B decays. Further requirements were made in order to reduce backgrounds from J/ψ decays to lepton pairs and converted photons.

The distribution of the opening angle, $\theta_{\ell\ell}$, between the leptons is shown in Figure 7 for events passing these cuts. If the leptons originate from two different B mesons, this distribution should be isotropic. Lepton pairs from continuum or the same B meson tend to be back-to-back. For the continuum, this just reflects the two-jet nature of the events. Since the momentum of B mesons produced in $\Upsilon(4S)$ decays is small, a B decay can be viewed as the decay, nearly at rest, of a b-quark into an oppositely travelling W boson and c-quark. Secondary leptons from the c-quark jet are thus aligned oppositely to the primary lepton from the W decay. Both these contributions are reduced by requiring $\cos\theta_{\ell\ell} > -0.85$.

Table 3 gives the number of lepton-pair events surviving these cuts both on the $\Upsilon(4S)$ resonance and in the continuum below. After continuum subtraction, there remain residual background contributions from lepton-hadron misidentification, secondary leptons from charm decays, J/ψ decays, and converted photons, remain. These must be determined and subtracted.

The background due to lepton-hadron misidentification is evaluated from data. To determine the fake rate per track we use our samples of $\tau^- \to \nu\pi^-\pi^-\pi^+ n\pi^0$ $(n = 0, 1)$ and $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays, which provide clean sources of high energy pions and kaons respectively. The number of faked dilepton events is extracted from the observed hadron momentum spectrum in the events containing fast like-sign and unlike-sign lepton-hadron pairs. The background due to secondary leptons is determined by a Monte Carlo simulation of B decays. A spectator model [8] is used to describe the decay of the b-quark, with the final state hadrons produced using the Lund string fragmentation model [26]. The uncertainty in the calculation is estimated to be $\pm 25\%$.

The number of background events from all these sources is given in Table 3. Out of the 50 like-sign events, $25.2 \pm 5.0 \pm 3.8$ are attributed to background sources, where the first error is statistical and the second the systematic uncertainty in the background determination. Thus, there remains a signal of $24.8 \pm 7.6 \pm 3.8$ events due to B^0-$\overline{B}^0$ mixing. The corresponding number of unlike-sign primary lepton pairs from B^0 and B^+ decays is $270.3 \pm 19.4 \pm 5.0$ events.

Like-Sign Dileptons	$e^{\pm}e^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$
Candidates			
$\Upsilon(4S)$ and Continuum	8	16	26
Continuum	0	0	0
$\Upsilon(4S)$ direct	8.0 ± 3.9	16.0 ± 4.8	26.0 ± 5.8
Background			
Fakes	0.7	5.7	4.9
Conversions	0.5	-	0.5
Secondary decays	2.3	2.9	4.6
J/ψ decays	0.7	0.9	1.5
Signal	$3.8 \pm 3.9 \pm 0.9$	$6.5 \pm 4.8 \pm 1.3$	$14.5 \pm 5.8 \pm 1.8$

Sum: 50 like-sign candidates

Background: $25.2 \pm 5.0 \pm 3.8$ events

Signal: $24.8 \pm 7.6 \pm 3.8$ like-sign events

Unlike-Sign Dileptons	$e^{+}e^{-}$	$\mu^{+}\mu^{-}$	$e^{\pm}\mu^{\mp}$
Candidates			
$\Upsilon(4S)$ and Continuum	60	92	149
Continuum	3	1	2
$\Upsilon(4S)$ direct	52.6	89.5	144.1
Corrected for J/ψ cut	$58.5 \pm 9.8 \pm 1.6$	$99.6 \pm 11.3 \pm 2.5$	$144.1 \pm 12.4 \pm 1.8$
Background			
Fakes	1.4	12.1	10.2
Conversions	0.5	-	0.5
Secondary decays	0.7	1.5	1.6
J/ψ decays	1.0	0.9	1.5
Signal	$54.9 \pm 9.8 \pm 1.6$	$85.1 \pm 11.3 \pm 3.1$	$130.3 \pm 12.4 \pm 1.8$

Signal: $270.3 \pm 9.8 \pm 5.0$ unlike-sign events

Mixing parameter r	$0.17 \pm 0.19 \pm 0.04$	$0.19 \pm 0.16 \pm 0.04$	$0.28 \pm 0.14 \pm 0.04$

Average: $r = 0.22 \pm 0.09 \pm 0.04$

Table 3. Observed number of dilepton events with estimated backgrounds.

The mixing parameter for dilepton events has the form:

$$r = \frac{N(\ell^{\pm}\ell^{\pm})(1+\lambda)}{N(\ell^{+}\ell^{-}) - N(\ell^{\pm}\ell^{\pm})\lambda}$$

where $N(\ell^{\pm}\ell^{\pm}) = N(\ell^{+}\ell^{+}) + N(\ell^{-}\ell^{-})$. Since the $\Upsilon(4S)$ decays with unknown rates f^{+} and f^{0} to $B^{+}B^{-}$ and $B^{0}\overline{B}^{0}$ pairs, and with unknown semi-leptonic branching fractions Br^{+}_{sl} and Br^{0}_{sl}, the factor

$$\lambda = \frac{f^{+}}{f^{0}}\left[\frac{Br^{+}_{sl}}{Br^{0}_{sl}}\right]^{2}$$

is introduced in order to account for the contribution from $B^{+}B^{-}$ pairs. We take λ to be 1.2, corresponding, for example, to the reasonable assumption that $f^{+} : f^{0} = 55 : 45$ and $Br^{+}_{sl} = Br^{0}_{sl}$. The average result from the three categories is:

$$r = 0.22 \pm 0.09 \pm 0.04.$$

This result is not sensitive to variation of the lepton momentum cut between 1.4 and 1.6 GeV/c.

1.4.2 B^{0}-Lepton Correlations

The second mixing search involved the reconstruction of one of the B^{0} mesons, described in section 2.1 above, and tagging the second through the charge of the fast lepton produced in semi-leptonic decays. This technique is considerably less sensitive to background from lepton misidentification since no $B^{+}B^{-}$ decays contribute. In addition, the particles forming the reconstructed B^{0} cannot fake leptons and only one of the two leptons in the event can be faked by hadronic tracks.

In the sample of events with a semi-leptonic B^{0} decay, if a second lepton with momentum larger than 1.4 GeV/c was required, the spectrum for the recoil mass against a $D^{*+}\ell^{+}$ system shown in Figure 8 is obtained. In addition, there were two events with a fast lepton where a B^{0} meson was reconstructed in one of the hadronic channels. Thus, there were a total of 28 events, classified on the basis of the charge of the fast lepton as 23 unmixed and five mixed. The background for the mixed sample was estimated to be 0.4 events due to misidentification and 0.5 events due to secondary charm decays, leaving an excess of 4.1 events attributed to B^{0}-$\overline{B}^{0}$ mixing. The corresponding background for the unmixed sample is 2.2 ± 1.1 events. The mixing parameter was determined to be:

$$r = \frac{N(B^{0}\ell^{+}) + N(\overline{B}^{0}\ell^{-})}{N(B^{0}\ell^{-}) + N(\overline{B}^{0}\ell^{+})} = 0.20 \pm 0.12$$

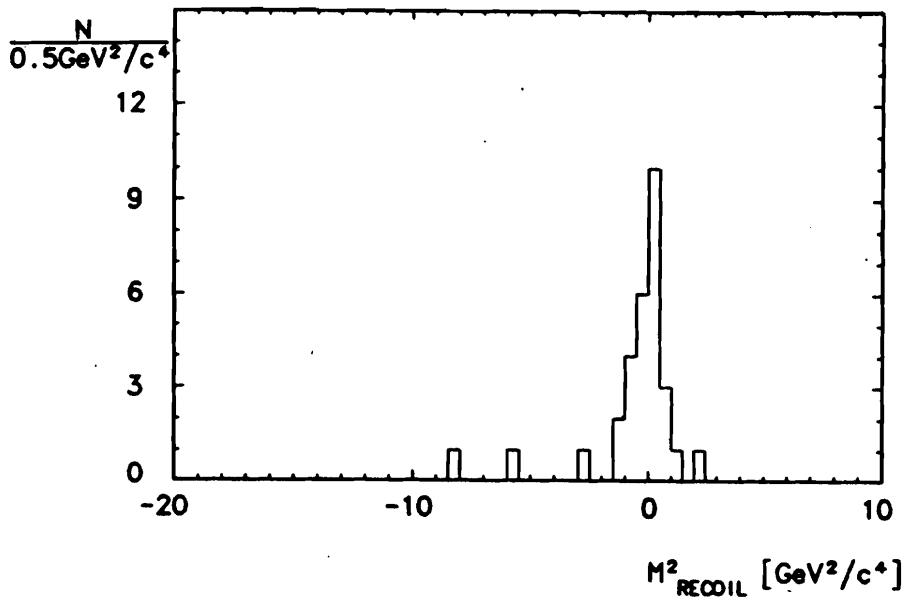

Figure 8. Recoil mass squared, M^2_{Recoil} for events containing a reconstructed decay $D^{*-} \to \overline{D}^0\pi^-$, $\overline{D}^0 \to K^+\pi^-$, $K^0_s\pi^+\pi^-$, $K^+\pi^-\pi^0$ and $K^+\pi^-\pi^-\pi^+$, one positive lepton with $p > 1.0$ GeV/c and a second lepton with $p > 1.4$ GeV/c. [21].

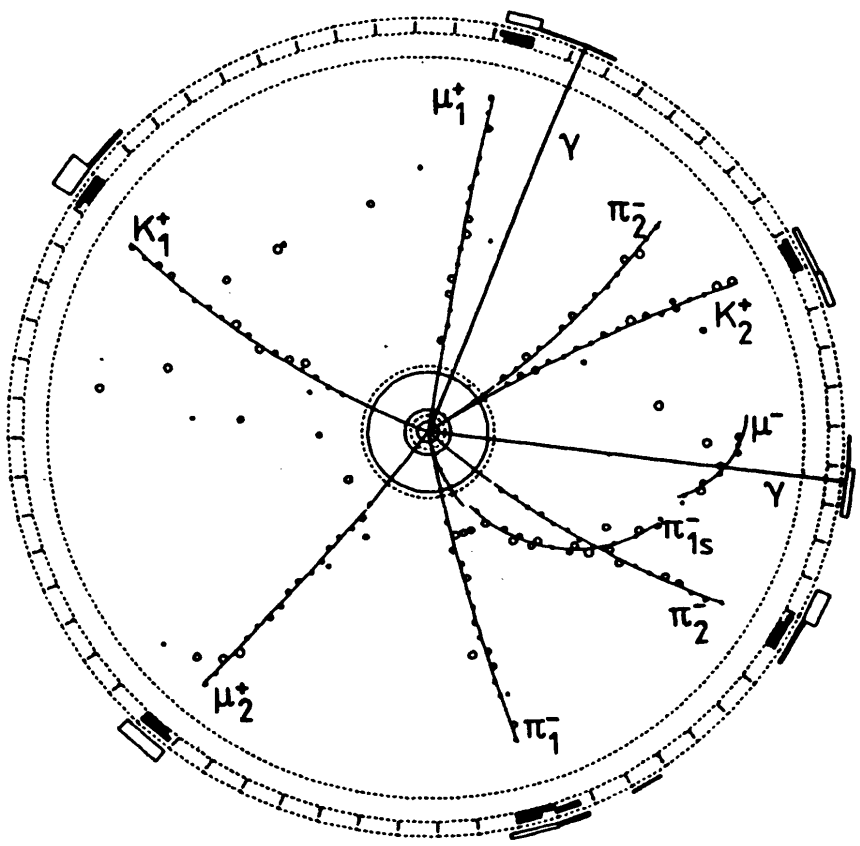

Figure 9. Reconstructed decay $\Upsilon(4S) \to B^0B^0$ [21].

Two like-sign and eleven unlike-sign events from this sample are also present in the dilepton sample. Taking this correlation into account, the combined result of the two methods is:

$$r = 0.21 \pm 0.08$$

for $\lambda = 1.2$.

1.4.3 Explicit Mixing: $\Upsilon(4S) \rightarrow B^0B^0$

The most direct evidence for mixing would be to reconstruct a complete $\Upsilon(4S)$ decay with two b- or $\bar{b}$-quarks. In the sample of events containing an identified B^0, an attempt was made to reconstruct the second B, now with a less restrictive choice of possible decay channels. In one case the search was successful, a decay $\Upsilon(4S) \rightarrow B^0B^0$, and thus a direct observation of B^0-$\overline{B}^0$ mixing. The two B^0 mesons decay as follows:

$$\Upsilon(4S) \longrightarrow B_1^0 B_2^0$$

where

$$\begin{array}{l} B_1^0 \longrightarrow D_1^{*-}\mu_1^+\nu_1 \\ \qquad\qquad \hookrightarrow \pi_{1s}^-\overline{D}^0 \\ \qquad\qquad\qquad\qquad \hookrightarrow K_1^+\pi_1^- \end{array}$$

and

$$\begin{array}{l} B_2^0 \longrightarrow D_2^{*-}\mu_2^+\nu_2 \\ \qquad\qquad \hookrightarrow \pi^0 D^- \\ \qquad\qquad\qquad\qquad \hookrightarrow K_2^+\pi_2^-\pi_2^- \end{array}$$

The event is shown in Figure 9. The masses of the intermediate states agree well with the table values [27]. Both D^{*-} mesons contain positive kaons of momenta $p(K_1)$=0.548 GeV/c and $p(K_2)$=0.807 GeV/c, which are uniquely identified by the measurements of specific ionization loss (dE/dx) and time-of-flight. The two positive muons are the fastest particles in the event with momenta $p(\mu_1)$=2.186 GeV/c and $p(\mu_2)$=1.579 GeV/c, and have dE/dx and shower counter information consistent with the muon hypothesis. One muon, μ_1, is clearly identified in the muon chambers, while the second, μ_2, is labelled a muon on the basis of the event kinematics. For a mixing strength of r = 0.2, we would

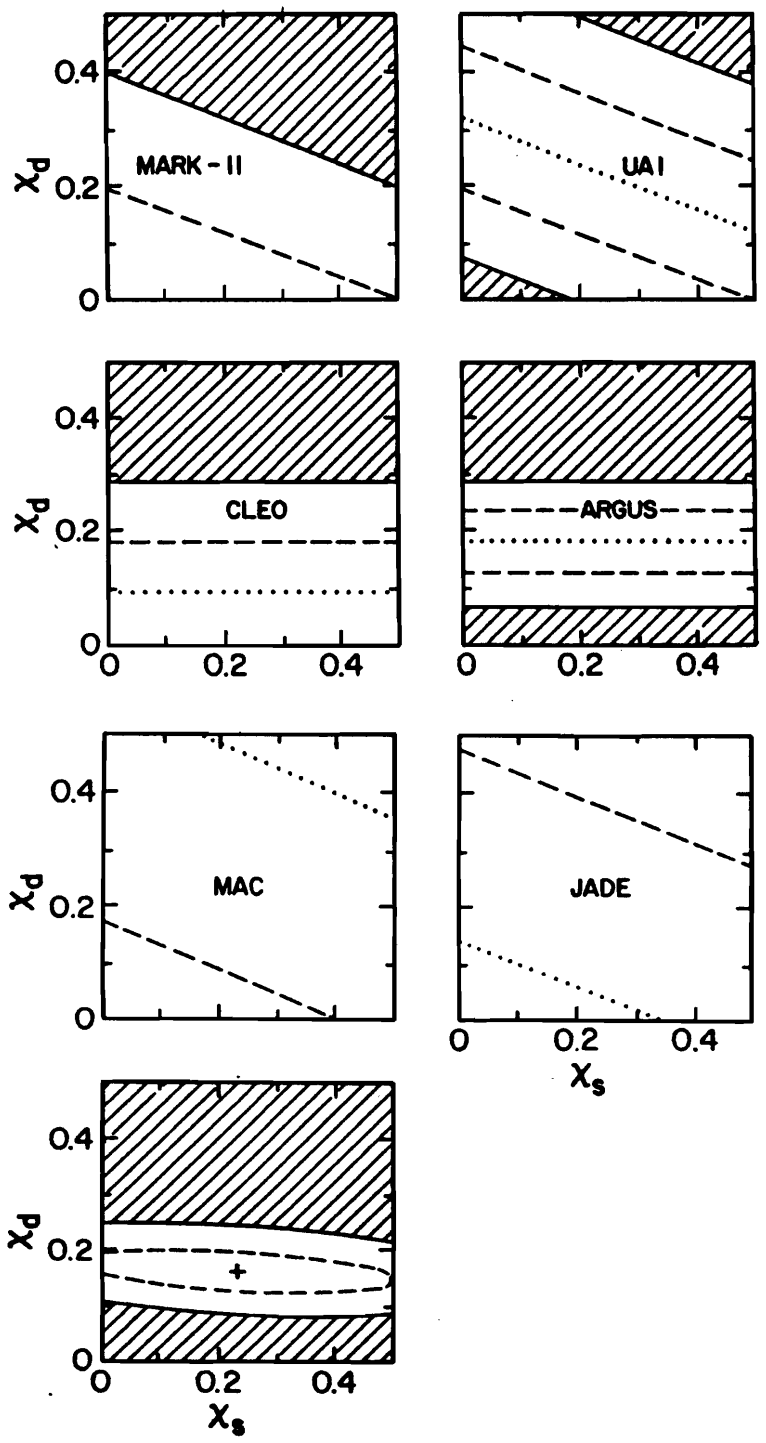

Figure 10. Summary of B-$\overline{\text{B}}$ mixing results [29]. The dotted, dashed and solid lines represent the central values, and the one and two standard deviation contours respectively. The last part of the figure is the average of the six measurements, assuming gaussian errors.

expect to reconstruct 0.3 events where both B mesons decay via $B^0 \rightarrow D^{*-}\ell^+\nu$. The estimated background is less than 1×10^{-4}.

1.4.4 Comparison of Mixing Results

Above the threshold for B_S^0 production, like-sign dileptons can originate from mixing of both B_d^0 and B_S^0 mesons. In order to compare the ARGUS result with other mixing searches, it is convenient to introduce the parameter:

$$\chi = \frac{r}{1+r}$$

which lies in the interval $[0, 0.5]$. Experiments are then sensitive to the sum [28]:

$$\chi_m = w_d \cdot \chi_d + w_S \cdot \chi_S$$

where w_d and w_S are the fractions, f_i, of B_d^0 and B_S^0 mesons produced in the fragmentation of the b-quark, weighted by the semi-leptonic branching ratio, BR_i. Specifically, with k species of b-flavoured hadrons produced, the w_i are defined by:

$$w_i = \frac{f_i \cdot BR_i}{\sum_k f_k \cdot BR_k}$$

A typical choice would be $w_d = f_d = 0.375$ and $w_S = f_S = 0.15$, based on fragmentation studies in continuum e^+e^- and assuming equal semi-leptonic branching ratios. The measured quantity, the ratio R' of like-sign to all dileptons, is:

$$R' = 2\chi_m(1 - \chi_m)$$

for incoherent $b\bar{b}$ production at high energies.

A search for like-sign dileptons has been made by the UA1 collaboration in $p\bar{p}$ interactions at 546 and 630 GeV centre-of-mass energies [30]. In a data sample corresponding to 692 nb^{-1}, they observe 399 opposite-sign and 142 like-sign dimuon events with $p_T > 3$ GeV/c, if at least one of the muons is isolated from other tracks in the event. The estimated number of background events in the samples due to misidentification is 116 and 58 respectively. After accounting for secondary leptons due to charm decays, a value of 0.121 ± 0.047 is derived for χ_m, a 2.9σ effect. It is not possible to determine whether B_d^0 or B_S^0 mixing, or some combination of the two, is responsible for the effect.

Similar studies of continuum dileptons have been undertaken by JADE [31], MARK II [32] and MAC [33], none with a significant signal. CLEO [34] has performed an analysis of $\Upsilon(4S)$ dilepton events, leading to an upper limit of 24% (90% CL) on B^0-$\overline{B}^0$ mixing.

The existing measurements are summarized in Figure 10, where the allowed values for χ_d and χ_S are shown. All limits are compatible with the ARGUS and UA1 results. Assuming gaussian errors, the product of the likelihood functions for the six observations leads to the average result shown as the last part of the figure. From this analysis, one concludes that $\chi_d = 0.16 \pm 0.04$, while any value for χ_S is allowed experimentally [29].

2 Near Future

2.1 Luminosity

For the purpose of evaluating the physics potential of the existing detectors at DORIS II and CESR, some reasonable assumption must be made about average luminosity at the storage rings. When last operational for HEP, DORIS II had achieved a peak luminosity of 1.5 pb^{-1} d^{-1}, with a long-term average of 0.6 pb^{-1} d^{-1}. A modest upgrade program, mostly improving reliability of operation, will raise this by a factor of two for the next run. It is expected that HEP at DORIS II will resume in June of 1988, with no further lengthy interruptions anticipated during the remaining lifetime of ARGUS. The Crystal Ball detector has been returned to SLAC, leaving free the second interaction region.

The CESR operations group has for a number of years pursued a vigorous program to improve luminosity, including a micro-β insertion and, more recently, successful seven bunch operation. The experiments are now consistently recording between 2 and 3 pb^{-1} d^{-1} [35]. Although the improvement efforts will continue, ultimately yielding up to 5 pb^{-1} d^{-1}, I assume 3 pb^{-1} d^{-1} for future running. There will be an break starting early in 1988 to assemble the CLEO II detector, with operation resuming by 1989.

Given these average rates, I would anticipate the following data sets will be available from running on the $\Upsilon(4S)$ during 1987-1989:

ARGUS	350 pb^{-1}	3.0×10^5 $B\overline{B}$ pairs
CLEO I	250 pb^{-1}	2.9×10^5 $B\overline{B}$ pairs
CLEO II	600 pb^{-1}	6.9×10^5 $B\overline{B}$ pairs

using $\Upsilon(4S)$ cross sections of 0.85 nb and 1.15 nb for DORIS II and CESR respectively. There will also be roughly 40% additional luminosity accumulated in the continuum below the open b threshold by the experiments.

2.2 New ARGUS Vertex Detector

Along with improvements in luminosity, a parallel upgrade program is planned for the detectors. In the case of ARGUS, this takes the form of a new high-precision vertex drift chamber (μVDC) [36], to be installed early in 1989. The aim of the device is to permit the use, on an event-by-event basis, of secondary vertex information for charmed hadron reconstruction. After extensive study of the vertex topology of $\Upsilon(4S)$ events, it was concluded that vertex tagging alone was an insurmountable task. A typical event is shown in Figure 11, both as generated and as reconstructed with optimal parameters for the vertex detector. Projected onto a single plane, an $\Upsilon(4S)$ decay appears impossibly tangled. There are at least 4 vertices within a cubic volume with sides of about 100 μm centred on the interaction point. None corresponds to the annihilation vertex itself, which is only constrained to lie within the beam spot (600×60 μm).

It is clear that the usual criteria for a vertex finding algorithm is not satisfied, namely that the initial set of tracks largely belong to a single vertex. Therefore, other strategies must be employed. A successful approach was to first select a suitable charm candidate from tracks observed in the rest of the detector, i.e., using invariant mass, then to use the vertex information to check consistency with this hypothesis. Specifically, the candidate tracks were required to form a common vertex, isolated from the other tracks in the event and with consistent momentum and line-of-flight vectors. In projection, even this approach was a failure: the candidate charm vertex was simply not sufficiently isolated from other random track crossings. Thus, from a pattern recognition standpoint, the vertex chamber must provide high-precision measurements in both $r - \phi$ and z.

These arguments have lead to the adoption of a vertex chamber with 16 layers of 5.1×5.1 mm drift cells. The precision z measurement is accomplished by wrapping the layers around a pentagonal support structure projecting out from the beam pipe, so that consecutive layers alternate at angles of $\pm 45°$ to the beam line when viewed from the side. Given the small drift lengths, sufficient resolution is achieved by high pressure. Extrapolation errors are minimized by placing the innermost layers as close to the interaction point as possible. In this case, considerations of storage ring operation limit us to a 0.5 mm thick Beryllium beam pipe with 18 mm radius. It is as yet unclear whether the photon flux from synchrotron radiation can be reduced to tolerable levels.

The goal of the μVDC is to obtain vertex resolutions in the 15-25 μm range. This will allow the use of vertex information to suppress backgrounds for charm signals to a low level, thereby making possible B reconstruction in decay channels involving not just

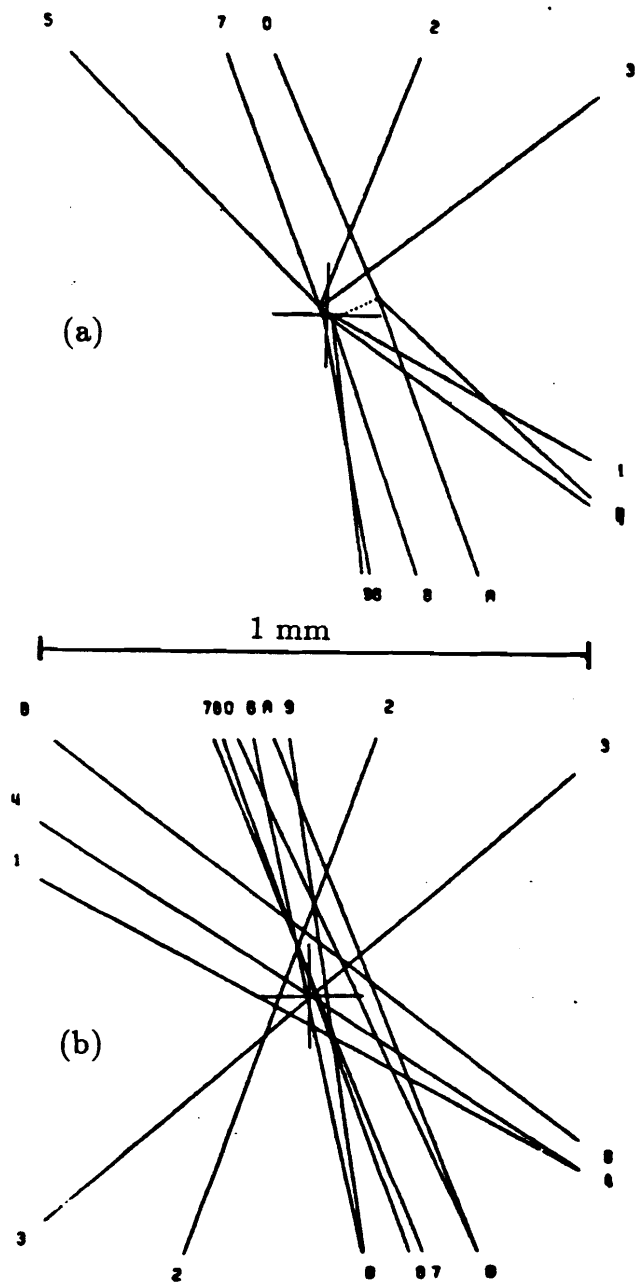

Figure 11. Vertex region for a typical $\Upsilon(4S)$ decay, showing a 1 mm $\times$ 1 mm area of the r-ϕ projection around the interaction point as (a) generated and (b) reconstructed with the proposed ARGUS vertex detector.

the D^{*+}, but also the D^0 and D^+. Because the latter are produced more prolifically and reconstructed more efficiently than the former, a roughly fivefold increase in the number of tagged B decays can be expected. With the recently demonstrated ability to tag using the semi-leptonic decay channels, exploiting the missing mass technique, this estimate may very well be too conservative.

Another benefit is the significantly improved suppression of fake and secondary backgrounds in the dilepton sample provided by more precise vertex information. This should allow a much better measurement of the B^0-$\overline{B}^0$ mixing rate, since rather severe momentum cuts are presently applied to lepton candidates, in order to remove most of the secondary decay leptons. High-precision vertex measurements will allow one to distinguish, in some fraction of the cases, whether or not both leptons originate from the same point in space. This will allow the momentum restriction to be relaxed, with large gains in acceptance.

2.3 CLEO II Upgrade

The CLEO collaboration is presently engaged in a phased upgrade of their detector. The intent of the new design has been to combine excellent charged and neutral particle detection in the same apparatus. When completed, CLEO II will be an all new detector [37]. A overview of the new design is shown in Figure 12a, along with a detailed cross-sectional drawing of the central region in Figure 12b. Already in place are a high-resolution vertex drift chamber (January, 1985) and the new main tracking chamber (June, 1986). The new central drift chamber (0.95 m radius $\times$ 2 m length) consists of 12240 rectangular drift cells (14 $\times$ 14 mm for axial layers) organized into 51 concentric layers (11 stereo), providing drift time and mean ionization loss (dE/dx) measurements for charged particles. Predicted momentum resolution of the combination of vertex and central tracking chambers is:

$$\left(\frac{\sigma}{p}\right)^2 = (0.0015 \cdot p_T)^2 + 0.0056^2$$

where p and p_T are in GeV/c. With an expected 6% RMS resolution for dE/dx, useful π/K separation in argon-ethane (50:50) should be possible below 900 MeV/c, and π/e over the whole momentum range. Considerable effort is also underway to explore the virtues of vertex tagging.

During 1988 the second phase of the improvement program will be completed. Outside the main drift chamber will be a new time-of-flight system, a CsI electromagnetic calorimeter, a superconducting coil to provide the 1.5 Tesla solenoidal field, magnet iron and muon chambers. The calorimeter, the most innovative part of the new detector, consists of an

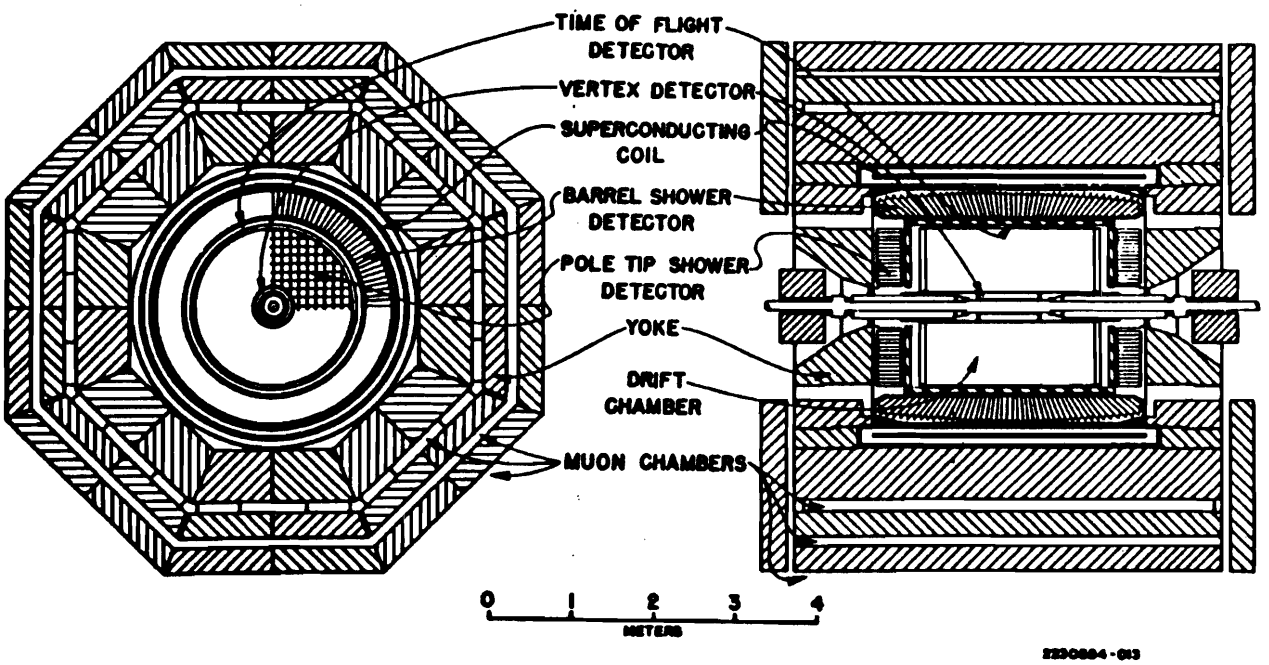

Figure 12. (a) End and side views of the proposed CLEO II detector [37].

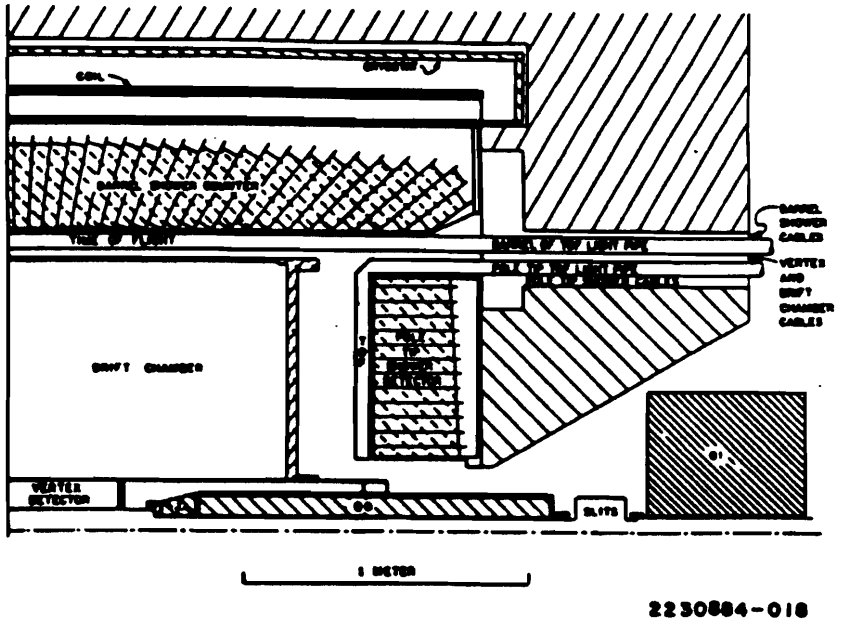

Figure 12. (b) Detailed side view of one quadrant of the CLEO II detector [37].

array of 7644 thalium-doped CsI crystals (5×5 cm $\times 16$ radiation lengths). Located inside the coil, the readout system uses 4 photodiodes per crystal. The expected resolution is:

$$\left(\frac{\sigma}{\mathrm{E}}\right)^2 = \left(\frac{0.013}{\sqrt{\mathrm{E}}} + 0.007 \cdot \mathrm{E}^{0.3}\right)^2 + \left(\frac{0.003}{\mathrm{E}}\right)^2$$

where E is in GeV. The calorimeter will also provide additional electron hadron separation.

It may take some time before all systems are calibrated and integrated into the analysis effort, possibly delaying definitive results from the first CLEO II running. However, the combination of a superior detector with the high luminosity delivered by CESR will undoubtedly allow CLEO II to dominate B physics from the existing threshold machines in the early 1990's.

2.4 Tagged Samples

With the assumptions described in the previous two sections, we are now in a position to speculate about the level of sensitivity which will be achieved by the threshold experiments. It is not possible to be comprehensive, or to anticipate discoveries of new analysis techniques. The extrapolation of present capabilities in the seen decay modes to the anticipated larger data sets is a straight-forward exercise. The results are shown in Table 4. The numbers for CLEO II assume that the D* efficiency will be about twice that of ARGUS, because of the fine electromagnetic calorimeter, and that the lepton efficiencies will be comparable. The tagged samples available to the two groups will be sizable. Taking $|V_{ub}/V_{cb}|$ to be 0.15, these samples would contain roughly 70 and 300 events respectively, where the recoiling B decays via a $b \to u$ transition. Perhaps some clever technique can be found to reliably identify these events, and so determine V_{ub} in an inclusive manner. However, given that kaons are not uniquely identified over the entire momentum range, this is a non-trivial task.

Channel	ARGUS	CLEO II
$\mathrm{B} \to \mathrm{D}^* \ell \nu$	1170	5400
$\mathrm{B} \to \mathrm{D}^* n \pi$	410(200)	1900(920)
$\mathrm{B} \to \mathrm{p}\bar{\mathrm{p}} n \pi$	185	420
Tagged sample	1555	6740

Table 4. Expected sample of reconstructed B mesons. Numbers in brackets are for clean channels only.

2.5 Rare Decays

As already noted, CLEO has reported a series of searches for charmless B decays into multi-pion final states. The limits obtained will improve with the square root of luminosity, so that ARGUS and CLEO II will reach the levels indicated in Table 5. Also shown are predicted branching ratios, again assuming $|V_{ub}/V_{cb}| = 0.15$. These are based on the model of Bauer, Stech and Wirbel [38], which introduces two scale-independent parameters a_1 and a_2, taken to be 1.05 and -0.31 respectively. The first is derived from the measurements of the branching ratios for $\overline{B}^0 \to D^+\pi^-$ and $\overline{B}^0 \to D^{*+}\pi^-$ [5], which give $a_1^2 = 1.11 \pm 0.32$. Similarly, from the known branching ratios for $B^- \to J/\psi K^-$ and $\overline{B}^0 \to J/\psi \overline{K}^{*0}$ one finds $a_2^2 = 0.095 \pm 0.025$. The sign assumed for a_2 is motivated by theoretical expectation. The parameters a_1 and a_2 are related to the QCD coefficients C_1 and C_2 for the charged and neutral current products of the effective quark Hamiltonian:

$$\begin{aligned} a_1 &\simeq C_1(\mu) + \xi \cdot C_2(\mu)|_{\mu=m_Q} \\ a_2 &\simeq C_2(\mu) + \xi \cdot C_1(\mu)|_{\mu=m_Q} \end{aligned}$$

where $\xi = 1/N_C$ is a colour mismatch parameter. The same model provides an excellent description of the observed branching ratios for charmed mesons in the limit of $\xi \to 0$ or $N_C \to \infty$. In this limit, a_1 and a_2 are expected to be 1.1 and -0.24 for B mesons.

Channel	Present [4]	ARGUS	CLEO II	Predicted BR
$\overline{B}^0 \to \pi^+\pi^-$	3.0	1.6	1.2	0.35
$\overline{B}^0 \to \rho^0\rho^0$	4.0	2.1	1.6	0.03
$\overline{B}^0 \to \pi^\pm A_1^\mp$	14.0	7.5	5.6	1.0
$B^- \to \rho^0\pi^-$	2.0	1.1	0.8	0.02
$B^- \to \rho^0 A_1^-$	36.0	19.2	14.4	0.57

Table 5. Measured and anticipated branching ratio limits for multi-pion B decays in units of 10^{-4}.

Based on these predictions, it appears unlikely that the threshold experiments will be able to observe a signal in any of these channels in the near future. Another way of stating this is that since the limit on $|V_{ub}/V_{cb}|$ falls with the fourth root of luminosity, a factor of 70 increase over the size of present $\Upsilon(4S)$ data sets would be needed even to achieve a limit of 15%. Except for surprises such as the decay to $p\overline{p}\pi^+(\pi^-)$, hadronic B decays to low-multiplicity charmless states do not seem a particularly viable approach to measuring V_{ub}.

Much more promising are the rare semi-leptonic channels, at least in terms of raw rate. The ratio of low-multiplicity $b \to u$ decays over the dominant semi-leptonic channel have been estimated by Wirbel, Bauer and Stech [39]:

$$\frac{\mathrm{BR}(\mathrm{B}^0 \to \pi^- \ell^+ \nu)}{\mathrm{BR}(\mathrm{B}^0 \to \mathrm{D}^{*-} \ell^+ \nu)} = 0.34 \cdot \left| \frac{\mathrm{V_{ub}}}{\mathrm{V_{cb}}} \right|^2$$

and

$$\frac{\mathrm{BR}(\mathrm{B}^+ \to \rho^0 \ell^+ \nu)}{\mathrm{BR}(\mathrm{B}^0 \to \mathrm{D}^{*-} \ell^+ \nu)} = 0.60 \cdot \left| \frac{\mathrm{V_{ub}}}{\mathrm{V_{cb}}} \right|^2$$

as well as several other authors [40]. With $|V_{ub}/V_{cb}| = 0.15$ and $\mathrm{BR}(\mathrm{B}^0 \to \mathrm{D}^{*-} \ell^+ \nu) = 7\%$, one expects $\mathrm{BR}(\mathrm{B}^0 \to \pi^- \ell^+ \nu) = 5 \times 10^{-4}$ and $\mathrm{BR}(\mathrm{B}^+ \to \rho^0 \ell^+ \nu) = 9 \times 10^{-4}$. In addition, the efficiency for the ρ^0 channel is about a factor of 50 larger than that for the D^{*-} channel. Unfortunately, the backgrounds are also considerably larger. Ultimately, the large branching ratio leads to limits on $|V_{ub}/V_{cb}|$ which at present are more than a factor of two better than those obtained via hadronic modes [41]. Assuming an overall efficiency of 20%, ARGUS would have about 60 events in the recoil mass distribution for the ρ^0 channel in the new data. The background near zero recoil mass would be roughly 10 times larger than the signal, in large part due to the decay $\mathrm{B} \to \mathrm{X}\rho^0 \ell^+ \nu$ via $b \to c$ transitions. However, the proposed high-precision vertex detector would do much to alleviate this difficulty, since the lepton and ρ^0 must form a common vertex.

Channel	Present [42]	ARGUS	CLEO II	Predicted BR
$\overline{\mathrm{B}}^0 \to \mathrm{J}/\psi \mathrm{K}^0_{\mathrm{S}}$	1	1	3	4×10^{-4}
$\mathrm{B}^- \to \mathrm{J}/\psi \mathrm{K}^-$	3	15	35	8×10^{-4}
$\overline{\mathrm{B}}^0 \to \mathrm{J}/\psi \overline{\mathrm{K}}^{*0}$	5	25	60	3×10^{-3}
$\mathrm{B}^- \to \mathrm{D}^0 \mathrm{D}^-$	0	2	5	3×10^{-4}
$\mathrm{B}^- \to \mathrm{D}^0 \mathrm{D}^{*-}$	0	2	6	3×10^{-4}

Table 6. Observed and expected number of events for potential CP violating channels.

Many rare decay modes are of importance for the planning of future CP violation searches and therefore should also be examined. In particular, it would be of considerable interest to have measurements of the relevant branching ratios. Estimates of the number of events which can be expected in the new data are given in Table 6, based on present detector efficiencies and predictions for the branching ratios using the model of Wirbel, Bauer and Stech. The last entry, for $\mathrm{B}^- \to \mathrm{D}^0 \mathrm{D}^{*-}$, would be detectable via a partial

reconstruction technique, where only the soft pion from the $D^{*-} \to \overline{D}^0\pi^-$ transition is required.

Searches for decays via electromagnetic penguins have been made, yielding limits which approach an interesting level of sensitivity. The inclusive process, $b \to s\gamma$, should occur with a branching ratio of roughly 10^{-3} [43]. Exclusive modes, such as $K^*\gamma$, may represent only 5% of the inclusive rate. However, the effect of a fourth generation could enhance these predictions by an order of magnitude. From an experimental point of view, the new CLEO II calorimeter will be a decisive advantage. For the two-body process, $B \to K^*\gamma$, the photon has a mean energy of 2.6 GeV. The energy resolution for such a photon in the ARGUS calorimeter is 220 MeV, while in CLEO II it could be as low as 45 MeV. In order to compare the effect of backgrounds under any potential signal, the relevant parameter is the energy resolution for the B candidate. This we will take to be dominated by the photon resolution. Thus in channels with backgrounds, the CLEO II detector will have an advantage of almost a factor of 2, in addition to the greater luminosity delivered by CESR. Shown in Table 7 are the reported and anticipated limits for the penguin searches. At present the charged B decay contains no background, and so this limit will improve linearly with luminosity until some background does appear. CLEO II should be on the verge of observing a positive signal for $b \to s\gamma$ around 10^{-3}. Note that searches are not limited to the $K^*(892)$, and channels involving higher K^* resonances are under investigation as well.

Channel	Present [5]	ARGUS	CLEO II
$B^+ \to K^{*+}\gamma$	10.	2.5	0.8
$B^0 \to K^{*0}\gamma$	4.	2.1	1.0

Table 7. Measured and anticipated branching ratio limits for electromagnetic penguins, in units of 10^{-4}.

Finally, we should consider the leptonic decay $B^+ \to \tau^+\nu_\tau$, which has a predicted branching ratio [8] of:

$$BR(B^+ \to \tau^+\nu_\tau) = 6 \times 10^{-3} \cdot \left|\frac{V_{ub}}{V_{cb}}\right|^2 \cdot \left(\frac{f_B}{0.150\ \text{GeV}}\right)^2$$

Observation of this channel, given a determination of $|V_{ub}/V_{cb}|$, would allow a measurement of the B form factor, f_B. However, the experimental difficulty is to find a distinguishing topology, because of the small boost for B mesons on the $\Upsilon(4S)$. One method would be to search for events in the tagged B^+ sample which have just one additional charged track and no neutrals. The single-prong mode with no neutrals represents almost 50% of all

tau decays. Unfortunately, in the ARGUS detector most tagged B mesons are neutral. However, for CLEO II such a procedure could lead to a limit of about 1×10^{-3} on the branching ratio or $f_B < 470$ MeV. ARGUS may also be competitive with the μVDC in place.

2.6 Semi-leptonic Branching Ratios

As described above, ARGUS has demonstrated that the recoil-mass technique can be used to identify B^0 decays to $D^{*-}\ell^+\nu$. In part, this is due to small backgrounds in the D^{*-} signal. Such a measurement should be repeated with the corresponding charged B decay, but this requires excellent photon detection in order to efficiently and cleanly reconstruct the $\overline{D}^{*0} \to \overline{D}^0\gamma$ or $\overline{D}^0\pi^0$ transition. ARGUS may yet be able to make such a study, but CLEO II will be in a position to perform a precision measurement. Modulo the uncertainty in the fraction of charged and neutral B production on the $\Upsilon(4S)$, a determination should be possible of the ratio:

$$\frac{BR(B^0 \to D^{*-}\ell^+\nu)}{BR(B^+ \to \overline{D}^{*0}\ell^+\nu)} = \frac{f^0}{f^+} \cdot \frac{N(B^0 \to D^{*-}\ell^+\nu)}{N(B^+ \to \overline{D}^{*0}\ell^+\nu)} \cdot \frac{BR(D^{*-} \to \overline{D}^0\pi^-)}{1} \cdot \frac{\eta(\pi_S^-)}{\eta(\gamma/\pi^0)}$$

The experiment should be able to measure the ratio of events to $\pm 10\%$, and the $BR(D^{*-} \to \overline{D}^0\pi^-)$ is known to the same precision, so the ratio of branching ratios, and hence of lifetimes, will be known to $\pm 15\%$.

An alternative approach to the same information is to use the appropriate ratios of doubly- and singly-tagged events. Consider two possible decay modes: $B^0 \to f_1$ and $B^0 \to f_2$. A practical example of some importance would be $f_1 = D^{*-}\ell^+\nu$ and $f_2 = X\ell^+\nu$. An experiment observes a certain number of events, N_1, where $B^0 \to f_1$, and N_{12}, where $B^0 \to f_1$, $\overline{B}^0 \to \bar{f}_2$. If the efficiencies for the two channels are η_1 and η_2 respectively, then it follows that:

$$\begin{aligned} N_1 &= 2N_{B^0\overline{B}^0} \cdot BR_1 \cdot \eta_1 \\ N_{12} &= N_{B^0\overline{B}^0} \cdot BR_1 \cdot \eta_1 \cdot BR_2 \cdot \eta_2 \end{aligned}$$

Clearly, from these measurements the inclusive rate BR_2 can be determined:

$$BR_2 = \left(\frac{2N_{12}}{N_1}\right)\frac{1}{\eta_2}$$

In our particular example, the inclusive branching ratio for B^0 semi-leptonic decays could thereby be separately extracted. This could be translated into a ratio of charged and neutral lifetimes, given that the average branching ratio for B^0 and B^+ is already known.

A parallel opportunity would be to observe the number of events, N_2, where $B^0 \to f_2$, and N_{21}, where $B^0 \to f_2$, $\overline{B}^0 \to f_1$. Then:

$$\begin{aligned} N_2 &= 2N \cdot BR_2 \cdot \eta_2 \\ N_{12} &= N_{B^0\overline{B}^0} \cdot BR_2 \cdot \eta_2 \cdot BR_1 \cdot \eta_1 \end{aligned}$$

From these, one can construct:

$$BR_1 = \left(\frac{2N_{21}}{N_2}\right) \cdot \left(1 + \frac{f^+}{f^0}\right) \frac{1}{\eta_1}$$

Thus, the branching ratio for $B^0 \to D^{*-}\ell^+\nu$ can be found independent of D^* and D^0 branching ratios. The increased data sets available to ARGUS and CLEO II will allow these kinds of studies.

2.7 B^0-$\overline{B}^0$ Mixing

If we use the central value for the mixing parameter $r = \Gamma(B^0 \to \overline{B}^0 \to X')/\Gamma(B^0 \to X)$, the present results from ARGUS can be extrapolated to the anticipated data set. The result is shown in Table 8. The error on the fake component of the background is statistical, and therefore will decrease with the size of the sample. It is also quite possible that the error on the Monte Carlo prediction for the secondary lepton pairs will improve as we gain a better understanding of B and D decays. Based on the projections, an error of ± 0.05 on the parameter r should be possible.

Channel	Total	Background	Signal
$e^\pm e^\pm$	32	3.5 ± 0.5	28.5 ± 5.7
$\mu^\pm \mu^\pm$	64	38.0 ± 1.8	26.0 ± 8.2
$e^\pm \mu^\pm$	104	46.0 ± 2.8	58.0 ± 10.6
		Like-sign total:	112.5 ± 14.6
		Opposite-sign total:	1081.2 ± 32.9

Table 8. Projected signals and backgrounds for dilepton study with the new ARGUS data sample.

2.8 Prospects for B_S^0-$\overline{B}_S^0$ Mixing

The original CLEO detector had a relatively poor electron and muon identification capability compared with ARGUS. This has been partially rectified with the present configuration

of the detector, since the installation of the new central drift chamber. The efficiency for electron identification should now be comparable, although some of the background rejection provided by the calorimeter is still not available. However, muon coverage remains inferior, hampering searches for like-sign pairs in both the dimuon and muon-electron categories. Nevertheless, CLEO should be able to obtain a measurement with an error of about ± 0.08 by the summer of 1988. These comments do not apply to the completed CLEO II detector, which with 600 pb^{-1} should be capable of better than ± 0.04.

While there were three rather uncertain parameters in the prediction for the level of mixing in the B_d^0 sector, most of these unknowns cancel in the ratio of mixing in B_S^0 versus B_d^0 systems. Ignoring possible small differences in the form factors of the B_d^0 and B_S^0, one expects [22]:

$$\frac{r(B_s^0)}{r(B_d^0)} = \left|\frac{V_{ts}}{V_{td}}\right|^2$$

With three generations, the ratio of these two Kobayashi-Maskawa matrix elements is bounded by unitarity: $|V_{ts}/V_{td}| > 2.2$ [27]. Inserting this bound, one finds that:

$$\frac{\chi_S}{\chi_d} > 4.8$$

i.e. mixing must be close to maximal in the B_S^0 system. As a direct test of the standard model, the case for a measurement of $r(B_S^0)$ is thus quite compelling. However, as we will see, with sizable mixing in the B_d^0 sector the experimental complications are formidable.

As an example, let us examine the possibility of a measurement on the $\Upsilon(5S)$, supposing that CLEO II records 1000 pb^{-1} there during 1990. Some assumption about B production on the $\Upsilon(5S)$ must be made. There have been several attempts to fit the total cross section measured by CLEO and CUSB during a scan in 1985 of the centre-of-mass region between 10.5 and 11.1 GeV [44]. Coupled-channel analyses [45] suggest that the $\Upsilon(5S)$ decays about 40% of the time into $B_S^0\overline{B}_S^0$ pairs, and the remaining 60% into $B\overline{B}$. Taking the total cross section to be 0.375 nb at the peak of the resonance, this translates into 1.5×10^5 $B_S^0\overline{B}_S^0$, 1.1×10^5 $B^0\overline{B}^0$ and 1.1×10^5 B^+B^- pairs in 1000 pb^{-1} of data. A word of caution should be introduced. Typically the cross section for a given channel changes quite rapidly with E_{cms}. Since only the B_d^0 and B^+ masses are experimentally determined, a corollary is that predictions vary quite strongly with, for example, assumptions about masses of the B_S^0 and B_S^{*0} states. In some cases the production of $B_d^0\overline{B}_d^{*0}$ is quite substantial [46], leading to further complication since mixing of such an L = even state is a factor of two larger than for direct $B_d^0\overline{B}_d^0$ (L = odd). First experimental indications about B_S^0 production may be forthcoming soon, as CLEO has recently accumulated about 90 pb^{-1} on the $\Upsilon(5S)$.

Channel	$B_S^0\overline{B}_S^0$	$B^0\overline{B}^0$	B^+B^-	Total
Like-sign	188	60	0	248
Opposite-sign	282	293	353	928
Total	470	353	353	1176

Table 9. Sources of like- and opposite-sign dileptons in a 1000 pb^{-1} sample on the $\Upsilon(5S)$.

Taking the mixing rates to be $\chi_d = 0.17$ and $\chi_S = 0.4$, the number of like- and opposite-sign dileptons which would be observed are given in Table 9. A 70% lepton identification efficiency and a typical momentum cut at 1.4 GeV/c were assumed. The experiment observes a total of 248 like-sign and 928 opposite-sign dileptons. There would also be about 100 dileptons from background sources, which are ignored for the remainder of this exercise. Clearly, in order to extract an actual measurement of χ_s, the fraction of B_S^0 production is required†. To measure the rate f_{B_S} for $\Upsilon(5S) \to B_S^0\overline{B}_S^0$, a double tagging method could be employed. Since the dominant decay mode of the B_S^0 should be $B_S^0 \to D_S^+X$, and the branching ratio for $D_S^+ \to \phi X$ is quite large, a comparison of the single and double-ϕ rates would yield the required fraction:

$$f_{B_S} = \frac{1}{4}\frac{N_{1\phi}^2}{N_{2\phi}}$$

Actually this is too simplistic, since there is sizable D_S^+, and hence ϕ production, in B decays. The inclusive branching ratio for $B \to \phi X$ has been determined to be $0.023 \pm 0.006 \pm 0.005$. Putting in this complication, one actually has:

$$\begin{aligned} N_{1\phi} &= 2N_{B_S\overline{B}_S} \cdot BR_S \cdot \eta + 2N_{B\overline{B}} \cdot BR \cdot \eta \\ N_{2\phi} &= N_{B_S\overline{B}_S} \cdot BR_S^2 \cdot \eta^2 + N_{B\overline{B}} \cdot BR^2 \cdot \eta^2 \\ N_{5S} &= N_{B_S\overline{B}_S} + N_{B\overline{B}} \end{aligned}$$

where

$$\begin{aligned} BR_S &= BR(B_S^0 \to \phi X) \\ BR &= BR(B \to \phi X) \end{aligned}$$

and η is the detection efficiency for a ϕ. If one assumes that $BR(D_S^+ \to \phi X)$ is 10%, then measurements of $N_{1\phi}$, $N_{2\phi}$ and N_{5S} will allow a 20% (10%) determination of f_{B_S} in 200 (1000) pb^{-1} of data.

†As alluded to previously, it is likely that a measurement of the $B^0\overline{B}^{*0}$ rate will also be needed, if it is sizable, a point which will be ignored.

With f_{B_s} known to $\pm 10\%$, we can return to the raw dilepton sample and subtract the $B\overline{B}$ contributions:

$$\begin{aligned} \text{like-sign:} \quad & 248 - 60 \pm 4.3 \\ \text{opposite-sign:} \quad & 928 - 646 \pm 43 \end{aligned}$$

leading to a value for χ_S of 0.4 ± 0.05. A 200 pb^{-1} sample would yield $\chi_S = 0.4 \pm 0.11$. If there were sizable $B_d^0 \overline{B}_d^{*0}$ production, it might be desirable to suppress the non-B_S^0 component in the dilepton sample, by requiring a ϕ in addition. This leads to a drastic reduction in statistics if $BR(D_S^+ \to \phi X)$ is only 10%, so that one would expect:

$$\begin{aligned} N(\phi \ell^\pm \ell^\pm) &= 7.6 \\ N(\phi \ell^+ \ell^-) &= 11.4 \end{aligned}$$

(with a possible small background from $B \to D_S \ell X$), giving $\chi_S = 0.4 \pm 0.11$. Would any of these measurements be a real test of the standard model prediction? The problem with time-integrating a large mixing rate is that you have no real sensitivity to the relevant parameter $\Delta M/\Gamma$. These experiments would show that χ_S is large, but even the best lie within a few sigma of $\chi_S = 0.25$ for example. One would really prefer to resolve the time dependence, but this presents a considerable experimental challenge.

3 Middle Term

With the exception of lifetime measurements and the indication of mixing at the CERN $p\overline{p}$ collider, essentially all information about the b-quark has been obtained by experiments running in e^+e^- colliders at the b-threshold. This is due to the unfavourable ratio of $\mathcal{L} \cdot \sigma_{e^+e^- \to q\overline{q}}$ in the continuum, aggravated by the reduced signal-to-background ratio. However, on the Z^0 this situation will change. Table 10 shows a comparison between the number of $b\overline{b}$ pairs produced at SLC [47] and LEP [27] versus CESR. The projectors for SLC are, of course, quite speculative at the moment. This is not so for LEP, which as a conventional storage ring should achieve design luminosity within a year or two of starting. Moreover, there are four LEP detectors, with varying capabilities for b-physics.

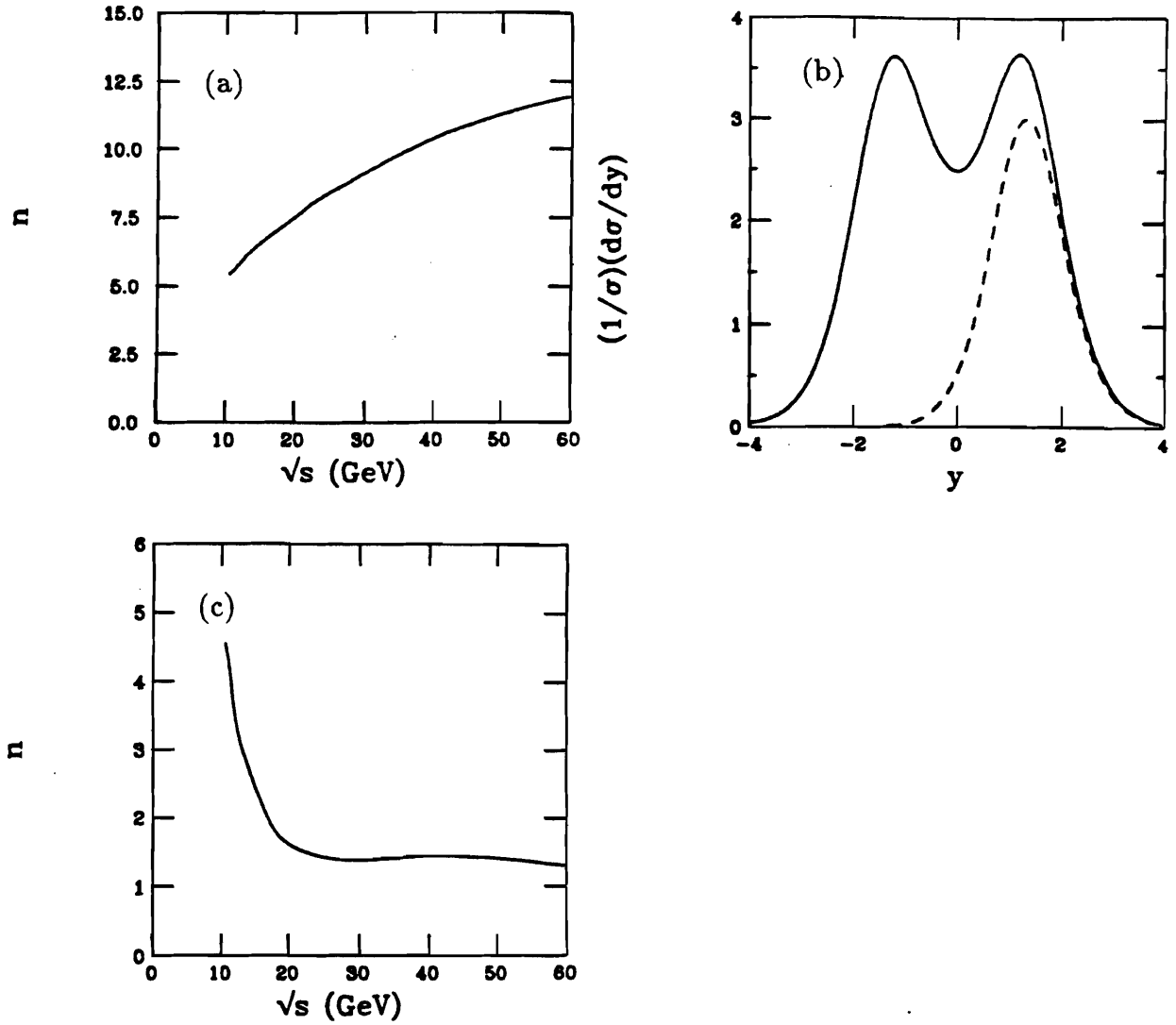

Figure 13. (a) Number of charged particles in a $b\bar{b}$ event belonging to the $\bar{b}$-flavoured hadrons or primary vertex, and not the b. (b) Distribution in rapidity with respect to the sphericity axis for all charged particles (full line) and for decay products of the b-flavoured hadrons moving in the +y direction (dashed line). (c) Mean number of charged particles not associated with the decay of a given b-flavoured hadron within the rapidity region populated by decay products of the b. All taken from reference [48].

	$\mathcal{L}_{\text{peak}}$	$N(Z^0)$/200 days*	$N_{b\bar{b}}$/200 days*
SLC	5×10^{29} cm^{-2} s^{-1}	7.4×10^4	1.0×10^4
LEP	1×10^{31} cm^{-2} s^{-1}	3.7×10^6	5.2×10^5
LEP	6×10^{31} cm^{-2} s^{-1}	-	5.0×10^5

*Assuming average luminosity is $0.5 \cdot \mathcal{L}_{\text{peak}}$.

Table 10. Comparison of present CESR conditions with anticipated b-event rates at Z^0 machines.

3.1 New Tools

With a competitive production rate for the Z^0 experiments, some of the advantages of having a moving b-system may come into play. On the Z^0, b-quarks are produced in jets, and will dress into leading hadrons with comparatively large momentum. This is essentially opposite to situation at threshold. Since b-decay products will be almost unmixed, there should be a much less severe combinatorial problem. The other obvious advantage to a moving b-system is the finite flight paths of b-flavoured hadrons, which surely can be exploited. There will be some learning curve associated with using these tools to advantage, but there is little doubt that the Z^0 experiments will be able to contribute to b-studies. In the analogous situation for charm-physics, the continuum e^+e^- experiments were never quite competitive enough with operation on the $\psi(3770)$. Compared with the b-system, D decays are relatively simple, and while fragmentation is some advantage, this alone was not sufficient. The severity of the $\Upsilon(4S)$ combinatorial problem, and the additional advantage of macroscopic decay distances, may change the balance more in favour of the continuum b-experiments.

These points were well illustrated by W.Hofmann et al. in the high luminosity PEP workshop [48]. Some of the salient comments I extract here, but the reader is referred to the original document for details. Figure 13a shows that the number of charged tracks other than those from the B candidate, i.e. belonging to the $\overline{B}$ and the fragmentation process, increases from 5.5 at threshold to around 12.5 at the Z^0. However, these additional particles are reasonably well separated in rapidity, as shown in Figure 13b. As a consequence, if one includes just those tracks in the B rapidity region, the number not associated with the B itself asymptotically approaches approximately one. In other words, the hard B production spectrum leads to a relatively clean separation between the B and tracks associated with the $\overline{B}$ or lighter fragmentation products.

While large flight paths for b- and c-flavoured hadrons should, at first sight, lead to

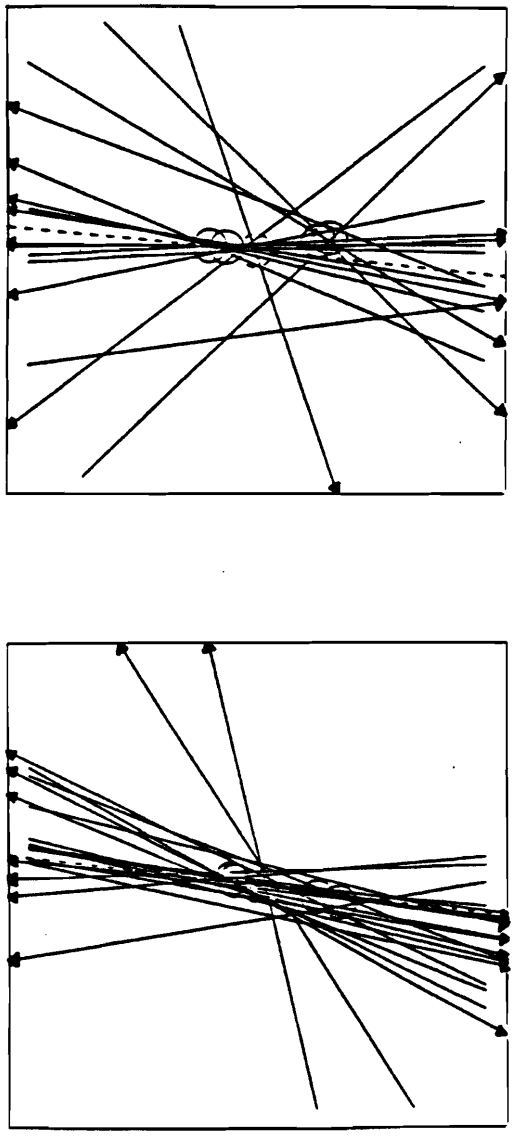

Figure 14. Simulated $b\bar{b}$ events as measured using a vertex detector [48]. The dashed and solid circles correspond to primary and charm or bottom decay vertices respectively. Each circle has a radius of 2 mm.

considerable advantage, the actual means to exploit this property may prove difficult, if not illusive. The situation on the $\Upsilon(4S)$ has already been illustrated. The PEP study independently arrived at quite similar conclusions. Shown in Figure 14 is an enlargement of the interaction region for a typical b-event as (a) generated and (b) reconstructed. The confusion in the r-ϕ projected views is enormous, leading to the same conclusion arrived at earlier that it would likely be necessary to have a precision z measurement as well to aid in exploiting the vertex topology. One distinct advantage for SLC in this game is the small beam spot, which can serve as a constraint to eliminate many of the tracks not originating from b- or c-vertices.

To an outsider it appears that the Z^0 experiments are only now giving serious thought to b-physics, as the probability recedes that the top mass is small enough to be produced there. A possible vertexing strategy has been studied by MARK II [49], with about a 40% efficiency per b-decay. They require 3 fast tracks with impact parameters of 3 sigma or greater with respect to the interaction point. By selecting only those events where the invariant mass of the three exceeds 1.95 GeV/c^2, most of the charm decays in the sample are removed, leaving less than 10% contamination from non-$b\bar{b}$ events. Referring again to the PEP study [48], it is clear that a strategy along these lines should be effective. The number of charged tracks originating from the B decay with momentum greater than 1 GeV exceeds four at the Z^0 (Figure 15a), while the fraction from the $\overline{B}$ decay drops to a little more than 10^{-3} (Figure 15b).

For the LEP detectors, the large diameter of the beam pipe will be a distinct disadvantage. However, if the operational history of other storage rings is a guide, less conservative choices for the beam pipe will no doubt be introduced over time. ALEPH and DELPHI, with vertex detection provided by silicon arrays, should be in a good position. Although there is no information about the algorithm employed, ALEPH claims a vertex efficiency of 10-20% for B decays from the Z^0, if a 5-10σ vertex separation is required [50].

3.2 Lifetimes

One of the obvious measurements for the Z^0 experiments is b-lifetimes. Average lifetimes could be measured to less than $\pm 5\%$. This probably doesn't have much meaning, since lifetime differences between b-flavoured hadrons are probably greater than this. The real interest lies in extracting separate measurements for the various species, in particular for B^0, B^+ and B^0_S. One crude method is to compare lifetimes measured with impact parameters of hadron versus lepton tracks [48]. The ratio of charged to neutral B mesons

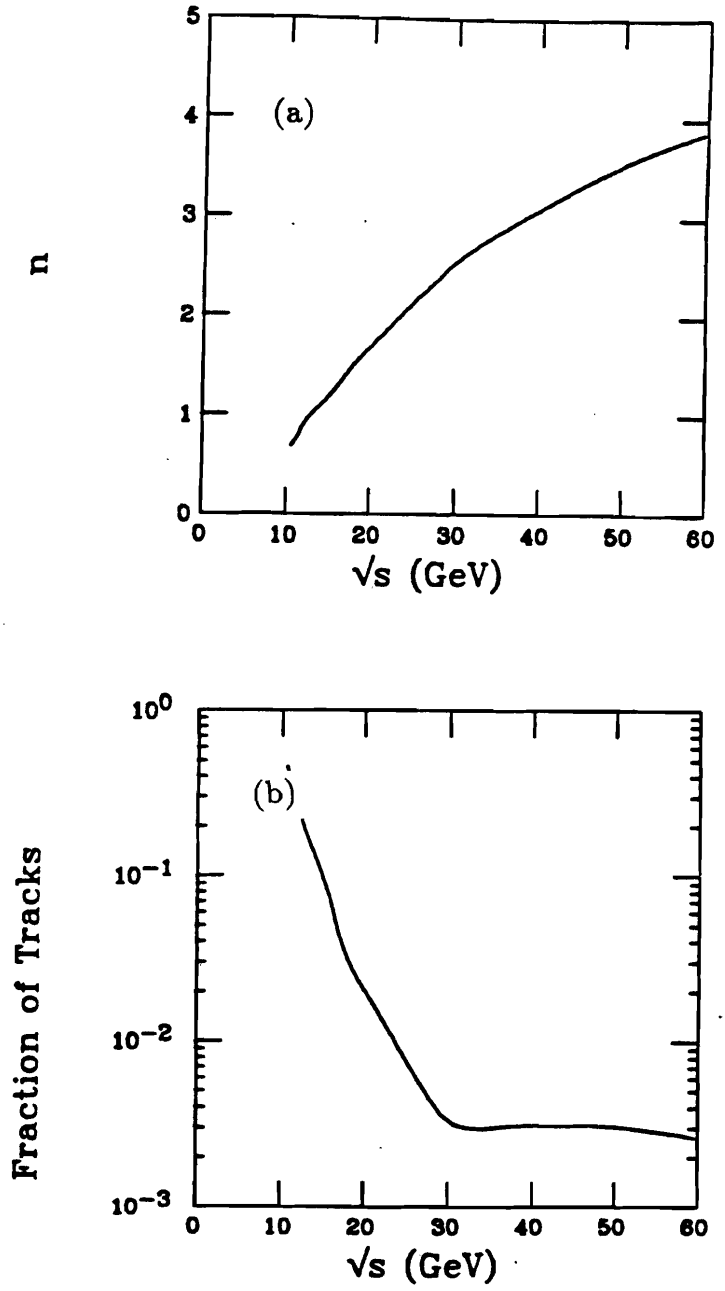

Figure 15. (a) Average number of charged tracks per b-decay with at least 1 GeV/c momentum. (b) Probability that a charged track with more than 1 GeV/c momentum is emitted into the hemisphere of the event opposite to the decaying b. Both are from reference [48].

in the sample will change for lepton versus hadron tracks if the lifetimes, and hence the leptonic decay widths, are different. If the lifetimes are comparable the method has little sensitivity, so that with an error of ±5%, one could only infer that the lifetimes were the same to ±20-30%.

What should be possible, at a considerable cost in efficiency, is to enrich one species or another via partial tagging techniques. Thus, if one studies the impact parameters of $D^0\ell^-$, $D^{*+}\ell^-$ or $D_S^+\ell^-$ combinations, one obtains samples with about 60% B^+, 90% B^0 or 60% B_S^0 respectively [48], because of the tendency for little fragmentation in semi-leptonic B decays. The small efficiency for charm reconstruction will require the large luminosity delivered by LEP.

3.3 Mixing

Another area where the Z^0 experiments were expected to contribute was a measurement of mixing, in particular mixing of the B_S^0. This program has become more difficult. Table 11 lists the expected number of like- and opposite-sign dileptons in a sample of 2×10^5 $b\bar{b}$ events [51], about 80 days of running at LEP design luminosity. As with an experiment running on the $\Upsilon(5S)$, the Z^0 study must disentangle the fraction of the like-sign events due to B_d^0 and B_S^0 mixing, without knowing the relative production rates. The one advantage is there are no complications due to coherent $B\overline{B}$ sources. Ali and Barreiro [52] suggested even before the ARGUS measurement that one could use rapidity correlations to tag B_S^0 production in the jet fragmentation process. They proposed using:

$$\Delta = \frac{N(\ell^-K^-K^-) - N(\ell^-K^+K^+)}{N(\ell^-K^-K^-) + N(\ell^-K^+K^+)}$$

as a variable mostly sensitive to B_S^0 mixing. One kaon is required to have high momentum ($p > 2$ GeV/c) and therefore predominantly originating from a B decay. The second can be softer, but must have momentum above 500 GeV/c to minimize contributions from far down the fragmentation chain. Under these circumstances, B_d^0 decays favour $\ell^-K_F^-K_S^+$ combinations. B_S^0 decays give $\ell^-K_F^-K_S^-$ and $\ell^-K_F^+K_S^-$ with roughly equal probability, and likewise $B_S^0 \rightarrow \overline{B}_S^0$ produces $\ell^-K_F^+K_S^+$ and $\ell^-K_F^-K_S^+$. Charm backgrounds are predominantly $\ell^-K^+K^-$. Figure 16 illustrates the change in Δ as a result of B_S^0-$\overline{B}_S^0$ mixing as a function of the p_T cut on the lepton [51]. Although heavily Monte Carlo dependent, the technique seems to hold the promise of distinguishing B_S^0 mixing. The note of concern expressed earlier about measurement of large mixing rates in a time-integrated fashion should, however, be borne in mind.

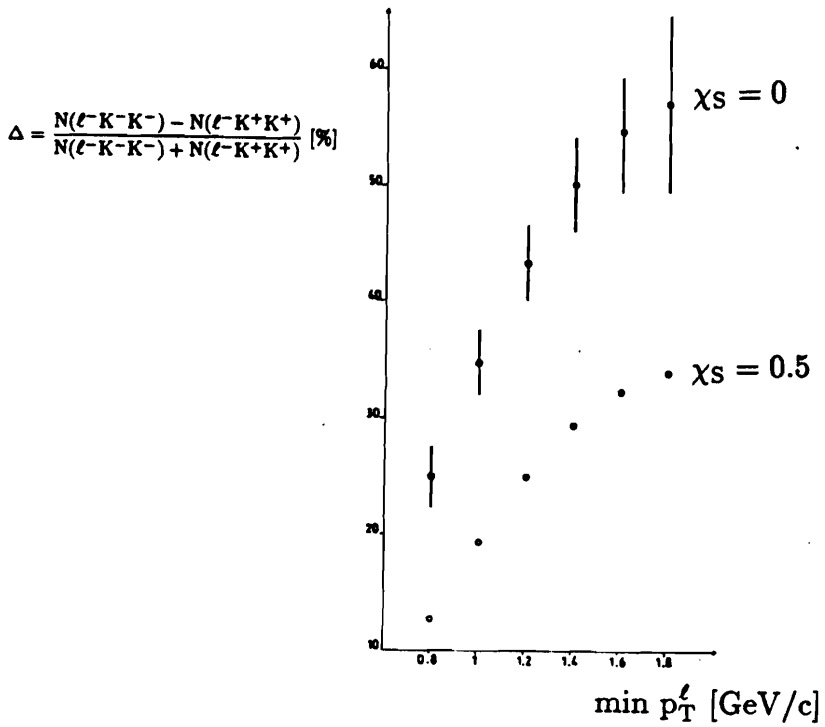

Figure 16. Distribution of the asymmetry Δ as a function of the p_T requirement for the lepton [51].

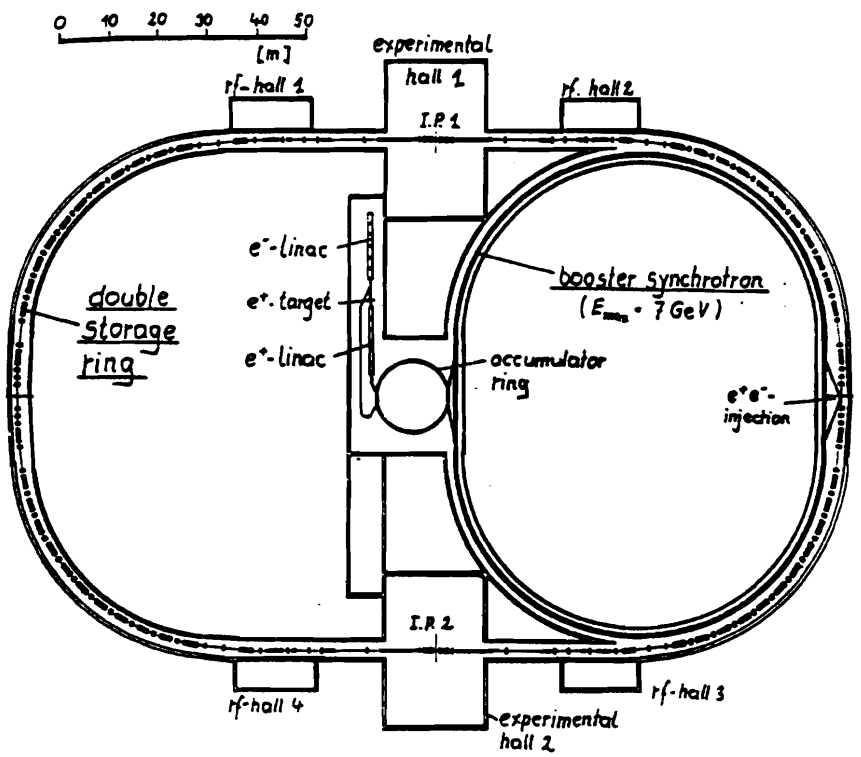

Figure 17. Schematic layout of the injector and booster synchrotrons for the proposed B meson factory at SIN [53].

$p_T(\ell) > 1.2$ GeV/c	Opposite-sign	Like-sign
$\chi_S = 0$, $\chi_d = 0$	908	135
$\chi_S = 0.5$, $\chi_d = 0$	832	211
$\chi_S = 0.5$, $\chi_d = 0.17$, $f_S/f_d = 0.5$	747	296

Table 11. Projected dilepton signals for 2×10^5 $b\bar{b}$ events at LEP. The third row has been adapted from the first two by this author.

4 New Machines

The Z^0 experiments, after some learning period, will likely begin to make valuable contributions to b-physics in the early 1990's. Nevertheless, the cleanliness of e^+e^- production at or near threshold is still enticing. There are currently several proposals for B factories, i.e. e^+e^- machines capable of 10^7 or more B mesons per year, under consideration. These can be broken down into three classes: double storage rings, rings with asymmetric beam energies and linear colliders.

The SIN proposal [53] is representative of the first of these: optimize storage ring design on the basis of present understanding. One maximizes luminosity by:

- operation in a high reliability mode at a dedicated facility
- using a small vertical β function ($\beta_z \leq 3$ cm)
- obtaining a large horizontal emittance
- using many bunches

The last requirement compels the choice of a double-ring design to minimize beam-beam interactions. The experience of DORIS dictates that such a double ring must have 0° crossing at the interaction point. This is one area which requires some work to develop a technique for separating the beams, either electrostatically or via an RF magnet. A schematic layout of the complex is shown in Figure 17. The luminosities which can be attained range from 5×10^{32} cm^{-2} s^{-1}, in the early stages of the project, to as much as 3×10^{33} cm^{-2} s^{-1} (Figure 18). A decision is expected before the end of 1988, with startup sometime in 1993 or later. As a reminder, 5×10^{32} cm^{-2} s^{-1} is equivalent to about 8×10^6 $B\overline{B}$ pairs per year on the $\Upsilon(4S)$. The design of a detector for this facility will be critical to exploitation of the anticipated luminosity. With the considerable investment in

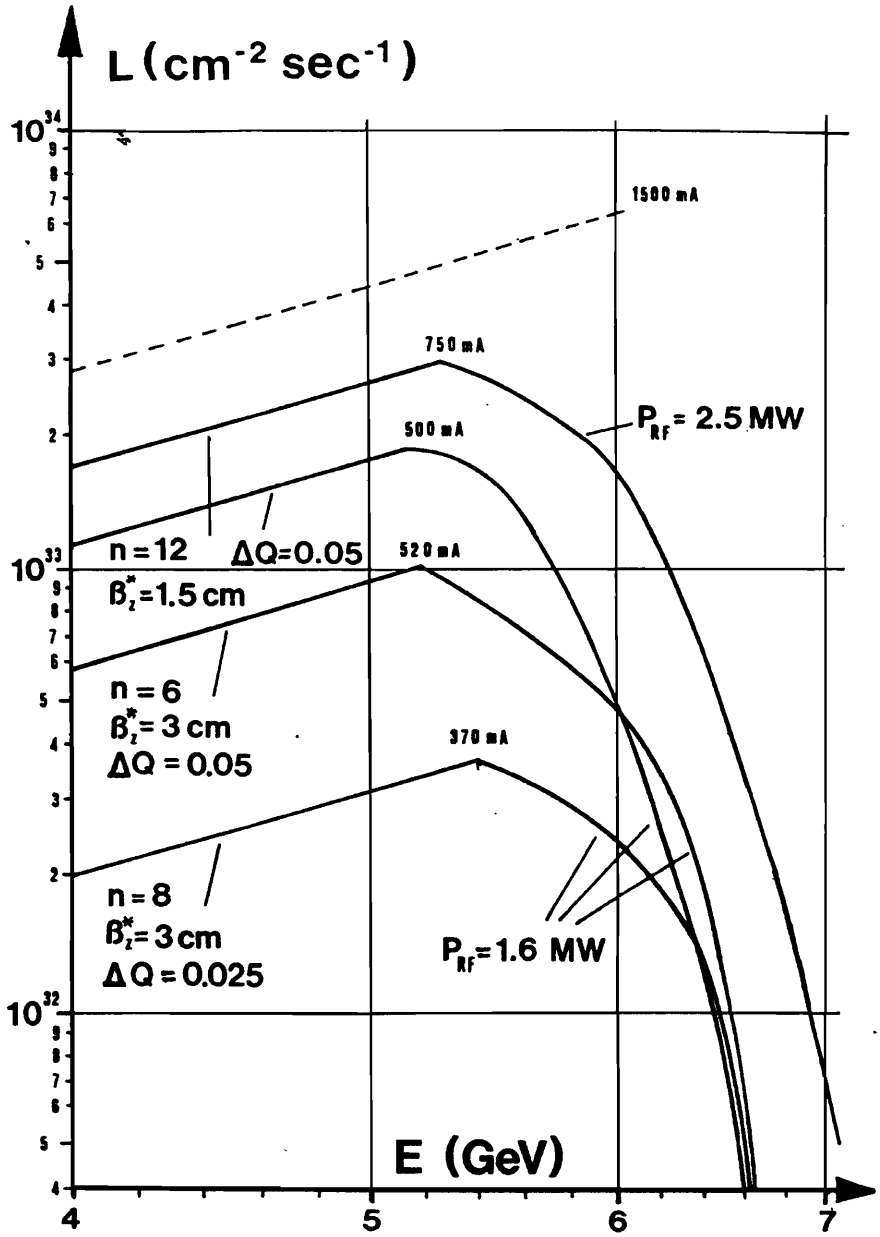

Figure 18. Anticipated luminosity of the SIN facility under various running scenarios [53].

hardware and experience embodied in CLEO II, it seems likely that efforts to maintain a competitive position for CESR will continue.

While the $\Upsilon(4S)$ has been a favourable B source, it does produce the $B^0\overline{B}^0$ pair in a coherent (L = 1) state. If one treats the time-integration symmetrically for the two B mesons, then it is not possible to observe mixing-induced CP violation effects [54]. Amplitude-induced effects in self-tagging charged B decays could still be observed. However, these will require a minimum of 10^8 B mesons [55], since these typically are brought about by interference between two competing diagrams in rare decays.

Therefore, it appears that the conventional B factory fails to meet the needs for a CP violation search in two essential ways: (1) insufficient luminosity and (2) production of the $\Upsilon(4S)$ in a way which does not allow a resolution of the B flight distances. The idea of an asymmetric set of storage rings, where 14 GeV electrons are collided with 2 GeV positrons, for example, is an attempt to rectify the second of these limitations by producing a boosted $\Upsilon(4S)$. It remains to be seen whether a suitable detector can be designed to take advantage of the peculiar asymmetric topology, or if the luminosities which can be achieved are competitive with the more conventional approach.

Another more speculative approach is the proposal to use high-frequency colliding linear accelerators. Representative among this class is the proposal of Amaldi and Coignet [56]. The design is in some sense a scaled-down version of the SLC, where the bunch frequency is increased from 180 Hz to 18 kHz. In addition, the disruption factor, which scales like $1/\gamma$, increase from 0.75 to 7.5, resulting in an increase in the pinch effect contribution by about a factor of 3. Taken together, a luminosity approaching 10^{33} cm^{-2} s^{-1} should be within reach. Considerable research and development work will be needed,

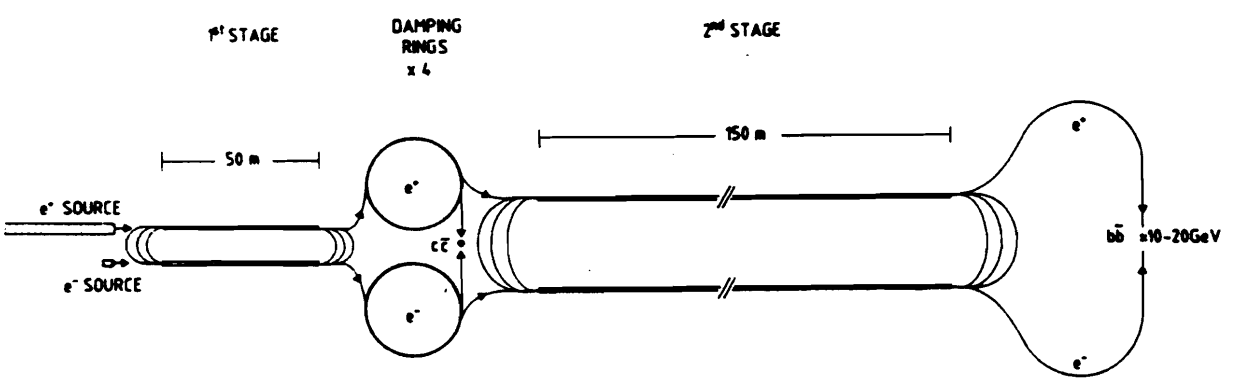

Figure 19. Schematic layout of a superconducting linear collider beauty factory [56].

in particular to develop a high intensity positron source and low-emittance beams. A schematic layout for the facility is shown in Figure 18.

The accelerator would operate in two modes. A high-resolution mode, with energy resolution of 3 MeV and a luminosity of 10^{33} cm^{-2} s^{-1}, has a transverse beam spot size of 1.1 μm. This permits the placement of vertex detectors very close to the interaction point and allows the precise definition of the production point for the B mesons. Thus, it would be possible to remove the necessity for integration over the B lifetime. In this case, the mixing-induced CP violation searches would be viable. Moreover, the design luminosity is equivalent to 10^7 B mesons per year on the Υ(4S), perhaps sufficient for the task. A low-resolution mode is also foreseen, with an energy resolution of 200 MeV and a transverse beam spot size of 0.6 μm. The design luminosity is 10^{34} cm^{-2} s^{-1}, or again 10^7 B mesons per year in the continuum, where the production is not coherent. In either scenario, if such a proposal were realized, one would be at the threshold for CP violation studies in the b-system.

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