An Asymmetric B Factory at 10^{36} Luminosity

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Abstract. The physics opportunities at an asymmetric B Factory operating at the unprecedented luminosity of 10^{36} cm^{-2}s^{-1} are unique and attractive. The accelerator appears to be practical and the challenges of performing a sensitive experiment in this environment can be met.

PHYSICS MOTIVATION

The physics of flavor is central to our understanding of the structure of matter. Recent developments in the quark and neutrino sectors have deepened our understanding of the Standard Model and pointed the way to further experimental studies in the search for new physics. This presentation addresses the future of the study of quark physics in e^+e^- annihilation, at the $\Upsilon(4S)$ and $\Upsilon(5S)$, over the next decade and beyond. A more detailed treatment can be found in Ref. 1.

The search for new physics in the quark sector involves direct searches for new particles (*e.g.* squarks or sleptons), precise tests of Standard Model predictions for rare decay branching fractions and decay distributions to search for new amplitudes in loop processes, and overconstrained tests of the CKM matrix. A very high luminosity asymmetric B Factory can make unique contributions to these studies, as well as providing capabilities complementary to those of experiments at hadronic machines.

Precision tests of CKM unitarity require the percent level precision on the measurement of $\sin 2\beta$ obtainable at a 10^{36} asymmetric B Factory as well as the several percent precision obtainable on $\sin 2\alpha$ and γ with very large samples of rare hadronic B decays. In particular, measurements of the separate branching ratios of $B^0 \to \pi^0\pi^0$ and $\overline{B}^0 \to \pi^0\pi^0$ decays (Fig. 1), possible only at an e^+e^- B Factory, are vital to obtain a precise value of α with minimal theoretical assumptions [2]. Taken together with concomitant improvements in our understanding of the magnitudes of CKM matrix elements, which require new techniques involving tagging and exclusive reconstruction of B semileptonic decays, as well as anticipated improvements in lattice gauge calculations, this program is capable of tests of CKM unitarity of exquisite precision. Measurements of the third angle γ are difficult, but can be done to excellent precision at a 10^{36} machine, both by the comparison of $b \to c\overline{u}s$ and $b \to u\overline{c}s$ decays using $B \to DK$ transitions at the $\Upsilon(4S)$ [3]-[5], and measurements of $B_s \to D^{(*)\pm}K^{(*)\mp}$ decays at the $\Upsilon(5S)$ [6] (see Fig. 2).

CP618, *Heavy Flavor Physics: Ninth International Symposium,* edited by A. Ryd and F. C. Porter

Table 1 summarizes the precision obtainable on the angles of the unitarity triangle at an e^+e^- experiment with 500 fb^{-1} and 10 ab^{-1}, corresponding to 1 year of running at 10^{36} luminosity, with that obtainable with planned and proposed experiments at hadronic colliders. The determination of γ using the $\Upsilon(5S)$ requires a separate data set of 1 ab^{-1}. In general, multiple complementary measurements of the CKM angles are possible. The 10^{36} collider has the capability to measure all three *CP*-violating angles of the unitarity triangle with superb precision.

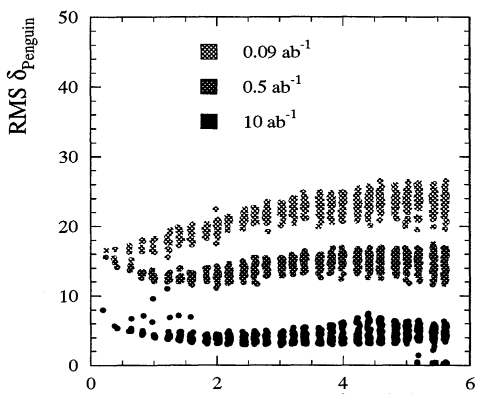

FIGURE 1. Uncertainty in the Penguin angle δPenguin = α_{eff}-α in degrees *vs.* the branching ratio for 90 fb^{-1}, 500 fb^{-1} and 10 ab^{-1}. (A. Roodman)

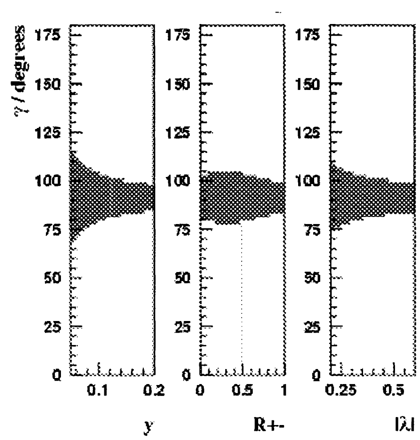

FIGURE 2. Statistical resolution on γ as a function of y_s, $R_\pm$ and $|\lambda|$ for 10,000 $D_s^{(*)\pm}K(*)^{\mp}$ events, corresponding to 1 ab^{-1} at the $\Upsilon(5S)$. A central value of γ=90° is assumed. (S. Petrak)

TABLE 1. Summary of estimated precision of CKM angle measurements for *BABAR* and Super*BABAR*, compared to planned experiments at hadronic colliders.

CKM Angle	*BABAR* (0.5ab^{-1})	Super*BABAR* (10 ab^{-1})	*B*TeV	LHC*b*	ATLAS/CMS
$\sin 2\beta (B^0 \to J/\psi K_s^0)$	0.037	0.008	0.025	0.014	0.021/0.025
$\sin 2\beta (B^0 \to \phi K_s^0)$	0.25	0.056			
$\sin 2\alpha (B^0 \to \pi^+\pi^-)$	0.14	0.032	0.024	0.056	0.10/0.17
$\alpha_{eff} - \alpha (B \to \pi^0\pi^0)$	< 18°	< 7°	-	-	-
$\sin(2\beta+\gamma)(B^0 \to D^*\pi)$	0.15	0.03			
$\gamma(B \to DK)$		<2.5°	<10°	<19°	
$\gamma(B_s \to D_sK)$		<15°	<7°	<13°	

Measurements to this precision would not be interesting if theoretical uncertainties affecting the determination of the precision of the sides of the unitarity triangle could not be commensurately reduced. Fortunately, improvements in lattice gauge theory techniques, through the replacement of quenched with unquenched calculations, improved actions and larger lattices, promise to improve on a time scale which keeps pace with the next generation of experiments [7]. Table 2 shows the expected improvement in both experimental and theoretical determinations of CKM matrix elements over the coming decade. Improvements in the determination of experimental inclusive and exclusive semileptonic branching ratios depend on larger data sets to reduce statistical errors, but also on new techniques, such as complete event reconstruction, made possible by the large data sets, that have smaller systematic and theoretical uncertainties.

TABLE 2. Projections for improvement in the experimental and theoretical contributions to the precision of CKM matrix elements.

V_{ij}	Experimental Measurement	σ 2001 stat/sys (%)	σ 2006 stat/sys (%)	σ stat/sys 2011 (%)	Theoretical Quantity	σ 2001 quenched (%)	σ 2-5 years unquenched (%)	σ 4-10 years unquenched (%)
V_{ub}	$\mathrm{B}(B \to \rho \ell \nu)$	4.3/8	8.6/2.4	1.4/2.4	$f_+(E_\pi)$	18	15	5
	$\mathrm{B}(B \to u \ell \nu)$	3.4/16	4.0/2.4	2.8/2.4	f_B †	10-15	10	2
	$\mathrm{B}(B \to \tau \nu)$		24	5	$\bar{\Lambda}, \lambda_1, \lambda_2'$ *	see note	see note	see note
V_{cb}	$\mathrm{B}(B \to D^* \ell \nu)$	3.1/4	0.4/2	0.1/1	$\mathcal{F}(1)$ ‡	2-4	2-4	1
	$\mathrm{B}(B \to c \ell \nu)$	2.5/2	0.3/1	0.07/0.5	$\bar{\Lambda}, \lambda_1, \lambda_2'$ *	25	15	5
V_{us}	$\mathrm{B}(K \to \pi \ell \nu)$	0.8	0.8	0.8	$f_+(q^2)$	15	15	2-5
V_{cd}	$\mathrm{B}(D \to \pi \ell \nu)$	7.1	1		$f_+(E_\pi)$	15	15	2-5
	$\mathrm{B}(D \to \ell \nu)$		2		f_D †	10-15	10	2
V_{cs}	$\mathrm{B}(D \to K \ell \nu)$		0.4		$f_+(E_K)$	15	15	2-5
	$\mathrm{B}(D_s \to \ell \nu)$		1		f_{Ds} †	10-15	10	2
V_{td}	Δm_d	1/1	0.2/0.5	0.05/0.2	$f_{B_d}\sqrt{B_{B_d}}$ #	~20	15	5
V_{ts}	Δm_s				$f_{B_s}\sqrt{B_{B_s}}$ #	~20	15	5

† 50% of the error on f_B / f_{D_s}

* from experiment: λ_2 from $m_{B^*} - m_B$; $\bar{\Lambda}$ and λ_1 from moments of $B \to cl\nu$ and $B \to s\gamma$ spectra

‡ lattice measures $\mathcal{F}(1)$ -1

\# $\xi = \dfrac{f_{B_s} / \sqrt{B_s}}{f_{B_d} / \sqrt{B_d}}$ error divided by 1.5-2

The last major area of experimental interest is rare decays, which provide sensitivity to new physics through loop diagrams. Table 3, also developed at Snowmass, compares the sensitivity of e^+e^- experiments with 500 fb^{-1}, the target total sample for *BABAR*, and with 10 ab^{-1}, corresponding to 1 year of running at 10^{36} luminosity, with that obtainable with planned and proposed experiments at hadronic colliders. The 10^{36} collider compares quite favorably with hadronic experiments, in

TABLE 3. Comparison of the number of reconstructed rare B decays in hadronic and e^+e^- experiments.

		Hadron Collider Experiments			e^+e^- B Factories	
Decay Mode	**Branching Fraction**	**CDF/D0 (2 fb^{-1})**	**BTeV/LHCb (10^7 s)**	**ATLAS/CMS (1 y)**	**BABAR/Belle (0.5ab^{-1})**	**Super$B$ABAR (10 ab^{-1})**
$B \to X_s \gamma$	$(3.3 \pm 0.3) \times 10^{-4}$				11K	220K
					1.7K (B tagged)	34K (B tagged)
$B \to K^* \gamma$	5×10^{-5}	170	25K		6K	120K
$B \to \rho(\omega) \gamma$	2×10^{-6}				300	6K
$B \to X_s \mu^+ \mu^-$	$(6.0 \pm 1.5) \times 10^{-6}$		3.6K		300	6K
$B \to X_s e^+ e^-$					350	7K
$B \to K^* \mu^+ \mu^-$	$(2 \pm 1) \times 10^{-6}$	60-150	2.2K/4.5K	665/4.2K	120	2.4K
$B \to K^* e^+ e^-$					150	3K
$B \to X_s \nu \bar{\nu}$	$(4.1 \pm 0.9) \times 10^{-5}$				8	160
$B \to K^* \nu \bar{\nu}$	5×10^{-6}				1.5	30
$B_d^0 \to \tau^+ \tau^-$	10^{-7}					
$B_s^0 \to \mu^+ \mu^-$	10^{-9}	5/1.5-6	5/11	9/7		
$B_d^0 \to \mu^+ \mu^-$	8×10^{-11}	0/0	1/2	0.7/20		
$B \to \tau \nu$	5×10^{-5}				17	350
$B \to \mu \nu$	1.6×10^{-7}				8	150
$B^0 \to \gamma\gamma$	10^{-8}				0.4	8

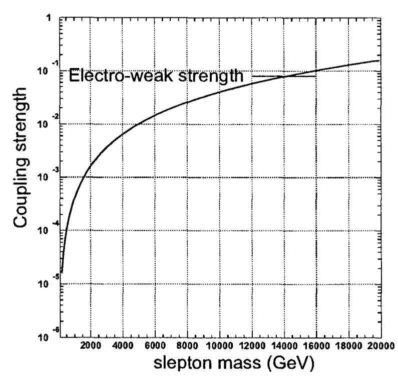

FIGURE 3. 90% confidence level limits on coupling *vs.* R-parity-violating *slepton* mass. (S. Yang).

rare inclusive and exclusive modes, and particularly in radiative modes. Note also that only an e^+e^- experiment can produce a sample of tagged $B \to X_s \gamma$ decays. Fig. 3 shows that the *slepton* mass sensitivity exceeds 10 TeV at standard electro-weak coupling for a $B_d^0 \to e^+e^-$ branching fraction limit of 10^{-9}, corresponding to 10 ab^{-1}.

SUPERPEP-II

The next generation B Factory requires a significant increase in luminosity, approaching $10^{36}cm^{-2}s^{-1}$, well beyond the already record-setting performance of PEP-II and KEKB. It appears that such a luminosity is feasible; initial parameters of SuperPEP-II, a very high luminosity e^+e^- B Factory are being developed, incorporating several new ideas from the successful operation of the present generation accelerators [8][9]. In this regime, the luminosity lifetime is primarily determined by the collisions themselves requiring continuous injection. This has a positive consequence: the ratio of average to peak luminosity in SuperPEP-II can be increased by 30% due to continuous injection, thereby directly improving the ability to integrate luminosity. With continuous injection, the operation of this accelerator will be qualitatively different from present e^+e^- colliders.

The next generation e^+e^- Factory will operate mainly at the $\Upsilon(4S)$ with a center-of-mass energy of 10.58 GeV with an energy asymmetry similar to those currently used, but a period of operation at the $\Upsilon(5S)$ may also be desirable. For the present study the PEP-II tunnel geometry was used as were the PEP-II beam energies of 9.0 and 3.1 GeV: a reduced energy asymmetry would reduce RF costs. To increase the luminosity about two orders of magnitude the beam currents must be raised an order of magnitude and the beam cross sectional area reduced an order of magnitude while keeping the beam-beam tune shifts under control. The parameters shown in Table 4 are self-consistent but further optimization is certainly possible.

The observed beam-beam tune shifts in PEP-II now approach 0.07 [10]. The expected tune shifts in this new accelerator should be larger for two reasons: the use of round beams at the collision point will increase the tune shifts by about a factor of two (there may be increased backgrounds from round beam operation, but significantly more backgrounds are expected from other sources as well), and it has been observed in PEP-II that by adjusting the tunes the luminosity can be increased significantly 10% at the expense of the beam lifetime [11]. (This beam lifetime will be called the beam-beam lifetime.) Higher luminosity for the same current means higher tune shifts. The new accelerator can take advantage of continuous injection to push the tune shifts to significantly higher values and consequently the beam-beam lifetimes to significantly lower values. The beam-beam lifetime in present colliders is about 100 minutes. The design assumption is that the tune shifts can be increased from 0.07 to 0.14 by reducing the beam-beam lifetime from 100 minutes to 10 minutes and by adopting round beams at the collision point.

The interaction region will likely have a geometry similar to that of PEP-II [12]. The cone angle separating the accelerator and detector components can be about 300 mrad, as at present. The LER quadrupoles for this accelerator can be moved significantly closer to the IP than in PEP-II using superconducting Q1 and Q2 magnets with stronger gradients, such as those used in the HERA upgrade [13]. The HER quadrupoles can also be moved closer because the LER quadrupoles have been moved. A crossing angle of about ±1.5 mrad is used to help separate the beams at the first parasitic beam-beam crossing. The beams are horizontally separated by about 12 σ_x at the first parasitic crossing.

TABLE 4. Parameters for a 10^{36} asymmetric *B* Factory in the PEP-II tunnel

Parameter	High Energy Ring (HER)		Low Energy Ring (LER)
Beam Energy (GeV)	9.0		3.1
Beam Particle	e^+		e^-
Center of mass energy (GeV)		10.58	
Circumference		2200	
RF frequency (MHz)		476	
RF voltage (MV)	50		30
Synchrotron radiation power (MW)	23		12
Number of bunches		3492	
Total beam current (A)	6.6		19.2
Number of beam particles	3.0×10^{14}		8.8×10^{14}
$\beta^*_{y/x}$ (cm)		0.32/0.32	
Emittance (*y*/*x*) (nm)		22/22	
Momentum compaction	0.001		0.0013
Bunch length (mm)	3.5		3.5
Approx. AC power (MW)	50		27
Beam lifetime (min)	5		5
Injected particles per pulse	7.3×10^{10}		5.3×10^{10}
Continuous injection rate (Hz)	20		80
Ring particles lost per second	1.1×10^{12}		3.2×10^{12}
Beam-beam tune shift	0.14		0.14
Transverse beam size (μm)	8.4		8.4
Luminosity ($cm^{-2}s^{-1}$)		10^{36}	

The HER vacuum system must dissipate over 16 kW/m of synchrotron radiation power. The chambers will likely be made with an antechamber with a continuous built-in photon stop. The design of bellows (expansion) modules would be very difficult for these high currents and short bunch lengths. Instead, the plan is to use a concept investigated for the PEP-II rings but not implemented. The vacuum system would be a continuous extrusion welded together with no bellows but with rigid supports to constrain thermal stresses [14]. A similar technique is used to build very long welded railroad tracks. The beam impedance will improve without bellows. The stainless steel chambers in the straight sections will have to be changed to a lower resistance material to reduce the resistive wall effect for the LER.

The beam lifetime from the beam-beam interaction will be reduced to about five minutes to maximize the beam-beam tune shifts.

Injection must be a continuous process because the beam lifetimes are short. Taking the SLAC site, the beams would come from the damping ring and linac complex. The SLAC system was built to provide about 1×10^{11} electrons per pulse at 120 Hz and about half that rate for positrons. The damping ring cavity RF frequency will be changed from 714 MHz to 476 MHz. In the damping rings, the particle bunches will be distributed uniformly over about half the circumference (35 m) in about 30 bunches. The other half of the ring circumference is used by the injection and extraction kicker rise times. The linac can operate at 120 Hz. The electron injection rate would likely be 80 Hz, the positron injection rate 20 Hz and the remaining 20 Hz used for positron production. Injection losses can cause detector problems. However, the damped injected beam will have transverse emittances smaller than the stored beam emittances. The linac bunch length and energy spread are well matched to the stored bunches, promising a relatively clean injection process. As some injection collimation will likely be needed, however, the injection efficiencies were assumed to be 75%.

SUPER*BABAR*

Doing a precision experiment at a 10^{36} asymmetric B Factory requires a new detector to cope with backgrounds and radiation levels[15]. Initial studies at Snowmass indicate that this is a tractable problem. A detector based on an all silicon tracking detector, and using short radiation length calorimeter crystals, would be more compact than *BABAR*. The higher physics and background rates are dealt with by employing detector systems with high segmentation and short integration times, such as pixel devices and fast scintillating crystals.

The overall scale of the detector studied at Snowmass, called Super*BABAR*, and shown in Fig. 4, is determined by the crystal calorimeter. We require scintillating crystals with greater radiation hardness and faster decay times than the CsI(Tl) deployed in current generation devices. Crystals such as LSO and GSO have these desirable characteristics, as well as shorter radiation length and smaller Molière radius. Thus a calorimeter having energy and angular resolution comparable to existing devices can be quite a bit smaller in volume.

This, of course, poses a challenge to the resulting smaller radius tracking system. The tracking detector would combine two pixel layers with seven layers of arched double-sided silicon strips, providing track and vertex reconstruction in a single system. A 3 Tesla superconducting solenoid provides momentum resolution comparable to that of larger current combined silicon/drift chamber systems in a weaker field, *albeit* with different contributions from measurement error and multiple coulomb scattering.

A DIRC Cherenkov device, based on that used in *BABAR*, but with a new compact readout that is much less sensitive to backgrounds, provides $\pi/K/p$ identification over the full kinematic range.

A straightforward extension of the open trigger approach traditionally employed in e^+e^- experiments appears to be quite practical. Techniques for detector readout pioneered for the new generation of experiments at the Tevatron and LHC appear to be generally applicable to a 10^{36} e^+e^- storage ring, allowing unbiased triggering on essentially all events of interest.

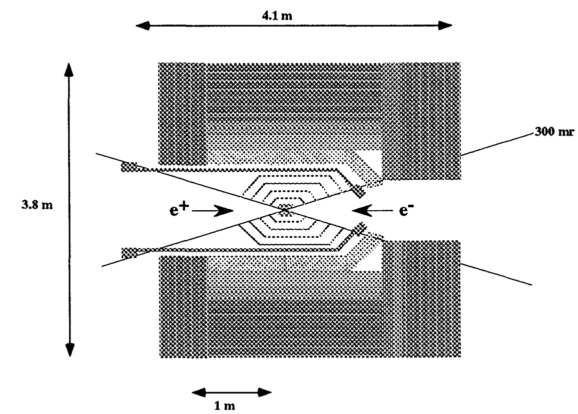

FIGURE 4. Elevation view of a concept for Super*BABAR*, a detector designed for a 10^{36} collider.

CONCLUSION

In summary, the physics case for a 10^{36} asymmetric *B* Factory is quite strong. The program has many unique aspects and is complementary to the programs at hadronic machines. The details of machine and detector design are far from mature, but both machine and detector appear to present reasonable challenges. Undoubtedly, developments in both theory and experiment over the next several years will sharpen our vision and allow a clearer determination of the importance of pushing flavor physics investigations to this new level in rare decays and precision measurements.

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