Detectors for ϕ , τ -charm and B Factories

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Abstract

We provide an overview of the physics goals and detector designs for ϕ , τ -charm and B Factories.

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1 Introduction

1.1 The Particle Factory

In order to make progress in particle physics, it is now widely recognized that the next generation of particle accelerators must pursue two complementary lines: the “high-energy frontier” and the “high-precision frontier”. Their common goals are to find answers to the open questions facing the Standard Model and to search for experimental clues towards a more fundamental theory. The basic approach of experiments at the high-energy frontier is to search for new particles and new interactions, whereas experiments at the high-precision frontier search for subtle discrepancies with the Standard Model, by examining previously-discovered particles with increased precision and sensitivity.

The “high-energy” path has been followed with great success by accelerators since their inception. The next-generation machines—the LHC and SSC hadron colliders with their high rates and energies of several 10’s of TeV—pose great challenges for the detectors. The primary detector requirement is high selectivity; signals as small as $\mathcal{O}(100)$ events per year must be extracted from $\mathcal{O}(10^{15} - 10^{16})$ interactions.

The “high-precision” approach has emerged more recently, for both technical and scientific reasons. The former are a consequence of continual improvements in the technology and performance of both accelerators and detectors since the original experiments took place at (what are now) low energies. This has opened up the possibility of exploring old experimental territory with greatly-improved sensitivity and precision, in a search for surprises. The scientific interest in this approach has also grown in recent years due both to the discovery that there appear to be only a limited number of fundamental fermions in Nature (the present three families), and also to the on-going improvements in the precision of the Standard Model predictions.

The high-luminosity machines that are required to explore the high-precision frontier are known as particle “factories” (a word coined from industry to describe the mass-production of particles). At such machines the primary detector requirement is high precision, implying careful optimization of both the detector and the machine for the particle(s) under study and, in most cases, high-resolution general-purpose detectors.

1.2 Choice of Accelerator and Energy

The primary requirements of a particle factory are to produce specific particles in copious quantities and with low backgrounds. High-luminosity e^+e^- colliders are well-suited to these requirements, and their design is now a subject of considerable world-wide interest, as this meeting[1] confirms.

The optimum energy to study a particular particle at an e^+e^- collider generally corresponds to the region near its pair-production threshold. In such regions are generally found the highest cross-sections, lowest backgrounds and other favourable experimental conditions. Other energies of interest correspond to production of the narrow vector resonances ($\phi, J/\psi, \Upsilon, Z^0, \dots$) which, in addition to being interesting particles in their own right, constitute high-rate secondary sources of lighter particles. The energies of interest for e^+e^- collider particle factories are summarized in Table 1, and the production cross sections and typical event rates for these machines are indicated in Fig. 1. As shown in Fig. 2, particle

Figure 1: The e^+e^- annihilation cross-section in the centre-of-mass energy range $1 \text{ GeV} < E_{\text{cm}} < 10 \text{ TeV}$.

Figure 2: The luminosity of present and future e^+e^- colliders in the centre-of-mass energy range $1 \leq E_{\text{cm}} \leq 200 \text{ GeV}$. The solid line represents the present envelope of the maximum luminosity. The dashed lines indicate the design luminosities of future factories.

Table 1: Summary of the energies of interest for e^+e^- collider particle factories.

E_{cm} (GeV)	Particle resonance	Particle threshold	Accelerator
1	ϕ	$s\bar{s}$	ϕ Factory
3-5	$J/\psi, \psi' \dots$	$\tau\bar{\tau}, c\bar{c}$	τc Factory
9-11	$\Upsilon(1S), \Upsilon(2S) \dots$	$b\bar{b}$	B Factory
91	Z^0	-	Z Factory
??	θ	$t\bar{t}$	T Factory

Figure 3: An example of a heavy-flavour threshold region: the energy range of the τ -charm Factory. The ratio $R = \sigma(e^+e^- \rightarrow \text{'hadrons'}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$, where 'hadrons' include both $q\bar{q}$ and $\tau^+\tau^-$ events. The data are from DELCO at SPEAR.

factories are expected to have 10 to 100 times the luminosities of present machines.

We may illustrate the favourable experimental conditions that exist near threshold with the example of the τ -charm Factory, which operates at 3–6 GeV total energy with $L_{\text{peak}} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at 4 GeV. This region is rich with resonances and particle thresholds (see Fig. 3). The cross-sections for τ and charm production in e^+e^- collisions are higher in this region than at any other energy. This is due to the overall E_{cm}^{-2} dependence of the cross-sections (as seen in Fig. 1) and also to the presence of charm resonances such as the $\psi''(3.77)$, which has a peak cross section of 5 nb (over a continuum level of 13 nb) and decays with equal probability to pure $D^0\bar{D}^0$ or D^+D^- final states. Furthermore, the various τ and charm signals can be turned on or off by adjusting the beam energy above or below each particular threshold. This provides a unique possibility to measure backgrounds *experimentally* rather than to estimate them by Monte Carlo simulations, with their inevitable uncertainties.

Operating near threshold also completely excludes background contributions from higher-mass particles such as, in this case, b quarks. In addition, the heavy-flavoured particles

appear in simple final states near threshold, unaccompanied by extra particles. As a consequence, each of the heavy-flavoured particles (D^0 , $D^\pm$, and $D_s^\pm$) can be tagged simply by observing the decay of its partner. This so-called “single-tagging”—which is unique to the threshold region—has important advantages: identification of the parent particle without pre-selection of its decay mode, reduced biases, presence of kinematic constraints, exact flux normalization and reduction of backgrounds. Near threshold, single-tagging is also possible for τ leptons since they can be produced below $c\bar{c}$ and $b\bar{b}$ thresholds, and so the $\tau^+\tau^-$ events can be cleanly isolated with simple selection criteria on one of the two τ 's. Finally, there are also several kinematic advantages which result from the low particle velocities near threshold (such as monochromatic spectra for two-body decays).

Figure 4: The transverse layout of the universal e^+e^- collider detector.

2 Detector Overview

2.1 Evolution of the Universal e^+e^- Detector

The universal e^+e^- detector, as illustrated in Fig. 4, has a familiar layout: cylindrical “onion” layers of sub-detectors and a solenoid magnet, arranged in order of increasing density with increasing radius. Almost all present and future collider detectors follow this basic layout, possibly with minor adjustments such as the location of the solenoid coil.

It is interesting to recall the origins of this style of detector. The most successful early pioneer of the “ 4π general-purpose detector” was the Mark I detector (Fig. 5)[2], which operated at SPEAR between 1973 and 1978. Mark I had all the by-now-standard features: a large-acceptance cylindrical tracking chamber in a solenoid magnet, particle identification (time-of-flight), electromagnetic calorimetry and μ identification. The discoveries of this detector are the stuff of text books on the history of science: the “ ψ ” part of the J/ψ , the charmonium system, the τ lepton, the charmed mesons, and the first evidence for hadronic jets.

Figure 5: The Mark I detector (1973-1978) at SPEAR.

Mark I dramatically demonstrated the importance of large acceptance for e^+e^- collider detectors, both to maximize the rate and also to permit a complete analysis to be made of all the particles in each event. However, by today's standard, the performance of Mark I was relatively crude with, for example, only 65% solid angle coverage, 30% energy resolution for γ 's, and 20% probability for a hadron to be mis-identified as an e or μ . This allowed room for important contributions from special-purpose detectors such as the Crystal Ball (emphasizing γ 's), DASP (particle identification and momentum resolution), DELCO (e identification), PLUTO (μ identification) and others.

Today we have 15-20 year's improvement in detector technologies since the original experiments, resulting in general-purpose detectors that can essentially "do everything" with little compromise in performance. An impressive example of such a detector is the CLEO II detector (Fig. 6)[3] operating at CESR, which represents one of the first detectors (along with L3 at LEP and the Crystal Barrel at LEAR) to combine high-resolution charged *and* neutral measurements. The next-generation detectors for particle factories will benefit from further technological advances and have even better performance. Faced with such high overall performance in general-purpose detectors, it has become difficult to identify a role for special-purpose detectors—although this may easily change in future as the physics develops and so too, perhaps, does the need for dedicated experiments.

Figure 6: The CLEO II detector at CESR.

2.2 General Design Considerations

Physics at particle factories is characterized by high precision—small systematic errors and sensitivities to rare decays—which demands critical attention to all aspects of the performance, reliability and monitoring of the detector, trigger, on-line and off-line computing. The detectors themselves are designed with large, uniform sub-systems to minimize the uncertainties in acceptance and performance at boundaries. The minimum number of sub-systems are used that can do the job. Due to the complex nature and poor access of the detectors, a high reliability and, in some cases, redundancy is required for the detector sub-systems. The need for internal redundancy applies also to the detection capabilities. This improves the overall performance and, most importantly, provides cross-checks of the performance of the individual detector sub-systems; in many experiments, a thorough understanding of the detector performance is vital in achieving the desired level of systematic errors.

At particle factories, particularly close co-ordination is required between the designs of the machine and detector. The physics requirements shape not only the design of the detector but also the design of the machine in aspects such as luminosity, choice of beam energies, continuous injection, monochromator optics, polarized beams, stable beam-energy and its precise calibration, etc. The machine and detector are intimately connected and each places physical constraints on the other. The most obvious example is the presence of the final-focus elements—the $\mu\beta$ quadrupole magnets—which project deep inside the detectors. For example, at the τ -charm Factory, the radius of the superconducting $\mu\beta$ quadrupole cryostats is 25 cm and their inner faces are only 80 cm from the interaction point. The $\mu\beta$ quadrupole magnets are necessary to achieve tight focusing of the beams at the collision point, and are present in all factory designs.

Table 2: Experimental environment at typical e^+e^- collider particle factories and, for comparison, at the LHC/SSC.

	ϕF	$\tau_c F$	BF	LHC/SSC
Luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	5×10^{32}	10^{33}	3×10^{33}	$10^{33}(10^{34})$
Total energy (GeV)	1	4	10	14-40 TeV
Bunch spacing (ns)	3	40	10	15
Peak event rate (Hz)	2×10^3	$10^3 - 10^4$	10^2	$10^8(\times 10)$
$\langle n_{ch} \rangle$ per event	3	4	8	100
Detector radiation dose (Gy/year)	$\lesssim 1$	$\lesssim 1$	$\lesssim 1$	$10^2 - 10^4(\times 10)$

2.3 Experimental Environment

The experimental environment at e^+e^- collider particle factories is rather mild compared with other future machines (Table 2), and can be accommodated with modest extrapolations of current experimental techniques.

As a consequence of the relatively low event rates (< 10 kHz) and low event multiplicities, the requirements for response time and granularity of the sub-detectors are not severe, and a broad range of detector technologies is suitable. The low energy and limited energy range of the secondary particles lead to detectors of modest depth, with fewer and thinner detection layers compared with LHC/SSC detectors.

The machine environment is also comparatively mild from the viewpoint of radiation damage to the detectors. The only detector elements that may suffer radiation damage are those close to the beam axis, where they may receive abnormal doses from unstable beam conditions such as during beam injection. The low event rates, together with the presence of circulating electrons rather than protons, mean that the detector can constitute the local shielding around the interaction point, resulting in good access to the local electronics of the detector.

Regarding machine-detector backgrounds, there are two basic types: synchrotron photons and beam-gas/wall interactions. The former contribute to the occupancy of the detector elements and to the aging of drift-chamber wires, especially in the region close to the vacuum chamber. Synchrotron radiation background is generally easier to control and of less concern than beam-gas/wall interactions since the latter lead to tracks in the detector and hence to events that are not easily rejected by simple triggers. However, experience has shown that the machine backgrounds at e^+e^- colliders can be sufficiently attenuated by suitable masks in the vacuum chamber near the interaction region and by adjustable aperture limits elsewhere in the ring. Of course, as yet there is no experience of the backgrounds from an *asymmetric* collider with transverse magnetic fields close to the interaction point, as will be the case for B factories. Here the main concern will be off-energy beam particles that are swept into the detector, but calculations[4] indicate that the backgrounds can be kept to acceptable levels by careful design of the masking.

2.4 Data Acquisition

The low event rates and multiplicities at e^+e^- particle factories (Table 2) result in data-flow rates that can be handled with present techniques: a 1 kHz event rate generates a data rate of about 20 Mbyte s^{-1} . However, in view of the short bunch-spacing, deadtimeless level 1/2 triggers are required, i.e. event data must be stored in pipelines while trigger decisions are being made. Furthermore, in order to avoid saturating the storage media and the off-line analysis, powerful on-line processors are required to analyze, select and compress the events of interest before writing them to tape or disk (an event rate of 20 Mbyte s^{-1} would fill a 10 Gbyte cassette every 8 min).

The trigger and data acquisition systems for factory detectors follow the same approach as those for experiments at future hadron colliders: pipelined front-end electronics, multi-level triggers and on-line processing of the events. Although the requirements are more modest for factory detectors than for hadron collider detectors, they are nevertheless sizeable by today's standards: on-line processing powers of $\mathcal{O}(10^4)$ MIPS (provided by a large "farm" of parallel processors) and data storage requirements of $\mathcal{O}(10^{14})$ byte per year. The processor farm and data storage requirements are doubled after including the off-line needs, which include re-analysis of the recorded data and the generation and analysis of Monte Carlo event samples comparable in size to those of the real data.

In view of the huge data sets that factories will generate each year, a challenging aspect of the experimental programme will be data storage, access and analysis. Although the bulk of the data will probably be stored on robot-controlled cartridges, a large amount of data [$\mathcal{O}(10)$ Tbyte per year] must be available on disk for rapid access. High-speed links are necessary to allow access to the central data library from computers at the collaborating institutes. A 2 Mbyte s^{-1} link is sufficient for most purposes except bulk data transfer, which is most efficiently executed by physically transporting cassettes containing selected data from the central library. High-speed network connections between the detector and the collaborating institutes are also important for remote trouble-shooting of the detector by experts.

3 ϕ Factory Detectors

3.1 Physics Goals

The main interest in the ϕ is as a pure source of $K_L^0 K_S^0$ events for investigating CP violation. The branching ratio $\phi \rightarrow K_L^0 K_S^0$ is large (34%) and the neutral kaons always appear as a $K_L^0 K_S^0$ pair since they are produced in a pure quantum state ($J^{PC} = 1^{--}$). The peak ϕ cross section is 4.4 μb , which corresponds to an event rate of 2.2 kHz at the DAΦNE reference luminosity of $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ [5, 6]. A ϕ Factory at this luminosity produces 7.6×10^9 $K_L^0 K_S^0$ pairs per year ($10^7 \text{ s} \times L_{\text{peak}}$). In addition, large samples of $K^+ K^-$ (1.1×10^{10} events per year) and $\gamma\eta$ (2.8×10^8 events per year) are generated. These have additional physics interest and also provide important calibration signals for the detector.

The primary physics motivation[7] for a ϕ Factory is to search for **direct CP violation**, i.e. evidence that CP violation occurs in direct $\Delta S = 1$ decays and not only in $\Delta S = 2$ transitions (involving $K^0 \leftrightarrow \bar{K}^0$ mixing). Indirect CP violation (due to mixing) is characterized by the parameter ϵ which describes the mass eigenstates K_L^0 and K_S^0 in terms of the CP

eigenstates K_1 and K_2 ($K_S^0 = K_1 + \epsilon K_2$ and $K_L^0 = K_2 + \epsilon K_1$). The parameter ϵ' characterizes direct CP violation, and a non-zero value would lead to a difference in the amplitude ratios $|\eta_{+-}|$ and $|\eta_{00}|$:

$$|\eta_{+-}| = \epsilon + \epsilon' = \frac{\text{Ampl}(K_L^0 \rightarrow \pi^+\pi^-)}{\text{Ampl}(K_S^0 \rightarrow \pi^+\pi^-)}$$

$$|\eta_{00}| = \epsilon - 2\epsilon' = \frac{\text{Ampl}(K_L^0 \rightarrow \pi^0\pi^0)}{\text{Ampl}(K_S^0 \rightarrow \pi^0\pi^0)}$$

Unfortunately, the Standard Model predicts extremely small values (few $\times 10^{-4}$) for the ratio ϵ'/ϵ . The present experimental error on ϵ'/ϵ from fixed-target experiments is 7×10^{-4} and the goal of the ϕ Factory is to measure this ratio to a precision of 10^{-4} . This will require a measurement of each of the branching ratios $\text{Br}(K_L^0/K_S^0 \rightarrow \pi^+\pi^-/\pi^0\pi^0)$ to 5×10^{-4} accuracy, which could be statistically achieved with a sample of 5×10^{10} ϕ decays (requiring 10 fb^{-1} , or two years at a luminosity of $5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$).

Further physics goals[7] of a ϕ Factory include:

- **Other searches for CP violation**, e.g. $K_S^0 \rightarrow \pi^0\pi^0\pi^0$ ($\text{Br} \simeq 2 \times 10^{-9}$), which is just observable, corresponding to ≈ 30 events in one year.
- **Rare K_S^0 decays**. By tagging a K_L^0 , a ϕ Factory effectively provides a pure K_S^0 beam of up to $\approx 10^{10}$ K_S^0 per year. This unique capability will lead to a substantial improvement in the measurements of many rare K_S^0 decays, such as $\pi^0\gamma\gamma$, $\pi^0\nu\bar{\nu}$, $l^+l^-\gamma$, $\pi^0l^+l^-$, etc.
- **Rare $K^\pm$ decays**, e.g. $\pi^\pm\gamma\gamma$ (present Br limit $< 10^{-6}$) and $\pi^\pm\mu^+\mu^-$ (flavour-changing neutral current decay; present Br limit $< 2 \times 10^{-7}$), etc.
- **Radiative ϕ decays**, e.g. $\phi \rightarrow \eta'\gamma$ ($\text{Br} \simeq 1.2 \times 10^{-4}$) and $\phi \rightarrow f_0(975)\gamma$. The experimental sensitivity is $10^{-6} - 10^{-7}$.
- **Rare η decays**, e.g. searches for C violation in the electromagnetic interaction, e.g. $\eta \rightarrow l^+l^+\pi^0$ and $\eta \rightarrow 3\gamma$.

3.2 Detector Requirements

The design of a ϕ Factory detector is driven by the requirements of the CP violation experiment to measure precisely the branching ratios for $K_S^0 \rightarrow \pi^+\pi^-$, $K_L^0 \rightarrow \pi^+\pi^-$, $K_S^0 \rightarrow \pi^0\pi^0$ and $K_L^0 \rightarrow \pi^0\pi^0$. The parent K_L^0/K_S^0 is distinguished by its observed decay length; the mean decay length ($\beta\gamma c\tau$) for a K_L^0 produced in ϕ decay is 343 cm, and for a K_S^0 it is 5.9 mm. A reconstructed decay having a vertex < 2 cm from the interaction point indicates a K_S^0 and tags a K_L^0 on the opposite side; a decay length > 20 cm indicates a K_L^0 and tags a K_S^0 .

A large-radius tracking detector is therefore required in order to accept a sufficiently high fraction of the K_L^0 decays. The $\pi^\pm$ are quite soft (50-250 MeV/c) and so a relatively-weak magnetic field is optimal. The electromagnetic calorimeter is the most demanding component of the detector. The vertex position of each $\pi^0\pi^0$ decay must be measured to a precision $\sigma \leq 1$ cm. This is necessary to maintain acceptable event losses for tagged K_S^0 , which are required to have an observed decay vertex inside a fiducial volume of 6 cm radius. (A major concern of the CP violation experiment is to achieve a precise understanding of the detection efficiencies for the four decays $K_L^0/K_S^0 \rightarrow \pi^+\pi^-/\pi^0\pi^0$, which are different and do not cancel.) In order to efficiently reject backgrounds from $3\pi^0$ decays, the calorimeter must

be hermetic and fully efficient down to γ energies of 20 MeV. Finally, the energy resolution must be fairly good: equivalent to a Pb-glass calorimeter or better. The main features of a ϕ Factory detector are summarized in Fig. 7.

Figure 7: Main features of a ϕ Factory detector.

3.3 Detector Example

The solutions to these requirements can be illustrated by the choices of the KLOE detector (Fig. 8)[8] at DAΦNE:

- Tracking detector:** The tracking detector is a 2 m-radius drift chamber. A superconducting solenoid generates an axial magnetic field of 0.6 T. The drift chamber uses a He-based gas and Al field wires in order to reduce the multiple Coulomb scattering for soft particles and also to minimize the regeneration of K^0_S inside the tracking volume. Similarly, a large-radius (8-10 cm) vacuum chamber is used in order to ensure that all the accepted K^0_S decays are free of regeneration backgrounds. The expected momentum resolution is $\sigma_p/p = 0.3\%$ and the $K^0 \rightarrow \pi^+\pi^-$ mass resolution is $\sigma_M = 0.9 \text{ MeV}/c^2$.
- Electromagnetic calorimeter:** This is a Pb/SCIFI sampling calorimeter (Fig. 9) using very thin (0.5 mm) Pb layers and 1 mm diameter plastic scintillating fibres, which are read out with mesh-dynode phototubes located inside the magnetic field. The resulting sampling fraction is $\simeq 14\%$ and $X_0 = 1.5 \text{ cm}$. This device measures the $\pi^0\pi^0$ vertex position by precise γ timing: the expected time resolution of $\sigma \simeq 50 \text{ ps}/\sqrt{E(\text{GeV})}$ will provide $\sigma = 300 \text{ ps}$ in the worst case, $E_\gamma \simeq 20 \text{ MeV}$. By combining the 4 γ 's in a $\pi^0\pi^0$ decay, an overall decay vertex precision $\sigma = 6 \text{ mm}$ can be achieved. The device is efficient for γ 's down to 20 MeV and has an acceptable energy resolution $[\sigma_E/E = 4.5\%/\sqrt{E(\text{GeV})}]$. The resulting $K^0 \rightarrow \pi^0\pi^0$ mass resolution is $\sigma_M = 3.1 \text{ MeV}/c^2$.

Figure 8: The KLOE detector for DAΦNE.

Figure 9: The Pb/SCIFI electromagnetic calorimeter for KLOE.

4 τ -charm Factory Detectors

4.1 Physics Goals

The physics interest of a τ -charm Factory encompasses three broad fields: the τ and ν_τ leptons; charm (D^0 , $D^\pm$, $D_S^\pm$, $\Lambda_c^\pm$, Σ_c , Ξ_c , Ω_c , etc.); and charmonium (J/ψ , ψ' , χ_c , η_c , etc.) and light quark/gluon spectroscopy. The rates for $\tau^+\tau^-$, $D^0\bar{D}^0$, D^+D^- or $D_S^+D_S^-$ events are $1\text{--}3 \times 10^7$ per year ($L_{peak} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$; $10 \text{ fb}^{-1} \text{ year}^{-1}$), depending on the beam energy (refer to Fig. 3). With standard optics, $\mathcal{O}(10^{10})$ J/ψ or ψ' events are generated per year (and up to 10^{11} J/ψ events per year may be possible with monochromator optics[9, 10]).

Unlike the ϕ or B Factories, the physics case for the τ -charm Factory does not primarily rest on a single compelling experiment but on a *comprehensive* precision study of the above three fields. Among the main physics goals[11, 12, 13] are the following:

- **A search for finite ν_τ mass:**
 - **Direct ν_τ mass measurement [$m > \mathcal{O}(1 \text{ MeV}/c^2)$].** This involves measurements of the end-point of the 5π mass spectrum in $\tau \rightarrow 5\pi \nu_\tau$, and of the end-point of the $K^-K^+\pi^\pm$ mass spectrum in $\tau^\pm \rightarrow K^-K^+\pi^\pm \nu_\tau$. With a two-year (20 fb^{-1}) sample at 3.67 GeV, the expected upper limit sensitivity (95% CL) is about $3 \text{ MeV}/c^2$, to be compared with the present limit of $31 \text{ MeV}/c^2$.
 - **Indirect ν_τ mass measurement [$\mathcal{O}(100 \text{ eV}/c^2) < m < \mathcal{O}(1 \text{ MeV}/c^2)$].** Any ν_τ heavier than $\mathcal{O}(100 \text{ eV}/c^2)$ would have to decay in order to agree with the observed density of the universe. The decays $\nu_\tau \rightarrow \nu_l X$ ($l = e, \mu$) may then occur, where X is a massless, weakly interacting, spin zero Goldstone boson (Majoron, familon, flavon, etc.). The τ lepton would then also be able to decay through same process $\tau^- \rightarrow l^- X$, and calculated branching ratios are in the range $10^{-6} - 10^{-2}$. At a τ -charm Factory these decays have the distinctive signature of monochromatic leptons. The sensitivity limit is $\text{Br} \simeq 10^{-5}$.
- **A search for insights into the generation puzzle**—the reason why there appear to be three families of elementary particles in Nature. This programme involves a number of precision tests of the Standard Model, such as:
 - **Precision τ branching ratios.** The goal is to measure all of the τ branching ratios with high precision—reducing the present errors by a factor of 10 or more. In particular, the one-prong decays—which are accurately known in the Standard Model—will be measured to $\mathcal{O}(0.1\%)$ precision. Precise measurements of τ branching ratios may also provide the most accurate measurement of the strong coupling constant α_S .
 - **Current structure of the τ - ν_τ -W vertex.** Here the aim is to measure the nature of the weak current in τ decays to a precision comparable to present μ decay experiments. (The latter have provided the most precise measurements so far of the pure V-A nature of the weak decay current.) The experiment involves a precise determination of the decay parameters— $\rho_l, \eta_l, \xi_l, \delta_l$ ($l = e, \mu$), and ξ'_μ —in the leptonic channels $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ and $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$.
 - **Precise measurements of the pure leptonic D decays.** Pure leptonic decays of $D_{(s)}^\pm$ mesons can be rigorously calculated in the Standard Model and are important

in determining the weak decay constants f_D and f_{D_s} which occur in calculations of second-order-weak processes (mixing, CP violation, etc.). In addition, the ratio of the $D^\pm$ and $D_s^\pm$ pure leptonic decay rates will provide a precise determination of the ratio of the CKM matrix elements V_{cd} and V_{cs} . The largest pure leptonic branching ratios are $\text{Br}(D_s^+ \rightarrow \tau^+ \nu_\tau) \simeq 3.3\%$, $\text{Br}(D_s^+ \rightarrow \mu^+ \nu_\mu) \simeq 3.6 \times 10^{-3}$, and $\text{Br}(D^+ \rightarrow \mu^+ \nu_\mu) \simeq 3.5 \times 10^{-4}$. Each of these channels can be measured to a precision of $\simeq 2\%$.

- **A study of the D semileptonic branching ratios**, and the determination of the CKM matrix elements V_{cd} and V_{cs} . Many of the semi-leptonic branching ratios are measurable to an accuracy better than 1%, to be compared with the present errors of 12% for $D^0 \rightarrow K^- e^+ \nu_e$ and 50% for $D^0 \rightarrow \pi^- e^+ \nu_e$. With precise data on a broad range of semi-leptonic decays, the theoretical (hadronic form factor) uncertainties may be largely removed and precise values obtained for V_{cd} and V_{cs} .
- **A search for CP violation outside the K^0 system:**
 - **CP violation in D decays.** $D^0 \bar{D}^0$ mixing (and consequently any CP violation due to mixing) is highly suppressed in the Standard Model, and so many of its extensions lead to enhanced rates which are “background-free” from standard physics. Signatures of mixing are like-sign dileptons from dual semileptonic decays ($l^\pm l^\pm X$) or dual identical hadronic decays, such as $(K^+ \pi^-)(K^+ \pi^-)$ or $(K^- \pi^+)(K^- \pi^+)$. The expected rate for $D^0 \bar{D}^0$ oscillations is $\simeq 10^{-5}$, which can be measured with one year’s data at a τ -charm Factory. In the case of CP violation, recent calculations[14] indicate the possibility of substantial *direct* CP violation asymmetries in the decay rates for several $D^\pm$ and $D_s^\pm$ Cabibbo-suppressed channels, e.g. $D^+ \rightarrow \bar{K}^{*0} K^+$, $\bar{K}^0 K^+$, $\rho^0 \pi^+$, $\pi^+ \eta$, etc., which have predicted rate asymmetries $a_{CP} \approx (1-3) \times 10^{-3}$, where $a_{CP} = [\text{Br}(D_{(s)}^+) - \text{Br}(D_{(s)}^-)] / [\text{Br}(D_{(s)}^+) + \text{Br}(D_{(s)}^-)]$. Since the Cabibbo-suppressed branching ratios are $\mathcal{O}(0.5\%)$, yearly samples of $\mathcal{O}(10^5)$ events can be collected in each channel—which is close to reaching the required sensitivity to detect CP violation asymmetries at the calculated levels.
 - **CP violation in hyperon decays.** It may be possible to observe direct CP violation by measuring differences in the decay parameters of hyperons and anti-hyperons produced in the processes

$$J/\psi \rightarrow \Lambda \bar{\Lambda} \rightarrow (p\pi^-) (\bar{p}\pi^+), \text{ and } \\ J/\psi \rightarrow \Xi^- \Xi^+ \rightarrow (\Lambda\pi^-) (\bar{\Lambda}\pi^+) \rightarrow (p\pi^-\pi^-) (\bar{p}\pi^+\pi^+)$$

Since the expected differences are small [e.g. $\mathcal{O}(10^{-3})$ in the polarization asymmetry parameter B'_Ξ], very large statistics ($> 10^{11}$ J/ψ decays) are required. These may be reached if a monochromator optics can be successfully implemented.

- **A high-statistics study of gluonic matter and its spectrum.** This involves a systematic mapping of the light quark and gluon (glueballs, hybrids, etc.) hadronic spectrum in the gluon-rich environment of charmonium decays ($J/\psi \rightarrow \gamma gg, ggg$; $\eta_c \rightarrow gg, \chi_c \rightarrow gg$, etc.), as well as a study of hybrid charmonium ($c\bar{c}g$) above $D\bar{D}$ threshold.
- **A search for physics beyond the Standard Model.** New physics may be found in almost any of the previously-described experiments. An additional approach to this question is to search for rare τ , D and J/ψ decays. The Br sensitivity is $\simeq 10^{-7} - 10^{-8}$.

4.2 Detector Requirements

The physics programme of a τ -charm Factory imposes broad requirements on the performance of the detector. There are experiments for which a primary concern is the quality of the momentum resolution (e.g. direct ν_τ mass measurement), of the lepton identification (e.g. indirect ν_τ mass measurement), of the hermeticity (e.g. pure-leptonic $D^\pm$ and $D_S^\pm$ decays), of the photon measurements (e.g. gluonium spectroscopy), and of the π/K separation (e.g. $D^0\bar{D}^0$ mixing and CP violation in D decays). Simply stated, a high-performance *general-purpose* detector is required for a τ -charm Factory. The main features of a τ -charm Factory detector are summarized in Fig. 10.

Figure 10: Main features of a τ -charm Factory detector.

4.3 Detector Example

The detector design for a τ -charm Factory has been studied at several workshops [11, 12, 13]. One of the detector concepts is shown in Fig. 11[13]. This detector represents a substantial improvement over previous detectors that have operated in this energy range (see Table 3). The main features are as follows:

- **Tracking detector:** This involves a drift chamber with a large solid angle ($90\% \times 4\pi$ sr) in the barrel region, where particles are measured with the highest precision. The outer radius of the tracking detector is about 85 cm and the magnetic field strength is 1-1.2 T. In order to achieve a precise momentum measurement for the (typical) low-energy tracks, special emphasis is placed on reducing the material in the tracking chamber to a minimum: a single scattering surface at the entrance (1 mm Be vacuum chamber), Al field-shaping wires and He-based drift gas. The tracking detector has conical end-plates to accommodate the $\mu\beta$ cryostats and to only accept tracks which come from the interaction point. This design minimizes the occupancy from background particles and improves the selectivity of the tracking trigger.

Table 3: Comparison of the performances of current and future detectors at τ cF energies. A BF detector will have similar overall performance as a τ cF detector. The symbol ' $\oplus$ ' denotes addition in quadrature.

	Mark III (SPEAR) / BES (BEPC)	τ cF (& BF)
<u>Charged particles:</u>		
Momentum res: σ_p/p (GeV/c)	$1.5\%p \oplus 1.5\%/\beta$ [MkIII] $0.7\%p \oplus 1.3\%/\beta$ [BES]	$0.3\%p \oplus 0.3\%/\beta$
p_{min}^π (MeV/c) for efficient tracking	80	50
Ω (barrel) ($\times 4\pi$ sr)	70%	90%
<u>Photons:</u>		
Energy resolution: σ_E/E (GeV)	$17\%/\sqrt{E}$	$2\%/E^{\frac{1}{4}} \oplus 1\%$
Angular resolution: $\sigma_{\theta,\phi}$ (mr)	10 [MkIII]; 5 [BES]	$4/\sqrt{E}$
2γ angular separation: $\Delta\theta_{2\gamma}$ (mr)	20	50
E_{min}^γ (MeV) for efficient detection	100	10
<u>Particle identification:</u>		
$h \rightarrow e$ rejection	4% at 0.5 GeV/c	0.1% (10^{-5} inc. RICH)
$h \rightarrow \mu$ rejection	5% at 1.0 GeV/c	$1\%/p(\text{GeV/c}) + 1\%$
$\pi \rightarrow K$ rejection	3σ at 0.7 GeV/c	3σ at 1.0 GeV/c (10^{-4} inc. RICH)
K_L^0/n detection efficiency	60%	95%
E_{min}^ν (MeV) for efficient ν tagging	-	$\simeq 100$

- **Electromagnetic calorimeter:** A CsI(Tl) [or CsI(Na)] crystal calorimeter is chosen in order to achieve high resolution measurements of γ 's, and high efficiency down to low energies of $\mathcal{O}(10)$ MeV. A novel feature of this calorimeter is that each crystal is split into two longitudinal sections with separate photodiode readouts.
- **Particle identification:** High-quality particle identification in the region below 1 GeV/c is achieved by a combination of dE/dx measurements in the central drift chamber, time-of-flight measurements based on scintillating-fibre counters and, possibly, a fast RICH using either a solid NaF or liquid Freon (C_6F_{14}) radiator (see Fig. 12).
- **Neutrino "identification":** The presence of ν 's is inferred on an event-by-event basis by ensuring that the detector is hermetic to all other particles. Charged particles and photons are measured with high efficiency and precision in the tracking detector and electromagnetic calorimeter (barrel and small-angle sections). The hermeticity is completed with a fine-grained outer hadron calorimeter/ μ detector which tags the presence of neutral hadrons. Demanding upper limits are placed on the inefficiency for γ 's in the electromagnetic calorimeter ($<1\%$), and for K_L^0/n 's in the hadron calorimeter ($<5\%$).

Figure 11: A detector concept for a τ -charm Factory.

Figure 12: The performance of possible particle identification detectors for a τ -charm Factory detector: a) Time-of-flight; $\sigma_{ToF} = 120$ ps (two layers) and minimum flight path = 0.95 m, and b) Fast RICH; 10mm-thick NaF radiator, a mean of about 20 photo-electrons per ring, and a total depth of 10 cm. The error bars indicate the 1σ measurement error on a single Cerenkov ring.

5 B Factory Detectors

5.1 Physics Goals

The physics interest of a B Factory[3],[15]–[22] is centered on bottom particles (B_d^0 , B_s^0 , $B^\pm$, Λ_b^0 , etc.), but there is also an extensive programme of two-photon physics and of heavy-flavour physics including bottomonium (Υ , χ_b , η_b , etc.), the τ lepton and charm particles.

The primary physics goal is to investigate CP violation in the $B^0\bar{B}^0$ system. Near $b\bar{b}$ threshold there are several resonances where the B mesons are produced with enhanced cross sections and in simple final states. The most important is the $\Upsilon(4S)$ resonance at 10.6 GeV, which has a peak cross section of 1.1 nb (over a continuum level of 2.6 nb) and decays with equal probability to pure $B_d^0\bar{B}_d^0$ or B^+B^- final states.

The CP-violation experiments involve observing a first decay at time t_1 that identifies whether the particle is a B^0 or $\bar{B}^0$, e.g. a B^0 semi-leptonic decay to μ^+X or e^+X . This tags the presence of an accompanying pure $\bar{B}^0$ at time t_1 , which subsequently propagates and may decay at time t_2 to a pure CP eigenstate, e.g. $J/\psi K_S^0$ ($\rightarrow l^+l^-K_S^0$). There are four possible different sequences for these decays depending on whether the tag or the CP eigenstate appears first, and whether it is a B^0 or $\bar{B}^0$. CP violation leads to differences between the rates of these time-ordered sequences. The experimental goal is to reach sufficient sensitivity to check whether the Standard Model description of CP violation—as a phase incorporated into the CKM mixing matrix—is correct. As well as the decay $B_d^0 \rightarrow J/\psi K_S^0$, this will require measurements of other decays to CP eigenstates such as $B_d^0 \rightarrow \pi^+ \pi^-$ and $B_s^0 \rightarrow \rho K_S^0$. Unfortunately, all of these branching ratios are very small [e.g. $\text{Br}(B_d^0 \rightarrow J/\psi K_S^0) = 3 \times 10^{-4}$] and consequently, large luminosities are required. Calculations indicate that an integrated luminosity $L \simeq 50 \text{ fb}^{-1}$ is required to cover most of the range of CP-violating effects allowed by the Standard Model. With this luminosity, the final number of reconstructed events is only $\approx 300 - 600$ from a parent sample of $3 \times 10^7 B_d^0\bar{B}_d^0$ events. This leads to a minimum required luminosity for an asymmetric B Factory of $3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (30 fb^{-1} per year).

Further physics goals[15]–[20] of a B Factory include:

- **$B_s^0\bar{B}_s^0$ mixing.** This measurement also needs an asymmetric machine and a precision vertex detector. The technique is to operate an asymmetric collider at the $\Upsilon(5S)$, which has a mass of 10.9 GeV/ c^2 and lies above $B_s^0\bar{B}_s^0$ threshold. The signature of mixing is like-sign dilepton events which, because of the expected rapid mixing, will display an oscillating intensity vs. decay time difference $\Delta(t) = t_2 - t_1$.
- **Rare B decays.** Decays such as $B \rightarrow K^*\gamma$ and $B \rightarrow K^*l^+l^-$ involve so-called “loop” or “penguin” higher-order diagrams and are an interesting area in which to search for signs of new physics. None has been observed so far, and expected branching ratios are in the region $\approx 10^{-6}$, which is well within the experimental sensitivity of a B Factory. Other interesting classes of rare B decays are flavour-changing neutral currents (e.g. $B^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow e^+e^-$) and lepton-number-violating decays (e.g. $B \rightarrow \mu^+e^-$). The experimental sensitivity to these decays is $\text{Br} \simeq 10^{-8}$.
- **Hadronic and semi-leptonic B decays.** Measurements of semi-leptonic decays such as $B \rightarrow D^*l\nu$ and $B \rightarrow \rho l\nu$ will provide a precise determination of the CKM matrix elements V_{cb} and V_{ub} .

- **τ and charm physics.** A B Factory with $L = 3 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ generates statistically comparable τ and charm data samples as a τ -charm Factory with $L = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. Consequently, a B Factory will perform, with similar statistical precision, many of the experiments described previously for the τ -charm Factory. However, the backgrounds will generally be larger (e.g. b backgrounds may contribute) and systematic rather than statistical errors may limit the final precisions of certain experiments. Nevertheless, in general there will exist the important possibility of verifying precision τ -charm results on two different machines with independent systematic errors.
- **Υ physics.** Bound states of heavy quark-antiquark pairs provide an interesting testing ground for many aspects of QCD.
- **Two-photon physics.** Two-photon physics at a B Factory covers the mass region up to $\approx 3 \text{ GeV}/c^2$ and will therefore provide valuable information on aspects of light quark spectroscopy. In particular, since they contain no electric charge, glueballs should be strongly suppressed. The two-photon results should therefore complement the study of radiative J/ψ decays at a τ -charm Factory, where glueballs should be produced abundantly.

5.2 Detector Requirements

Measurements of the CP asymmetries in $B^0\bar{B}^0$ events require knowledge of the decay time of the B^0 and $\bar{B}^0$. Although the decay *time* is very small ($\simeq 1 \text{ ps}$) and not directly measurable, it can be translated into a measurable decay *distance* by boosting the $\Upsilon(4S) \rightarrow B_d^0\bar{B}_d^0$ events [the mean B flight path is only $30 \mu\text{m}$ from an $\Upsilon(4S)$ at rest]. This has led to the design requirement of an *asymmetric* collider, i.e. having unequal beam energies, operating in the 10 GeV centre-of-mass energy region. Beam collision energies of about 9.33 GeV on 3 GeV represent the optimum compromise between sufficient boost and loss of detection efficiency due to increased collimation along the beam axis. At these beam energies, the average separation of the B_d^0 and $\bar{B}_d^0$ decay vertices is $\Delta z = 210 \mu\text{m}$ [20]. This separation can be measured by precision tracking techniques such as silicon strip detectors, which can provide a vertex separation resolution $\sigma(\Delta z) = 50 \mu\text{m}$.

Both the CP violation experiments and the rest of the physics programme at a B Factory impose broad requirements on the performance the detector. The overall requirements are similar to those of a τ cF detector—i.e. a high-resolution general-purpose detector—but with the important additions of a precision vertex measurement and particle identification over an extended energy range (up to $\simeq 5 \text{ GeV}$). Furthermore, in order to preserve a uniform acceptance in the centre-of-mass, the detector is generally extended along the direction of the high-energy (e^-) beam. The main features of a B Factory detector are summarized in Fig. 13.

5.3 Detector Example

Several conceptual designs have been prepared for B Factory detectors[3], [15]–[20]. Their overall performance is similar to a τ cF detector (Table 3). As an example, the HELENA detector[20] for the proposed B Factory at DESY is shown in Fig. 14. The main features of this detector are as follows:

Figure 13: Main features of a B Factory detector.

- **Vertex detector:** This comprises three layers of double-sided silicon strip detectors arranged in a forward and barrel part which cover $\theta = 12^\circ - 150^\circ$ (Fig. 15). The innermost layer is located as close as possible to the beam axis in order to achieve the best vertex precision; the vacuum chamber has a radius of only 25 mm. A vertex precision $\sigma_z = 30 \mu\text{m}$ is expected for a strip pitch of 25 μm . A drawback of silicon strip detectors is their mass, which adversely affects the measurements of low-momentum charged particles; the barrel vertex detector represents $0.85\%/\sin\theta$ radiation lengths (which is comparable to the total material in the large central tracking chamber).
- **Tracking detector:** This is a cylindrical drift chamber of outer radius ≈ 1 m. As with a τcF detector, the main emphasis of the tracking detector is to reconstruct low momentum tracks with high precision. Also similar is the use of conical end-plates but, in this case, with an asymmetric geometry. However, rather than the traditional solenoid, the analyzing magnet involves a pair of Helmholtz coils which provide a magnetic field $B = 1$ T. The advantages of this magnet are an improved access to the barrel electromagnetic calorimeter and, to a lesser extent, a reduced cost. The disadvantages are a (few per cent) non-uniformity of the field and concentrated regions of un-instrumented material. The field non-uniformity, however, can be readily handled in the analysis. It is of interest to note that the field axis is tilted by 7° with respect to the beam/detector axis, in order to provide the transverse field required for beam separation.
- **Electromagnetic calorimeter:** As with a τcF detector, charged and neutral particles must be measured with comparable high precision and efficiency, and the calorimeter of choice is a CsI(Tl) crystal calorimeter.

Figure 14: The DESY B Factory detector, HELENA.

Figure 15: The silicon strip vertex detector for HELENA: a) r-z view, b) barrel cross section at A, and c) forward modules B-E.

- **Particle identification:** Particle identification is achieved by a combination of dE/dx measurements in the drift chamber and either time-of-flight counters or a fast RICH (see Fig. 12). The fast RICH is expected to provide 3σ π -K separation at 5 GeV/c, and much better separation at lower energies. A possible alternative to a RICH—but with reduced performance—is a time-of-flight detector with 100 ps time resolution.

6 Conclusions

Progress in particle physics will require particle factories to complement the high-energy colliders. All factories have the same basic goal: to investigate and extend the Standard Model by precision experimental studies of the known quarks and leptons. High statistics and low backgrounds are the primary requirements for these experiments, indicating the need for e^+e^- colliders with high luminosities, 10 to 100 times the presently-achieved values. In order to take full advantage of these high statistics, however, very careful control is required of the experimental systematic errors. This, in turn, means that both the machines and the detectors must be carefully designed and optimized for specific physics goals.

The required performances of the detectors can be met with reasonable extrapolations of present technologies. Detectors at e^+e^- collider particle factories will carry out experiments with precisions characteristic of high-statistics fixed-target experiments (with several generations of experience); few, if any, of the experiments will be easy. The main challenge will be the overall control of systematic errors in the detector, trigger, on-line and off-line software; redundancy, reliability, monitoring and calibrations are all vital aspects.

The experiments at ϕ , τ -charm and B factories are complementary. For example, BF physics is presently limited by poor experimental data at τ -charm threshold, e.g. f_D , $D_S^\pm$ absolute Br's, hadronic form factors in D semileptonic decays, etc. Different factories can provide cross-checks of the experimental results, with independent systematic errors. Together, the particle factories should be able to provide a sharp and reliable picture of the precise nature of the present fundamental particles and their interactions.

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