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CP-violation studies in b decays at the TESLA Z-factory

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Abstract

The possibility of studying CP violation in b decays produced in 10^9 hadronic Z^0 decays at the TESLA linear collider 'Z-factory' is examined. Various channels for measuring the CKM unitarity triangle angles α, β, γ and $\delta\gamma$ are studied and the likely precision of the analyses calculated. These results are compared to those attainable at e^+e^- b factories and hadron colliders. Whilst no 'golden' measurement is found that cannot be done at other facilities, many measurements can be performed with useful and competitive precision.

1 Introduction

Although the primary motivation for an e^+e^- linear collider is the study of e^+e^- collisions at energies beyond 200 GeV, it may also be interesting to run at high luminosity on the Z^0 pole. By adding an auxiliary high intensity positron source, the TESLA linear collider may be able to achieve a luminosity of $7 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$, allowing the accumulation of 10^9 Z^0 in a reasonable time [1]. The primary motivation for such a run, corresponding to approximately 100 times the combined LEP1 luminosity, is the precision measurement of electroweak parameters, in particular A_{LR}. However, this run would also produce 4×10^8 b hadrons, which may allow a competitive measurement of rare CP-violating b decays in a much cleaner environment than at a hadron collider. This possibility is studied in the present note, and the results compared with those achievable at BaBar, CDF, ATLAS and LHC-b (taken as representative also of the results achievable at BELLE, D0, CMS and B-TeV respectively).

The following assumptions are made in this note:

Luminosity: The studies are done assuming a data sample of 1×10^9 hadronic Z^0 decays, corresponding to an integrated luminosity of about $30\,\mathrm{fb^{-1}}$. At a sustained luminosity of $7\times10^{33}\,\mathrm{cm^{-2}s^{-1}}$, this corresponds to a running time of about 50 days with a hadronic Z^0 trigger rate of 230 Hz. This data sample contains 4×10^8 b decays, to be compared with *e.g.* 6×10^7 in one nominal year at BaBar, and 10^{12}–10^{13} at LHC.

Polarisation: Both electron and positron beams can be polarised, with $\mathcal{P}^- = \pm0.8$ and $\mathcal{P}^+ = \pm0.6$. Opposite polarisation allows very clean tagging of the directions of the initial b and $\bar{\mathrm{b}}$ quarks, vital for competitive CP violation measurements (see section 2). It is assumed that 90 % of the data is taken with opposite sign polarisation of the e^+ and e^- beams, and 10 % with same sign polarisation, the optimum division for the measurement of A_{LR}.

Detector: The standard 'reference' detector, as described in the linear collider CDR [2] is assumed. In particular, no dedicated particle identification devices (*e.g.* Cherenkov detectors) have been added, but the use of $\mathrm{d}E/\mathrm{d}x$ information in the TPC is explored. No triggering losses are considered, as it is assumed that the entire data sample of $Z^0 \to \mathrm{b\bar{b}}$ events can be triggered on and stored without losses.

Detailed simulation studies have been performed for several of the channels discussed in this note, using the fast simulation program SIMDET (version 3.1 [3]) and the full GEANT simulation BRAHMS (version 1.02 [4]), the latter incorporating the DELFIT package for track reconstruction. Both of these simulation tools implement the detector geometry as described in the CDR [2].

2 Initial state tagging

Most of the CP violation studies of interest involve measuring the time-dependent asymmetry in the decay of B^0 and $\bar{\mathrm{B}}^0$ mesons to a CP eigenstate f_{cp}: $\mathrm{B}^0, \bar{\mathrm{B}}^0 \to f_{\mathrm{cp}}$. The asymmetry $A(t)$ takes the form:

$$A(t) \equiv \frac{N_{\mathrm{B}^0}(t) - N_{\bar{\mathrm{B}}^0}(t)}{N_{\mathrm{B}^0}(t) + N_{\bar{\mathrm{B}}^0}(t)} = a_{\cos} \cos \Delta m\, t + a_{\sin} \sin \Delta m\, t \tag{1}$$

where Δm is the $\mathrm{B}^0 - \bar{\mathrm{B}}^0$ mixing parameter. Since the final state is a CP eigenstate (*e.g.* $\mathrm{J}/\psi \mathrm{K}^0_{\mathrm{s}}$, $\pi^+\pi^-$), the initial state (B^0 or $\bar{\mathrm{B}}^0$) must be determined ('tagged') from information elsewhere in the event. In most experiments, this is done by exploiting the pair production of $\mathrm{b\bar{b}}$, and tagging the state (b or $\bar{\mathrm{b}}$) of the other quark in the event (which in general does not decay to a CP eigenstate). However, both the efficiency and the purity of this procedure is low, leading to a significant 'mistag' (events tagged incorrectly).

The use of polarised beams at TESLA, combined with the large forward-backward asymmetry of the b quark coupling to the Z^0, allows a different method to be used, as at SLD [5]. With polarised beams, the differential cross section for $\mathrm{e^+e^-} \to \mathrm{Z}^0 \to \mathrm{b\bar{b}}$ takes the form:

$$\frac{d\sigma}{d\cos\theta} = (1 - A_{\mathrm{e}}\mathcal{P})(1 + \cos^2\theta) + 2A_{\mathrm{b}}(A_{\mathrm{e}} - \mathcal{P})\cos\theta \tag{2}$$

where $A_{\mathrm{e}} = 0.15$ and $A_{\mathrm{b}} = 0.93$ are the fermion couplings to the Z^0 [6], and $\mathcal{P} = (\mathcal{P}^- - \mathcal{P}^+)/(1 - \mathcal{P}^-\mathcal{P}^+)$ is the effective polarisation resulting from the polarisation of the electron beam by $\mathcal{P}^-$ and the positron beam by $\mathcal{P}^+$. This cross section is plotted in Figure 1(a) for the expected polarisation levels of $\mathcal{P}^- = \pm 0.8$ and $\mathcal{P}^+ = \pm 0.6$. The very large asymmetry resulting from the high level of effective polarisation when $\mathcal{P}^-$ and $\mathcal{P}^+$ have opposite signs is clearly seen.

This asymmetry can be used to tag the initial b quark flavour, by simply assuming (for $\mathcal{P}^- < 0$) the forward ($\cos\theta > 0$) hemisphere contains the b quark and the backward ($\cos\theta < 0$) contains the $\bar{\mathrm{b}}$ antiquark. The resulting mistag rate is 0.5 (equivalent to purely random tag assignment) when $\cos\theta = 0$, but drops to *e.g.* only 6% at $|\cos\theta| = 0.9$. The tagging power can be quantified by means of the 'separation power' s, defined generally as $s = \epsilon D^2$ where ϵ is the tagging efficiency and D the dilution $D = (1 - 2\eta)$ [7]. The dilution represents the reduction in the size of the measured asymmetry due to the imperfect initial state tagging, and $s = \epsilon D^2$ gives the corresponding loss in the total number of events—one imperfectly tagged event is equivalent to s perfectly tagged events. With the polarisation tag, the mistag depends strongly on $\cos\theta$, and the effective separation is given by the integral:

$$< s > = \frac{\int_0^{\cos\theta_{\max}} \frac{d\sigma}{d\cos\theta}(1 - 2\eta(\cos\theta))^2 \,\mathrm{d}\cos\theta}{\int_0^{\cos\theta_{\max}} \frac{d\sigma}{d\cos\theta} \,\mathrm{d}\cos\theta}$$

where $\eta(\cos\theta)$ is the mistag rate at any particular value of $\cos\theta$. For $\mathcal{P}^- = 0.8$, $\mathcal{P}^+ = -0.6$ and $\cos\theta_{\max} = 0.9$, *i.e.* assuming a uniform event reconstruction efficiency up to $\cos\theta = 0.9$, the separation is $s = 0.47$. For the 10% of the luminosity assumed to be taken with same sign polarisation, the separation is only $s = 0.09$, and is not useful. These values should be compared with typical values of 0.20 in LEP B^0 oscillation analyses, 0.06 at CDF (for the $\sin 2\beta$ analysis [8]), similar values of about 0.06 for future hadron collider experiments and 0.2–0.3 expected for BaBar at an e^+e^- b factory [7].

It is clear that the initial state tagging with polarised beams offers an important advantage over other facilities, and the tagging can be further improved by combining the polarisation information

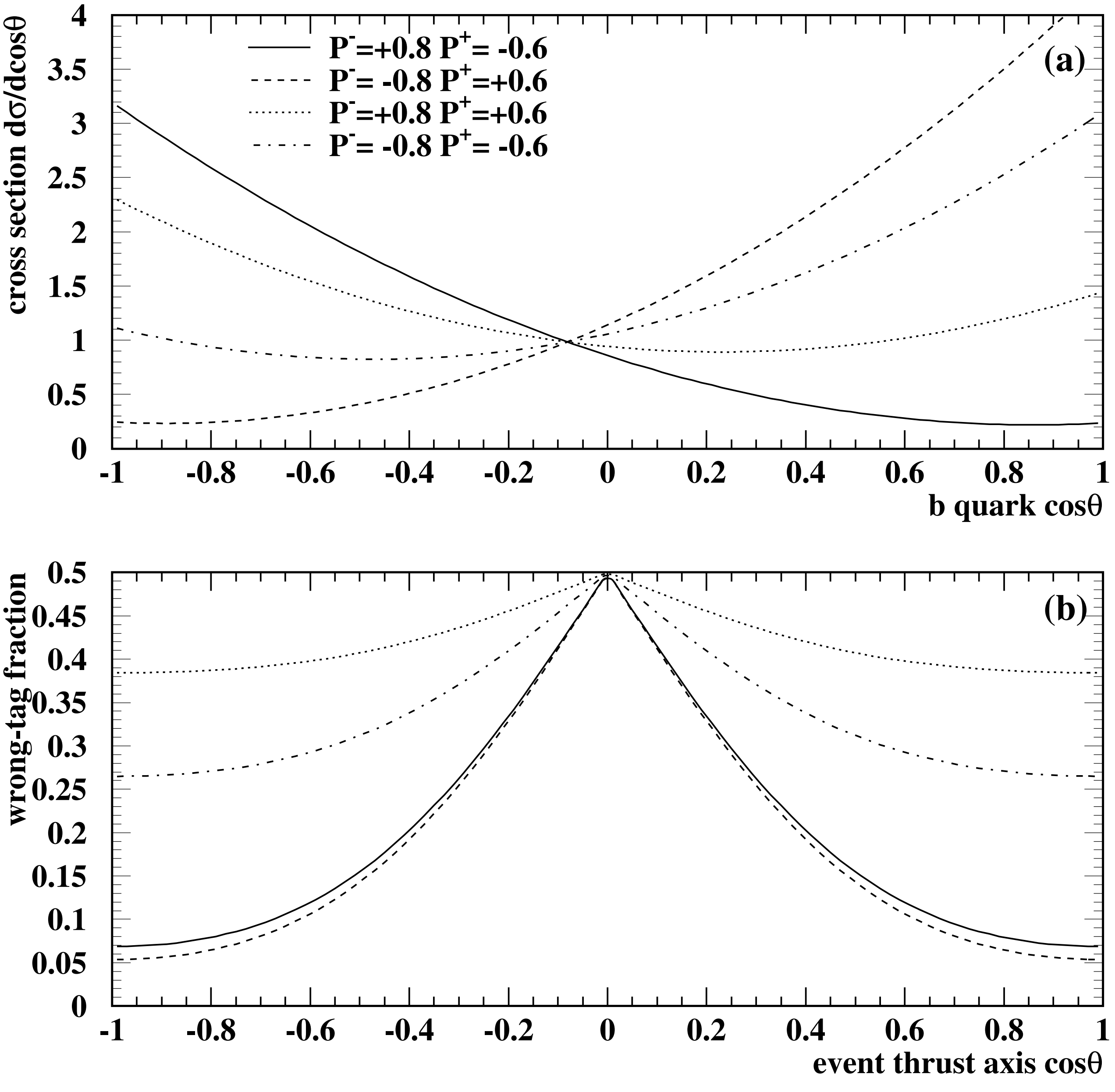

Figure 1: (a) Differential cross section for $e^+e^- \rightarrow Z^0 \rightarrow b\overline{b}$ as a function of the b quark polar angle $\cos\theta$, for various polarisations of the incoming electron and positron beams; (b) resulting wrong-tag fraction when the b quark hemisphere is inferred from the thrust axis direction.

with all the other tags used at LEP and SLD. A separation of $s = 0.45$ has been used throughout this note, and even higher values may be achievable with appropriate combination of tags.

3 Measurement of β

The cleanest way to measure the angle β is to study the decay mode $\mathrm{B}^0, \bar{\mathrm{B}}^0 \to \mathrm{J}/\psi \mathrm{K}^0_\mathrm{s}$, where the time dependent asymmetry follows equation 1 with $a_{\sin} = -\sin 2\beta$ and $a_{\cos} = 0$. The decay is easy to reconstruct with $\mathrm{J}/\psi \to e^+e^-$ or $\mu^+\mu^-$ and $\mathrm{K}^0_\mathrm{s} \to \pi^+\pi^-$, and first results have already been obtained from existing experiments [8,9]. With 10^9 Z^0 and a reconstruction efficiency of 30 % (OPAL achieved 20 % with inferior tracking and mass resolution), a total of 1900 reconstructed events would be expected. The effects of time resolution and combinatorial background should be small, leading to an expected error on $\sin 2\beta$ of ± 0.04. This should be compared with 0.12 for BaBar in 1 year of running ($30\,\mathrm{fb}^{-1}$) [7], 0.08 for CDF from run II ($2\,\mathrm{fb}^{-1}$) [10], 0.02 from ATLAS in 1 year [11] and 0.01–0.02 from LHC-b [12].

It is clear that in this relatively easy decay channel, the huge number of events reconstructed at LHC gives a decisive advantage. However, $\sin 2\beta$ can also be measured in many other B^0 decay modes, for example $\mathrm{J}/\psi \mathrm{K}^0_\mathrm{L}$, $\mathrm{J}/\psi \mathrm{K}^{*0}$, $\psi' \mathrm{K}^0_\mathrm{s}$, and $\mathrm{D}^{(*)}\mathrm{D}^{(*)}$. An important part of the b factories' physics program will be to measure $\sin 2\beta$ in all these modes, and demonstrate consistent results. Some of these decay modes are difficult at hadron colliders, but should be accessible in the cleaner environment of the e^+e^- linear collider. With the larger number of events and better tagging than at b factories, the linear collider should be able to significantly improve on some of these measurements.

4 Measurement of α

The measurement of α requires the study of a decay with a contribution from $\mathrm{b} \to \mathrm{du}\bar{\mathrm{u}}$. The simplest such decay is $\mathrm{B}^0, \bar{\mathrm{B}}^0 \to \pi^+\pi^-$, whose asymmetry can be used to measure $\sin 2\alpha$ in the same way as the asymmetry in $\mathrm{B}^0, \bar{\mathrm{B}}^0 \to \mathrm{J}/\psi \mathrm{K}^0_\mathrm{s}$ measures $\sin 2\beta$. However, in the $\pi^+\pi^-$ decay, there are significant complications resulting from so called 'penguin' diagrams, which destroy the simple relationship between $\sin 2\alpha$ and the measured asymmetry [7,12]. In the absence of penguin contributions, the asymmetry takes the form given by equation 1 with $a_{\cos} = 0$ and $a_{\sin} = -\sin 2\alpha$, but penguin contributions introduce decay amplitudes with different strong phases, leading to $a_{\cos} \neq 0$ and $a_{\sin} \neq -\sin 2\alpha$. The measured values of the coefficients $a_{\cos}$ and $a_{\sin}$ can be used to extract $\sin 2\alpha$, providing the amount of penguin contribution is known.

Unfortunately, the contribution of penguin decays is now expected to be significant, as the penguin dominated decay $\mathrm{B}^0 \to \mathrm{K}^+\pi^-$ has been measured to have an unexpectedly large branching ratio of $(1.4 \pm 0.3 \pm 0.2) \times 10^{-5}$, whilst only an upper limit of 0.84×10^{-5} has been set on the branching ratio of $\mathrm{B}^0 \to \pi^+\pi^-$ [13]. This has two serious implications for the determination of $\sin 2\alpha$ in the $\pi^+\pi^-$ channel:

1. The decay $\mathrm{B}^0 \to \pi^+\pi^-$ has a large background from $\mathrm{B}^0 \to \mathrm{K}^+\pi^-$, which must be cleanly separated, since it is also expected to have a (different) non-trivial CP violating asymmetry.

2. The relative contributions of tree and penguin decays in $\mathrm{B}^0 \to \pi^+\pi^-$ must be determined, to allow the extraction of $\sin 2\alpha$ from the measured values of $a_{\cos}$ and $a_{\sin}$. One promising technique is to use an isospin analysis, which requires measurement of the three branching ratios for the decays $\mathrm{B}^0 \to \pi^+\pi^-$, $\mathrm{B}^0 \to \pi^0\pi^0$ and $\mathrm{B}^+ \to \pi^+\pi^0$.

Hence a determination of $\sin 2\alpha$ requires both a measurement of the asymmetry in $\pi^+\pi^-$ and measurement of the three branching ratios for the isospin analysis. These measurements are discussed in more detail below.

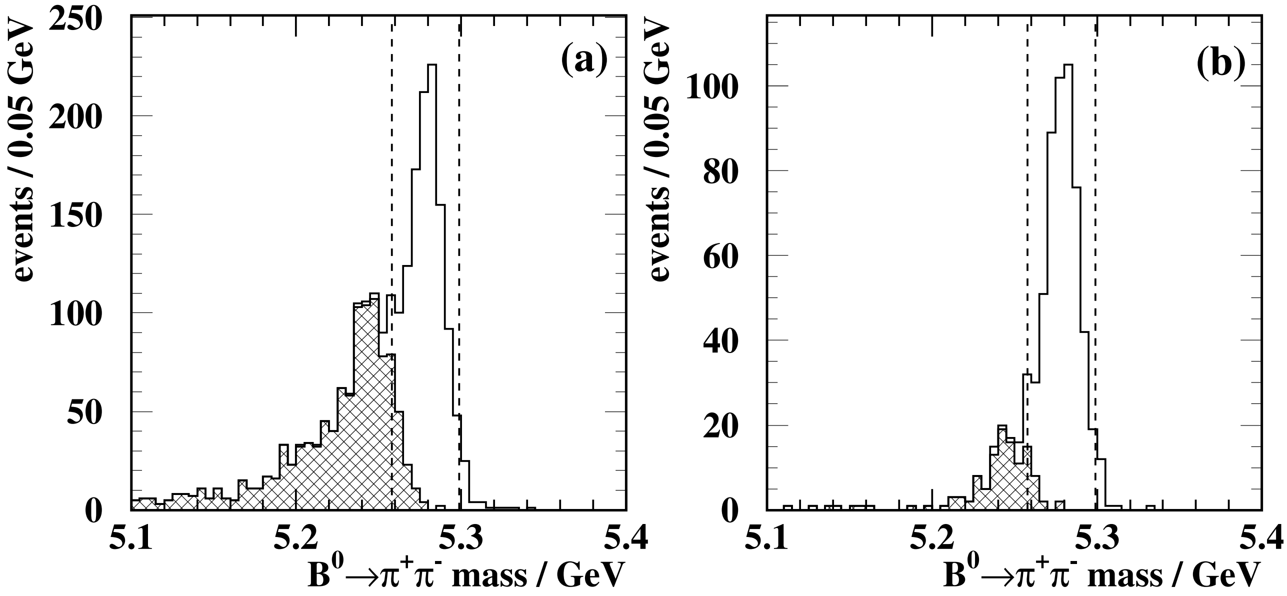

Figure 2: Invariant mass distributions of reconstructed $\mathrm{B}^0 \rightarrow \pi^+\pi^-$ decays (open histogram) and $\mathrm{B}^0 \rightarrow \mathrm{K}^+\pi^-$ decays (hatched histogram), without (a) and with (b) a $\mathrm{d}E/\mathrm{d}x$ requirement. The positions of the mass cuts are shown by the dotted lines.

4.1 Asymmetry measurement for $\pi^+\pi^-$

The reconstruction of $\mathrm{B}^0 \rightarrow \pi^+\pi^-$ decays has been studied with the full detector simulation program BRAHMS, but simulating only the tracking detectors. The candidate selection was based on the OPAL search for this decay [14]. After requiring the direction of the thrust axis to satisfy $|\cos\theta_\mathrm{T}| < 0.9$, jets were reconstructed using a cone algorithm with half-angle 0.65 rad and minimum jet energy 5 GeV. All possible opposite-charge pairs of tracks in each jet were then combined as possible B^0 candidates, requiring the vertex probability to exceed 1 %, the decay length significance L/σ_L to exceed 3 and the b hadron candidate energy to exceed 25 GeV. Additionally, the opening angle ϕ between the two tracks was required to be less than 0.5 and the angle θ^* of the π^+ in the rest frame of the B^0 was required to satisfy $|cos\theta^*| < 0.8$ [14]. Finally the reconstructed mass of the candidate was required to be in the range 5.258–5.299 GeV. The entire selection is 46 % efficient for $\mathrm{B}^0 \rightarrow \pi^+\pi^-$ and results in about 900 selected events from 10^9 Z^0 decays for a branching ratio of 1.2×10^{-5}, as assumed in [7].

The resulting invariant mass spectrum for $\mathrm{B}^0 \rightarrow \pi^+\pi^-$ and $\mathrm{K}^+\pi^-$ decays is shown in Figure 2(a), assuming equal branching ratios for the two decay modes. The very good tracking resolution of the linear collider detector gives a signal peak with RMS of 11 MeV, and this is enough to largely separate the signal from the $\mathrm{K}^+\pi^-$ background. Within the mass region of 5.258–5.299 GeV, the signal to background ratio is about 10:1. This is in contrast to other experiments, where particle ID has to be used to separate the two decays. By making an additional cut $\cos\theta^* > 0$, exploiting the correlation between the decay angle and the effective reconstructed mass for the $K^+\pi^-$ decay, the background can be reduced to a negligible level for a 50 % loss in signal. The mass resolution depends mainly on the curvature resolution of the tracking, and not on multiple scattering—if the magnetic field is reduced from the default 3 T to 1.5 T, the mass resolution is degraded from 11 MeV to 18 MeV. Running the detector with a lower magnetic field for the Z-factory option is therefore disfavoured in this channel.

The very good mass resolution allows the effective suppression of the $\mathrm{K}^+\pi^-$ background without particle ID. However, the TPC of the proposed detector offers the possibility of using some $\mathrm{d}E/\mathrm{d}x$ information. The performance of this has been estimated to give 1.5–2σ separation between pions and kaons in the momentum range of interest (10–30 GeV) [15]. This modest $\mathrm{d}E/\mathrm{d}x$ performance allows the signal to noise ratio to be increased to 40:1 for a 50 % loss in signal efficiency, as shown in Figure 2(b), before the application of the additional $\cos\theta^*$ cut. Hence it may provide a useful extra contribution to the background rejection.

Apart from the $\mathrm{B}^0 \to \mathrm{K}^+\pi^-$ decay, the main background is expected to be combinatorial in nature. This has been evaluated in two ways (i) with a sample of 10^5 Z^0 decays simulated in BRAHMS, and (ii) by making extrapolations from the background seen in the OPAL search for the $\mathrm{B}^0 \to \pi^+\pi^-$ decay [14], accounting for the better mass resolution of the linear collider detector. Both methods are statistically limited, and lead to an expected signal to noise ratio of 3:1 or better.

The precision to which the parameters $a_{\cos}$ and $a_{\sin}$ can be measured can be used as a 'figure of merit' for the various experiments. Assuming a signal to background level of 3:1, no residual contamination from $\mathrm{B}^0 \to \mathrm{K}^+\pi^-$ decays and no CP violation in the combinatorial background, a simple fit to the asymmetry gives $\delta a_{\cos} = 0.05$ and $\delta a_{\sin} = 0.07$ in 10^9 Z^0 decays. The latter uncertainty can be interpreted as a statistical error on $\sin 2\alpha$ in the absence of penguin contributions. The equivalent numbers for other experiments are 0.26 for BaBar [7], 0.10 for CDF [10], 0.14 for ATLAS [11] and 0.05 for LHC-b [12], from the same integrated luminosities as discussed in section 3. It should be noted that ATLAS has no particle ID and insufficient mass resolution to separate the $\pi^+\pi^-$ and $\mathrm{K}^+\pi^-$ final states, so the analysis will be very difficult in the presence of this background. It can be seen that in this measurement the linear collider is very competitive with other experiments, offering comparable precision to LHC-b in a very different environment.

4.2 Branching ratio measurements for $\pi^0\pi^0$ and $\pi^+\pi^0$

The extraction of the penguin and tree amplitudes in $\mathrm{B}^0 \to \pi^+\pi^-$ can be achieved by measurement of the three branching ratios $\mathrm{B}^0 \to \pi^+\pi^-$, $\mathrm{B}^0 \to \pi^0\pi^0$ and $\mathrm{B}^+ \to \pi^+\pi^0$. The first can be easily be measured as a by product of the asymmetry analysis discussed above, but the other two are more difficult. In particular, $\mathcal{B}(\mathrm{B}^0 \to \pi^0\pi^0)$ is expected to be extremely small, theoretical predictions being of the order 10^{-6} and the experimental upper limit 9×10^{-6} [13].

The feasibility of measuring the latter two branching ratios has been studied using the fast simulation SIMDET, which contains a parameterisation of the calorimeter response to overlapping particles derived from the full BRAHMS simulation. The reconstruction is similar to that used for the $\pi^+\pi^-$ channel, but requires the explicit reconstruction of π^0 mesons in the calorimeter. The π^0 have a mean energy of about 15 GeV, at which the two photons from the π^0 decay have a typical angular separation of 0.04 rad, corresponding to a spatial separation of 5 cm at the calorimeter front face. Since the granularity of the electromagnetic calorimeter in the CDR is 0.015 rad, many π^0 are not clearly resolved into 2 photons but appear as a single wide electromagnetic cluster. Both pairs of identified photons with an invariant mass between 0.1 and 0.2 GeV, and single identified photons were therefore considered as π^0 candidates. The photon identification was taken directly from SIMDET, which includes an 'energy flow' matching algorithm to identify neutral and charged particles from the reconstructed tracks and calorimeter clusters.

Reconstructed π^0 candidates were combined in pairs or with charged hadrons to form B^0 and B^+ candidates, in both cases requiring the energy of each pion to exceed 8 GeV and that of the b hadron to exceed 25 GeV. The resulting invariant mass spectra in signal events containing $\mathrm{B}^0 \to \pi^0\pi^0$ or $\mathrm{B}^+ \to \pi^+\pi^0$ are shown in Figure 3. The invariant mass resolutions are dominated by the π^0 reconstruction, and are 160 and 120 MeV respectively, much worse than in the $\pi^+\pi^-$ mode. This resolution is dominated by angular rather than energy resolution effects—improving the stochastic term in the electromagnetic calorimeter resolution from $10\,\%/\sqrt{E}$ to $5\,\%/\sqrt{E}$ only decreases the $\pi^0\pi^0$ mass resolution to 120 MeV. Large tails to lower masses are also visible in the reconstructed mass distributions, caused by π^0 overlapping with other particles (from fragmentation) in the same jet,

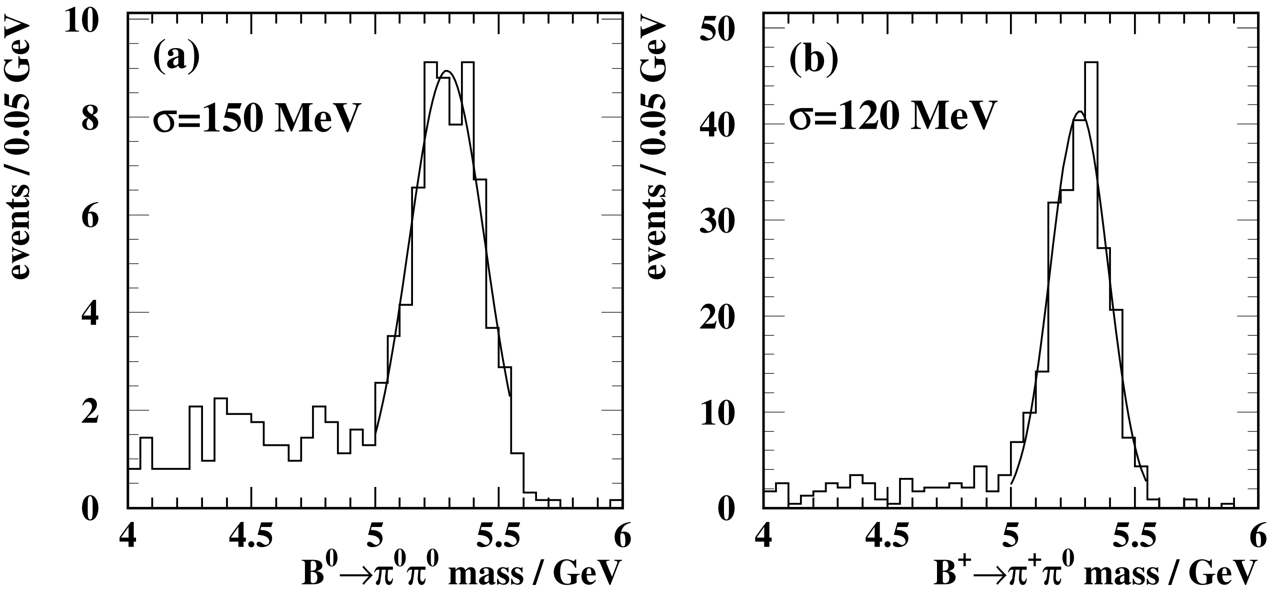

Figure 3: Reconstructed invariant mass distributions for (a) $B^0 \to \pi^0\pi^0$ and (b) $B^+ \to \pi^+\pi^0$ signal events. The mass resolutions (excluding the tails of low mass events) are indicated.

spoiling the energy measurement.

Due to the lower mass resolution and difficult π^0 reconstruction, these channels suffer from very large combinatorial background. This can be reduced by applying a b-tag on the opposite hemisphere of the event—an efficiency of 50 % for $b\overline{b}$ events with negligible contribution from other flavours was assumed. The remaining combinatorial background was assessed using a sample of 2×10^6 $b\overline{b}$ events processed through SIMDET. These studies show that the background is composed mainly of random tracks and clusters from b decays and fragmentation forming the correct invariant mass. It can be reduced by applying a track based anti b-tag in the signal hemisphere (after first removing the candidate π^+ track in the $\pi^+\pi^0$ case). The number of charged tracks from b decays in selected background hemispheres is shown in figure 4(a) and (b). Although the b decay multiplicity is lower than average (about 5) in these hemispheres, a veto on any tracks with significant impact parameter can still be used to effectively suppress this background. A rejection factor of 10 (*i.e.* 90 % of background events rejected) for negligible loss of signal has been assumed.

After applying the anti-b tag in the signal hemisphere, the expected numbers of signal and background events in the mass window 5–5.5 GeV for various different branching ratio assumptions are listed in Table 1. The expected statistical errors on the branching ratio, taking into account the numbers of signal and background events and no uncertainty on the background level, are also given, and compared to those expected from BaBar after 10 years of running at nominal luminosity (300 fb^{-1}) [7]. It can be seen that these errors are somewhat larger than those from BaBar, and are in fact similar to those expected after only 5 years of running at nominal luminosity.

The expected invariant mass spectra for $\mathcal{B}(B^0 \to \pi^0\pi^0) = 3 \times 10^{-6}$ and $\mathcal{B}(B^+ \to \pi^+\pi^0) = 5 \times 10^{-6}$ are shown in Figure 4(c) and (d). The background histograms are extrapolations from the small number of surviving $b\overline{b}$ events, so their shapes are somewhat uncertain. Nevertheless, it is clear that a good understanding of the background shape will be necessary to measure the signal branching ratios, and this may be rather difficult to achieve.

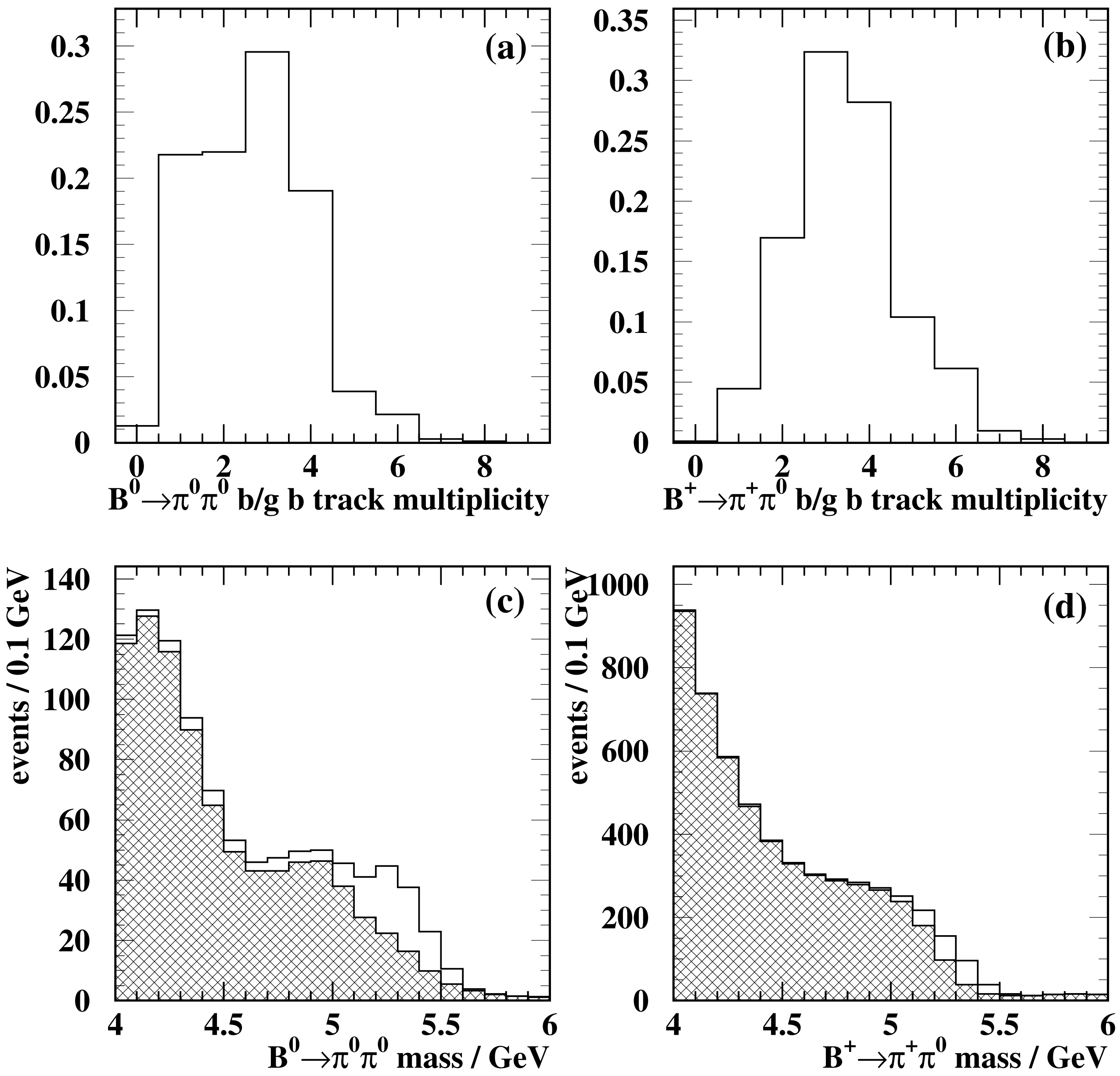

Figure 4: Background to $B^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ selections: Number of tracks from b decays in (a) $\pi^0\pi^0$ and (b) $\pi^+\pi^0$ background candidate hemispheres passing all cuts except signal hemisphere b-tag requirement; resulting mass spectra for signal and background events for (c) $\pi^0\pi^0$ and (d) $\pi^+\pi^0$ decays. The signal is shown by the open histogram and the background by the hatched histogram in each case. Signal branching ratios of $\mathcal{B}(B^0 \to \pi^0\pi^0) = 3 \times 10^{-6}$ and $\mathcal{B}(B^+ \to \pi^+\pi^0) = 5 \times 10^{-6}$ have been assumed.

Decay	$\mathcal{B}/10^{-6}$	Signal events	Background events	$\sigma_{\mathcal{B}}/\mathcal{B}$ LC	$\sigma_{\mathcal{B}}/\mathcal{B}$ BaBar
$B^0 \to \pi^0\pi^0$	1	26	107	0.44	0.29
	2	52	107	0.24	0.17
	3	78	107	0.17	-
	5	130	107	0.12	0.08
$B^+ \to \pi^+\pi^0$	2.5	95	577	0.27	0.20
	5	190	577	0.15	0.11
	7.5	285	577	0.10	0.08
	10	380	577	0.08	0.06

Table 1: Number of signal and background events, and resulting fractional statistical error $\sigma_{\mathcal{B}}/\mathcal{B}$ on the branching ratio, for various values of $\mathcal{B}(B^0 \to \pi^0\pi^0)$ and $\mathcal{B}(B^+ \to \pi^+\pi^0)$. Results for BaBar, assuming $300\,\mathrm{fb}^{-1}$ integrated luminosity, are also given [7].

In summary, the measurement of the branching ratios $\mathcal{B}(B^0 \to \pi^0\pi^0)$ and $\mathcal{B}(B^+ \to \pi^+\pi^0)$ would be an important contribution to the understanding of CP violation in b decays, since it cannot be performed at hadron colliders. However, it looks rather difficult with the present detector and uncertainties in the level of background. To proceed further probably requires a more realistic calorimeter simulation and a more detailed study of the π^0 reconstruction and background rejection.

5 Measurement of Δm_s, γ and $\delta\gamma$

The study of time dependent asymmetries in B_s decays provides a method of determining the CKM angle γ and the small angle $\delta\gamma$ (which is the 'tilt' of the second unitarity triangle formed from the relation $V_{ud}^*V_{td} + V_{us}^*V_{ts} + V_{ub}^*V_{tb} = 0$). B_s mesons are not produced at all in $\Upsilon(4S)$ decays (so are inaccessible to e^+e^- b factories unless they run at a higher resonance) and are only produced in 10 % of b decays at higher energies. The B_s mixing frequency Δm_s is also at least 25 times higher than that for B^0 mesons, so requiring very good time resolution to see the oscillations and asymmetries. Both of these factors make studies of B_s decays much more challenging experimentally than studies of B^0 decays.

5.1 Measurements in $B_s \to D_s^- K^+$ and $B_s \to D_s^-\pi^+$

Searches for B_s oscillations at LEP, SLD and the Tevatron have so far been carried out mainly using semi-inclusive modes such as $B_s \to D_s\ell\nu X$ and $B_s \to \ell\nu X$. In these analyses, the energy of the B_s (which is necessary to calculate the decay proper time) is estimated using reconstructed and missing energy. However, the limit on Δm_s is now $12.4\,\mathrm{ps}^{-1}$ [16], and measuring significantly higher frequencies can only be done with rare fully reconstructed decays. The decay chain $B_s \to D_s^-\pi^+$, with $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$ provides a suitable decay mode to measure or set a limit on Δm_s, whilst the similar $B_s \to D_s^\mp K^\pm$ provides a way of measuring $\gamma - 2\delta\gamma$.

These channels have been studied using the full GEANT simulation BRAHMS. The decay chain was fully reconstructed, requiring two oppositely charged tracks to make a ϕ candidate with $1.015 < m_\phi < 1.025\,\mathrm{GeV}$, combined with another track to make a D_s candidate with $1.959 < m_{D_s} < 1.979\,\mathrm{GeV}$ and a further opposite signed track to make a B_s candidate. The 3 tracks from the D_s were required to make a good vertex, as were the extrapolated track from the D_s and the π^+ from the B_s. The latter vertex was used to define the B_s decay length. The B_s energy was additionally required to exceed 20 GeV, but no particle ID ($\mathrm{d}E/\mathrm{d}x$) cuts were applied. The resulting mass distribution is shown in Figure 5(a), for $B_s \to D_s^-\pi^+$ signal events, and the same events reconstructed assuming the π^+ from the B_s decay to have the kaon mass. The latter distribution, which forms a 'reflection' background for the reconstruction of $B_s \to D_s^{\mp}K^{\pm}$ is reasonably separated from the signal, without the need for particle ID. The signal mass resolution is about 8 MeV, without the application of any kinematic fit.

The reconstruction efficiency for this selection is about 20 %, but many of the losses occur in requiring good vertices, which may be improved with better tracking code. Assuming $\mathcal{B}(B_s \to D_s^- \pi^+) = 3 \times 10^{-3}$ (by analogy with $B^0 \to D^- \pi^+$ [6]) and $\mathcal{B}(D_s^- \to \phi\pi^-) = 3.5\,\%$ [6] gives a total of about 500 reconstructed events in 10^9 Z^0 decays.

The proper time of each decay was reconstructed from the measured decay length (between the reconstructed primary vertex and the intersection of the D_s^- and π^+ tracks) and reconstructed energy of each candidate. The energy resolution is extremely good (0.5 %) and the proper time resolution is dominated by the decay length reconstruction. This was simulated separately for each of the vertex detector options available in BRAHMS—CCD vertex detectors surrounding 1 cm and 2 cm radius beampipes, and an APS vertex detector with a 2 cm beampipe. The resulting proper time resolutions are shown in Figure 5(b)–(d), together with the resolutions obtained from a double Gaussian fit to the distribution of reconstructed minus true proper time. The resolution clearly depends strongly on which vertex detector option is chosen.

The sensitivity to B_s oscillations as a function of Δm_s can be quantified by means of the amplitude method [17]. The amplitude A of oscillations at each 'test' value of Δm_s is measured, in a method analogous to Fourier analysis. Oscillations are excluded if the value $A = 1$ is excluded by the measurement, whilst exclusion of $A = 0$ is required to establish a signal. The significance of the analysis is then quantified by the inverse of the error on A, σ_A^{-1}, which must be at least 5 to claim a signal ('5σ discovery'), and at least 1.645 to set a 95% confidence level exclusion. The expected error can be calculated approximately by:

$$\sigma_A^{-1} = \sqrt{\frac{N}{2}} f_{\text{sig}}(1 - 2\eta)\exp(-\frac{1}{2}(\sigma_t \Delta m_s)^2)$$

where N is the number of events in the sample, f_{sig} the signal purity, η the mistag and σ_t the proper time resolution. The results of this calculation for $f_{\text{sig}} = 0.5$ and $f_{\text{sig}} = 0.9$ are shown in Figure 6 for each of the vertex detector options. The background to the $B_s \to D_s^- \pi^+$ signal is expected to be combinatorial and very small, due to the very good mass resolution and two intermediate mass constraints (ϕ and D_s). Hence values of f_{sig} close to one are expected to be realistic, although this has not been studied with simulation. With $f_{\text{sig}} = 0.9$, it can be seen that B_s oscillations can be discovered between 20 and 40 ps^{-1}, depending on the vertex detector options. This is comparable with the reach of CDF and ATLAS, though slightly lower than the 50 ps^{-1} expected by LHC-b [12]. The larger reach of LHC-b is due to the much higher numbers of reconstructed events—30000 as opposed to 500 for the linear collider, though the proper time resolutions are similar and the tagging better at the linear collider. However, such high values of Δm_s should also be visible through their effects on the B_s width difference ($\Delta\Gamma/\Gamma$), and are currently disfavoured within the framework of the Standard Model.

The decay $B_s \to D_s^{\mp}K^{\pm}$ can be used to measure the CKM angle $\gamma - 2\delta\gamma$. However, its branching ratio is expected to be at least an order of magnitude smaller than that for $B_s \to D_s^- \pi^+$, so only around 50 reconstructed events are expected in 10^9 Z^0 decays—not enough to measure the 4 time dependent decay rates necessary for this analysis. LHC-b expects around 2500 events per year in this channel [12] so the linear collider is clearly not competitive, even with the large statistical advantage in tagging power.

5.2 Measurements in $B_s \to J/\psi\phi$

The decay $B_s \to J/\psi\phi$ is the B_s analogue of the $B^0 \to J/\psi K_S^0$ decay, and can be used to measure the CKM angle $\delta\gamma$. This asymmetry is expected to be very small in the Standard Model, so a significant asymmetry would be a sign of new physics. However, as with the other B_s decay modes discussed above, the relatively small number of B_s mesons produced at the linear collider make it uncompetitive with LHC-b, and also with ATLAS and CMS in this decay channel which is easy to trigger on.

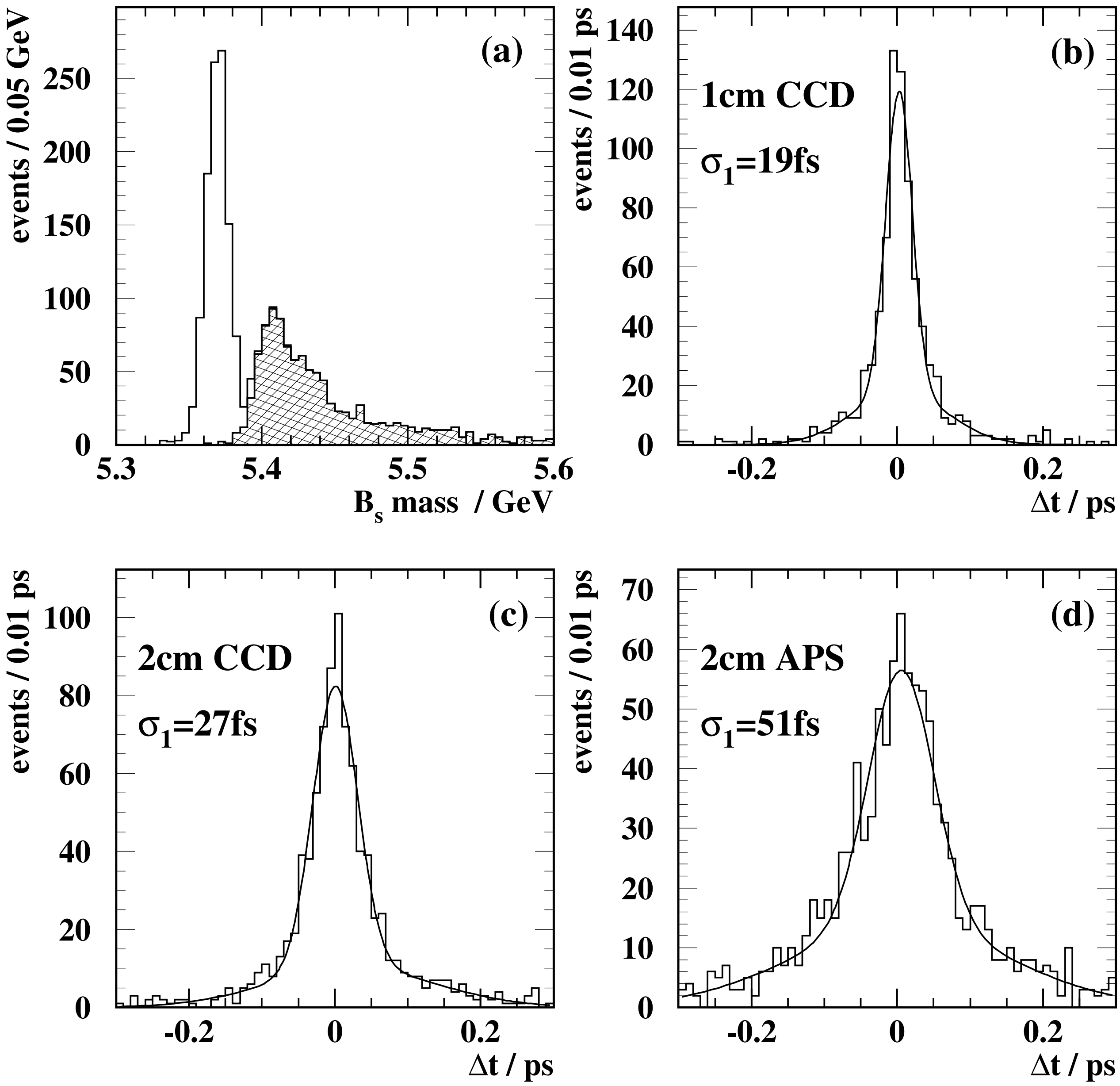

Figure 5: (a) Reconstructed invariant mass distributions for signal $B_s \to D_s^- \pi^+$ (open histogram) and the same events reconstructed as $B_s \to D_s^- K^+$ (hatched histogram); (b)–(d) reconstructed proper time resolutions for $B_s \to D_s^- \pi^+$ events with different vertex detector options. Double Gaussian fits to the resolutions are superimposed, and the widths of the narrow Guassians (σ_1) are indicated.

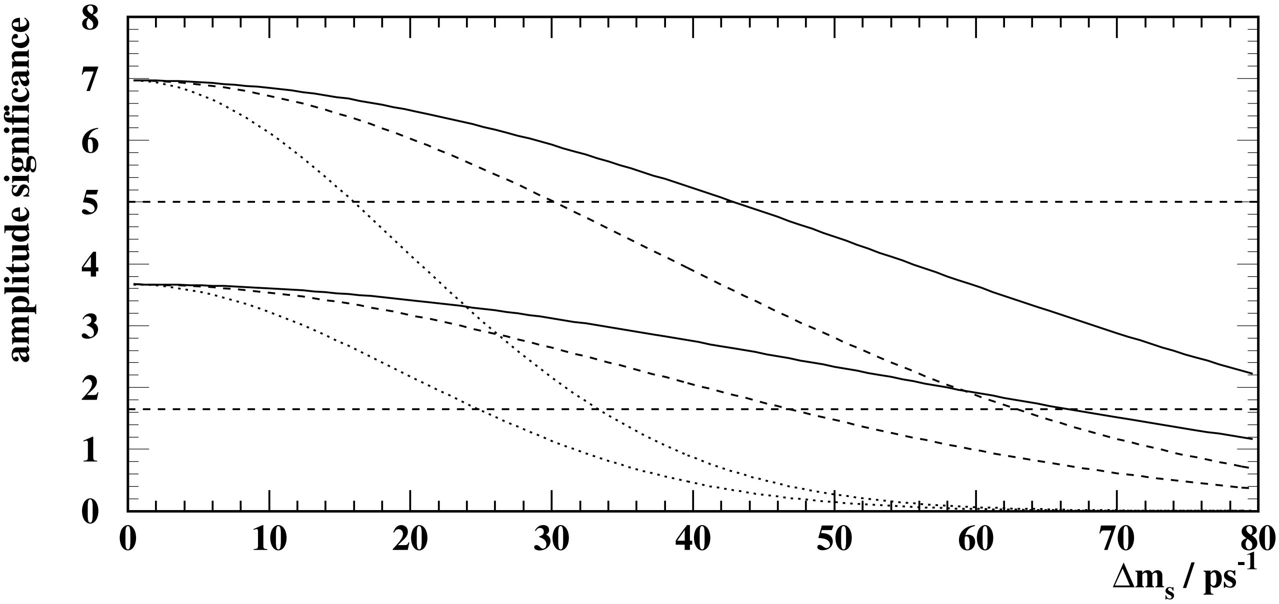

Figure 6: Amplitude significance σ_A^{-1} *vs.* $\Delta m_{\rm s}$ curves for $\rm B_s \to D_s^- \pi^+$ oscillation analyses assuming a CCD vertex detector with 1 cm radius beampipe (solid line), CCD vertex detector with 2 cm beampipe (dashed line) and APS vertex detector with 2 cm beampipe (dotted line). The upper set of curves refer to a signal fraction of 90 %, the lower to a signal fraction of 50 %. The 5σ discovery and 1.65σ exclusion significances are indicated.

The reconstruction of $\rm B_s \to J/\psi\phi$ is similar to $\rm B^0 \to J/\psi K_s^0$, and with a 30 % reconstruction efficiency 700 events are expected in 10^9 $\rm Z^0$. ATLAS and LHC-b expect around 40000 events [11, 12], so again the linear collider is at a severe statistical disadvantage.

5.3 Measurements in $\rm B^+$ and $\rm B^0$ decays

Various other strategies, involving the decays of $\rm B^+$ and $\rm B^0$ mesons, have been proposed to extract or constrain γ. Some of these have been studied for BaBar [7] and LHC-b [12]. One method is to use rare $\rm B^+ \to D^0 K^{*+}$ and $\rm B^0 \to D^0 K^{*0}$ decays, however the combined branching ratios are so small that only a few events per year are expected at BaBar, and a few tens of events at LHC-b. In 10^9 $\rm Z^0$ the linear collider should collect similar numbers to LHC-b, so if these analyses are possible at all, the linear collider should be able to make a useful contribution. However, these channels have not yet been studied in detail.

Another proposed method is to make use of flavour symmetries in $\rm B^0 \to K^\pm \pi^\mp$ and $\rm B^+ \to K^0 \pi^+$ decays. The feasibility of reconstructing two body B decays has been discussed in Section 4. The reconstruction of $\rm K_s^0$ has not yet been studied but should present no major problems. Again, if this analysis is possible, the linear collider should be able to make a useful contribution. However, the measurement of $\rm B^+ \to \pi^+ \pi^0$ is also required, and if the penguin decay $\rm B^+ \to K^+ \pi^0$ is also important, the linear collider will be at a disadvantage in not having particle ID—the mass resolution cannot be used effectively in final states containing reconstructed π^0.

6 Summary and Conclusions

The feasibility of doing various CP violation measurements in b decays using 10^9 hadronic Z^0 produced at the TESLA linear collider 'Z factory' has been studied. Whilst no 'golden' measurements have been found that can be performed better than at any other facility, many useful measurements can be made that are complementary, and of a competitive precision, to those at e^+e^- b factories, the Tevatron and LHC. The particular features of the linear collider and detector important for these measurements are:

- Polarized electron and positron beams, which allows a very good initial state tag from the b quark forward-backward asymmetry. This tag has higher performance than any based on tagging the 'other' b hadron in a $b\overline{b}$ event, which must be relied upon at other machines.
- The excellent mass resolution from the very high performance tracking. This allows final states involving π^+ and K^+ to be distinguished without using particle ID. The modest dE/dx performance of the TPC provides limited particle ID, but the addition of a dedicated detector (*e.g.* a RICH) does not seem necessary.

Useful contributions can be made to the study of the CKM angles α and β in a variety of decay modes. However, the study of γ, which mainly requires B_s meson decays, does not appear to be competitive with the LHC, due to the much larger numbers of b decays produced at the latter machine.

Finally, it should be emphasised that this study has concentrated on 'established' methods of studying CP violation in b decays, which are well suited to the e^+e^- and hadronic b factories currently being commissioned or planned. There may be other methods, impossible *e.g.* at LHC, which may be feasible in the high-statistics e^+e^- environment of the linear collider. Additionally, there are many other b physics measurements, *e.g.* rare b decays, b spectroscopy and polarisation studies, which may be uniquely possible at a Z^0 factory, but these have not yet been investigated.

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