Search for Matter-Antimatter Asymmetries Using τ Lepton Decays

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ABSTRACT

The matter-antimatter asymmetry problem in cosmology will be presented, and the mechanism to differentiate between matter and antimatter in particle physics is discussed. Some examples of matter-antimatter asymmetries observed in certain particle systems will be reviewed, and other possible sources generating these asymmetries will also be explained. One possible candidate for such sources is τ decay. The feasibility of using the τ lepton to study the matter-antimatter asymmetry is supported by some preliminary studies and an estimate of the precision of the potential measurement is presented.

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1 Introduction

1.1 Big Bang and Matter-Antimatter Asymmetry

At the time of the Big Bang, the Universe started out to be very hot and pairs of matter and antimatter particles were constantly created from the energy that permeated throughout the Universe. As the Universe cooled down, the matter was left at the end to form galaxies and different stellar structures. In order to form such structures, there must be more matter than antimatter; otherwise, all matter and antimatter would annihilate and the Universe would be filled purely with energy. The conclusion is that a matter-antimatter asymmetry occurred shortly after the Big Bang.

The crucial question one would raise then is how the Universe distinguished between matter and antimatter. The mechanism of distinguishing between matter and antimatter may lie in understanding the so-called "CP symmetry" in nature[1]. If CP symmetry was an exact symmetry in Nature, all physical laws would be equally applicable to particles and antiparticle. For example, the transition rates for the particle decay $(N \to f)$ versus the antiparticle decay $(\bar{N} \to \bar{f})$ would be the same if CP symmetry is not broken. However, the existence of galaxies and different stellar structures implies the contrary. Consequently it is important to search for particle systems where the rate of decay of the particle is different from that of its antiparticle. Experimental observations of such decays are referred to as evidence for "CP Violation". To date CP violation has been observed in K and B meson systems. This work will discuss the feasibility of using τ leptons to test CP symmetry.

[1]The CP transformation is a combination of the C operator (C for charge conjugation), which takes particles to antiparticles, and the P operator (P for parity), which reverses all spatial coordinates.

1.2 Baryogenesis and Sakharov's Conditions

The crux of the matter-antimatter asymmetry problem lies in determining the necessary conditions for baryogenesis in the Universe. Baryogenesis is the process that generates baryons (particles composed of three quarks) in the Universe, which are the main constituents of visible matter. Three conditions, proposed by Sakharov, are necessary for baryogenesis to happen after the Big Bang [1]:

1. There must be processes that do not conserve baryon number. At the beginning, there was no matter in the Universe, and the total baryon number of the Universe was zero. Consequently, there must be a mechanism by which the Universe can evolve to what is observed today: a Universe filled with galaxies and stellar structures formed by baryons.

2. There must be CP-violating processes in nature. If CP is a conserved quantity, the same amount of matter and anti-matter will be generated. They will annihilate and eventually no matter is left to form galactic structures. CP violation is observed in K and B meson decays.

3. There must be stages early in the Universe expansion that were not in thermal equilibrium. If baryogenesis occurs under conditions of thermal equilibrium, then time becomes irrelevant globally; consequently, any process is equally likely to proceed backwards. More specifically, any process that creates a net baryon number will be cancelled out by the corresponding reverse process.

   Another reason of why the non-equilibrium condition is necessary is that particles and anti-particles must have identical masses by CPT theorem[2]. Statistical mechanics

[2]CPT Theorem states that given that a quantum theory is Lorentz-invariant, all physical quantities will be the same after applying the charge conjugate (C), parity (P) and time reversal (T) operators to the system. These operators will take particle to antiparticle states, then flip the coordinates, and then reverse time. Lorentz invariance implies that the theory is the same in all inertial frames of reference [2].

equations such as the Boltzmann equations can only differentiate particles with different masses; the equations do not distinguish between particles of different charges. Therefore statistical mechanics will rule out any asymmetry in the abundances of particles and anti-particles when equilibrium is achieved.

1.3 Motivation for Studying τ Decays

If our understanding of CP violation is complete, and all CP-violating dynamics are understood, one should be able to predict the matter-antimatter asymmetry observed in the Universe. However, if one were to calculate the matter-antimatter asymmetry in the Universe using the current observed values for CP violation in the Standard Model, one would discover that the calculated matter-antimatter asymmetry will fall short of what is currently observed in cosmological data. For example, the baryon-to-photon ratio in the Universe is predicted to be $n_B/n_\gamma \sim 10^{-20}$, which differs from current cosmological observations by orders of magnitude [3]. This indicates that there should be unobserved sources of CP violation.

CP violation has indeed been observed in two particle systems: the K and B meson systems. Currently, there is no direct evidence suggesting that leptons such as the electron, μ and τ (and thus associated neutrinos) will undergo some CP-violating processes. CP-violating decays in the lepton sector may help provide part of the missing portion of the CP asymmetry. Among the three charged leptons, the τ lepton is most likely to yield CP violation. It is more massive than the electron and the μ, which allows it to decay into many different final states.

τ decays were originally not expected to give rise to CP violation under the Standard Model; however, Bigi and Sanda [4] demonstrated that τ decaying through K_S will give rise

There are theories postulating CPT violation occurs, but presently there are no experimental evidence indicating such would be true.

to CP violation. Studying the matter-antimatter asymmetry generated in $\tau^- \to \pi^- K_S^0 \nu_\tau$ not only advances our understanding of CP violation in the Standard Model, but also serves as a precursor for studies on new physics dynamics. Since the matter-antimatter asymmetry is well-measured in the K meson system, analysis of the matter-antimatter asymmetry generated by SM in $\tau^- \to \pi^- K_S^0 \nu_\tau$ decays provides a powerful calibration of the corresponding background in new physics studies.

This document will describe CP violation in the K meson sector, followed by the CP violation in the related Standard Model τ leptonic decays. We will also explore the possibility of observing new physics dynamics inducing matter-antimatter asymmetry in τ decays. Finally, the feasibility of the project is going to be discussed.

2 CP Violation in the K Meson Sector

Current observations of CP violation are successfully described by the complex phase in the quark mixing mechanism known as the Kobayashi-Maskawa mechanism. The CP violation in the K meson sector is relevant in the description of the CP violation in τ decays and will be discussed in this section.

CP violation was first observed in K^0 decays [5]. Two mesons, K_0 (consists of a down quark and an anti-strange quark) and $\bar{K_0}$ (antiparticle of K_0), are both neutrally charged. Although the K^0 and $\bar{K^0}$ are produced in reactions (e.g. $\pi^- p \to \Lambda K^0$), it is the K_S and K_L mesons that are detected in the final state. The K_S is a short-lived meson (with a lifetime of $\mathcal{O}\left(10^{-10}\right) s$) and the K_L is a long-lived meson (with a lifetime of $\mathcal{O}\left(10^{-8}\right) s$). The interpretation is that the K^0 and $\bar{K^0}$ are admixtures of the K_L and K_S (and vice versa). The K^0 and $\bar{K^0}$ are considered the flavour eigenstates and the K_S and K_L the mass eigenstates. The reason behind the difference in lifetimes is their decay modes. If CP symmetry holds true in K^0 decays, K_S will then only decay into 2π (CP=+1) and K_L will only decay into 3π (CP=-1). Phase space favours the 2π decay over the 3π decay, and so the K_L's decay time will be longer than that of K_S.

The mass eigenstates can be written as linear combinations of the flavour eigenstates:

$$|K\rangle = \alpha|K_0\rangle + \beta|\bar{K_0}\rangle \tag{1}$$

If CP symmetry is preserved in a particular dynamical process, then the Hamiltonian will commute with the CP operator. In other words, they share the same set of eigenvectors. Therefore, finding the eigenstates for CP will mean finding the mass eigenstates.

Applying the CP operator on $|K_0\rangle$ gives:

$$\begin{aligned} \mathcal{CP}|K^0\rangle &= |\bar{K^0}\rangle \\ \mathcal{CP}|\bar{K^0}\rangle &= |K^0\rangle \end{aligned}$$

When only $\Delta S = 0$ dynamics are considered, the eigenstates for CP are:

$$\begin{aligned} |K_S\rangle &= \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K^0}\rangle\right) \\ |K_L\rangle &= \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K^0}\rangle\right) \end{aligned} \tag{2}$$

$|K_S\rangle$ and $|K_L\rangle$ yield different eigenvalues under CP:

$$\begin{aligned} \mathcal{CP}|K_S\rangle &= \frac{1}{\sqrt{2}}\left(|\bar{K^0}\rangle + |K^0\rangle\right) = |K_S\rangle \\ \mathcal{CP}|K_L\rangle &= \frac{1}{\sqrt{2}}\left(|\bar{K^0}\rangle - |K^0\rangle\right) = -|K_L\rangle \end{aligned}$$

Furthermore:

$$\langle K_S|K_L\rangle = \frac{1}{2}\left(\langle K^0| + \langle\bar{K^0}|\right)\left(|K^0\rangle - |\bar{K^0}\rangle\right)$$

$$= \quad 0$$

If only the $\Delta S = 0$ dynamics is considered, no CP violation will then be observed under the Standard Model because K_0 cannot turn into a $\bar{K_0}$ or vice versa. The results above confirm that K_L and K_S are orthogonal.

The situation is different when one considers the CP violation in $\Delta S = 2$ ($s \rightarrow \bar{s}$) transitions, in which case the s quark can turn into an $\bar{s}$ through the following second-order processes:

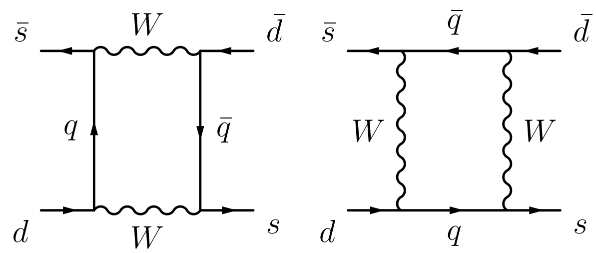

Fig. 2: $s\bar{s}$ transitions in the K meson sector in $\Delta S = 2$ dynamics. q represents u, c or t.

CPT invariance and results from linear algebra will lead to the following:[4][6]

$$\begin{aligned} |K_S\rangle &= p|K^0\rangle + q|\bar{K^0}\rangle \\ |K_L\rangle &= p|K^0\rangle - q|\bar{K^0}\rangle \end{aligned} \tag{3}$$

For proper normalisation, $|p|^2 + |q|^2 = 1$ is required.

Without the conservation of CP symmetry, K_L and K_S are no longer orthogonal. Instead:[4]

$$\begin{aligned} \langle K_L|K_S\rangle &= \left(p^*\langle K^0| - q^*\langle\bar{K^0}|\right)\left(p|K^0\rangle + q|\bar{K^0}\rangle\right) \\ &= |p|^2 - |q|^2 \end{aligned}$$

This can be determined empirically. In 1964 Fitch and Cronin observed CP violation in the K meson sector for the first time. They prepared a beam of K mesons, and if CP was a perfect symmetry in the K meson system, all K_S should have decayed away by the time they reached the end of the beamline. Instead they observed 45±10 out of the 22,700 K_L that would decay into 2π, which is a clear indication of violation of CP symmetry.

The number of $K_L \rightarrow 2\pi$ decays indicates that K_L and K_S are not pure eigenstates of CP symmetry; rather, they are linear combination of different CP eigenstates. From the number of decays, one can determine [4]:

$$|p|^2 - |q|^2 \approx (3.27 \pm 0.12) \times 10^{-3}$$

3 CP Violation in the Lepton Sector

CP violation has not been observed in the lepton sector yet. Charged leptons cannot form CP eigenstates through a superposition of the particle and antiparticle states, nor can a charged lepton turn into its antiparticle. The only way that CP violation can manifest itself in the charged lepton sector is through the different reaction rates between the lepton and its antiparticle.

A neutral lepton (i.e. neutrino), on the other hand, can turn into its antiparticle and vice versa. However, neutrinos are notoriously difficult to detect, so analysing the interaction mechanism and determining its CP properties can be very challenging.

CP violation in the neutrino sector is currently an active area of research. Recent discoveries have shown that neutrinos have different masses [7]. Neutrinos of different masses are then able to turn into one another through the MNS (Maki-Nakagawa-Sakata) matrix, analogous to the CKM matrix in the quark sector. It has been demonstrated that if the MNS matrix contains a complex phases similar to the CKM matrix, then it is possible for CP violation to occur in the neutrino sector [8]. Hence neutrinos can provide a new mechanism for CP violation in Nature, which may provide another piece to the matter-antimatter asymmetry puzzle. New neutrino experiments such as the T2K project in Japan and the CNGS project at CERN in Europe are expected to be able to shed insight into the subject.

3.1 Standard Model Theory of CP Violation in τ Decay

According to Standard Model, the following transition amplitudes are equal:

$$T\left(\tau^- \rightarrow \bar{K^0}\pi^-\nu\right) = T\left(\tau^+ \rightarrow K^0\pi^+\nu\right) \tag{4}$$

However, observations are made with the mass eigenstates K_L and K_S, not the flavour eigenstates K_0 and $\bar{K_0}$. The mixing of the eigenstates is exactly the same as what is presented in the previous section.

Since K_L and K_S are not orthogonal, both $K_L \rightarrow 2\pi$ and $K_S \rightarrow 2\pi$ are possible. The charge asymmetry for the $\tau^- \rightarrow K_S\pi^-\nu_\tau$ is then [4]:

$$\begin{aligned} A &= \frac{\Gamma\left(\tau^+ \rightarrow'' K_S''\pi^+\bar{\nu_\tau}\right) - \Gamma\left(\tau^- \rightarrow'' K_S''\pi^-\nu\right)}{\Gamma\left(\tau^+ \rightarrow'' K_S''\pi^+\bar{\nu}\right) + \Gamma\left(\tau^- \rightarrow'' K_S''\pi^-\nu\right)} \\ &= |p|^2 - |q|^2 \\ &\approx (3.27 \pm 0.12) \times 10^{-3} \end{aligned} \tag{5}$$

where "K_S" (in quotation marks) represents both K_S and K_L decays to the $\pi^+\pi^-$ final state. The description given above does not specify the dynamics that generate $|q| \neq |p|$; rather, it only relies on the assumption that the τ decay is described by SM dynamics [4]. Measuring this CP asymmetry due to Standard Model dynamics will be the focus of the study of τ decays containing three charged tracks, which are known as 3-prong decays.

3.2 Supersymmetric CP-Violating Effects

While the Standard Model is well-tested in many experiments, it gives an incomplete description for particle interactions. One of the most favoured extensions of the Standard Model is Supersymmetry (SUSY). SUSY postulates a particle of opposite statistics for every particle in the Standard Model (i.e. for every fermion in the Standard Model, there is a supersymmetric bosonic partner). Although there is no direct evidence for SUSY, the model seems to provide solutions to many of the unanswered questions in Standard Model. In the Minimum Supersymmetric extension to the Standard Model (MSSM), there are five Higgs particles instead of one as described in the Standard Model.

It is possible that certain τ decay modes involve SUSY processes, which may provide new mechanisms that are CP-violating. One simple change to the Standard Model decay of the τ lepton is via a charged Higgs rather than a W boson:

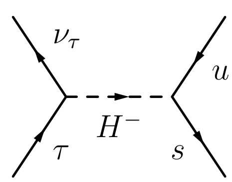

Fig. 3.2: τ decaying via a charged Higgs boson.

The $s\bar{u}$ will subsequently decay into a charged pion and a neutral K meson, as in the case for Standard Model dynamics. It is this neutral K meson which will decay and give rise to CP violation in the τ sector. Even if the τ decays through a supersymmetric particle, the CP violation induced is still described by the Standard Model, as outlined above in the description presented in the previous section, and no additional CP violation is expected to arise. However, if the charged Higgs in any way introduces additional CP violation in τ decays, the CP asymmetry may be amplified. In addition, if one considers the possibility of supersymmetric intermediate states formed in the decay, it is possible that additional

CP violation can occur (see, for example, Ref. [9]).

4 Objective for the Study of 3-Prong τ Decays

The goal of the study is to measure the charge asymmetry of the $\tau^- \to h^- K_S\,(\geq 0\pi^0)\,\nu_\tau$ where h^- is a charged hadron such as a K^- or a π^-. The Standard Model predicts an asymmetry of 0.3%, and any deviations will indicate that some new source of CP violation is present. It may be possible to determine the new physics dynamics should a charge asymmetry larger than 0.3% be observed. In the most optimistic scenario, different models describing new physics interactions can be distinguished.

5 Methodology

5.1 PEP-II and the BaBar Detector

This work will use τ pair events generated by the PEP-II accelerator at Stanford Linear Accelerator Center (SLAC). The events will be recorded at the BaBar detector.

PEP-II consists of two independent storage rings (see Fig. 1): one for the electrons while the other for positrons. At the time of construction of the PEP-II storage rings, the motivation was to produce $B - \bar{B}$ mesons from collisions between electrons, with energy 9 GeV, and positrons, with energy 3.1 GeV. The asymmetry in the energies of the two beams is necessary for CP violation measurements of B mesons.

To measure the CP violation in B meson decays, a detector requires:

- Good vertex resolution: this is necessary for measuring the decay time difference between the B mesons and discriminating vertices due to bottom, charm and light-quarks.

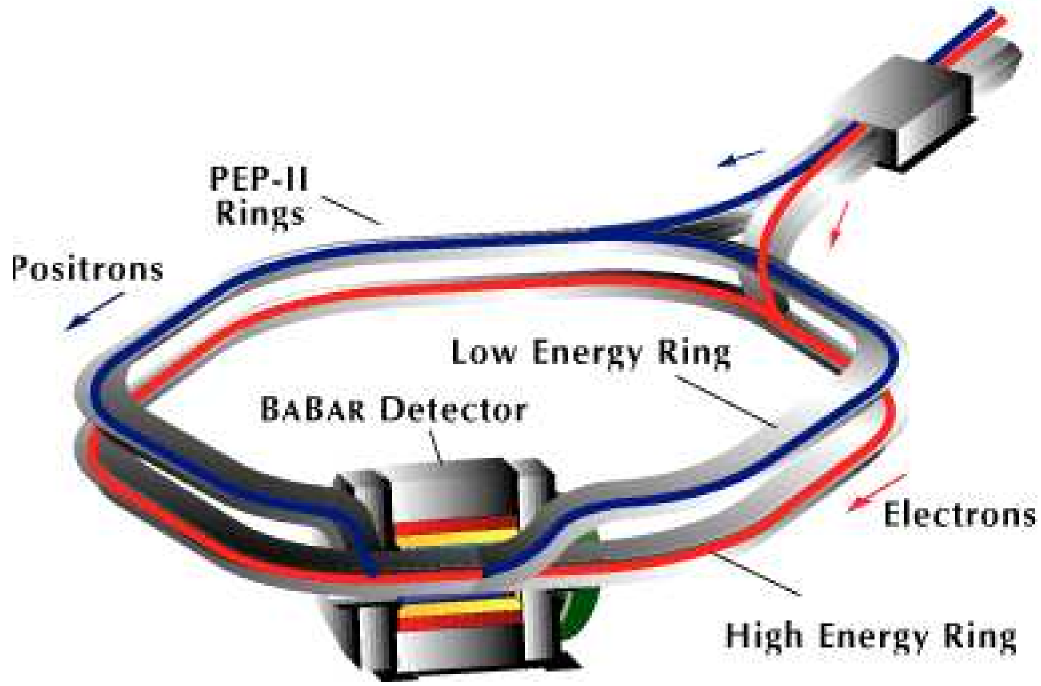

Figure 1: PEP-II rings at SLAC. The diagram shows the electron and positron beams moving in opposite direction and colliding at the BaBar detector.

- To be able to discriminate between different charged particles (e.g. e, μ, π, K and p) over a wide range of momenta.
- To detect γ and π^0's.
- Ability to identify neutral hadrons.

The BaBar detector (see Fig. 2) was designed to meet the requirements listed above. Some of the features of the BaBar detector includes [10]:

1. A Silicon Vertex Tracker (SVT): provides position of charged tracks.
2. A Drift Chamber (DCH): provides the main momentum measurement for charged particle and helps identify particles through energy loss measurement.
3. A Detector of Internally Reflected Cherenkov light (DIRC): designed for charged hadron identification.

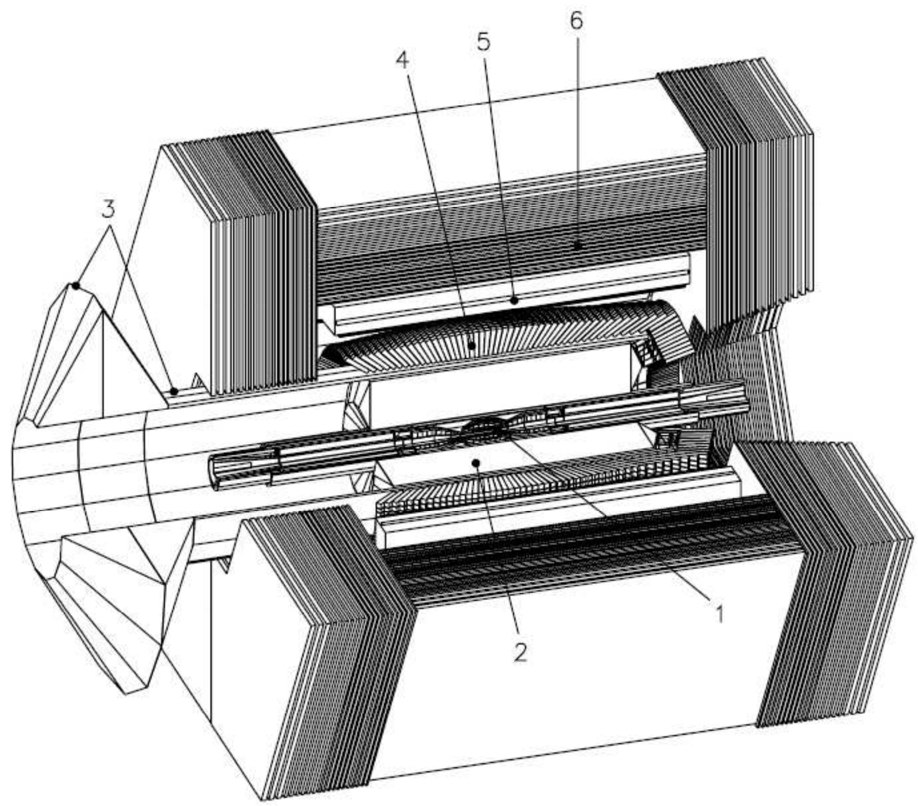

Figure 2: BaBar detector, comprised of (1) a Silicon Vertex Tracker; (2) a Drift Chamber; (3) a Detector of Internally Reflected Cherenkov light; (4) an Electromagnetic Calorimeter; (5) a super-conducting coil and (6) an Instrumented Flux Return (Ref. [10])

4. An Electromagnetic Calorimeter (EMC): provides kinematic information on neutral electromagnetic and hadron particles, and good electron identification.

5. A superconducting coil: provides a 1.5T magnetic field to bend the charged tracks.

6. An Instrumented Flux Return (IFR): provides muon and neutral hadron identification.

In addition to PEP-II being a B factory, it also produces many τ's (PEP-II produces roughly the same number of τ's as B meson [11]). It is estimated that by 2008, BaBar will record 1000 fb^{-1} of e^+e^- data and have a sample of 900 million τ pairs.

5.2 Event Selection

τ pairs are produced via the $e^+e^- \rightarrow \tau^+\tau^-$ reaction in the detector. Since the momenta for the beams of electron and positron do not have any component in the transverse direction, the two τ's must be back-to-back in the centre-of-mass frame. Our strategy is to search for one of the τ's decaying through the signal channel ($\tau^- \rightarrow K^0_S\pi^-\nu_\tau \rightarrow \pi^+\pi^-\pi^-\nu_\tau$ with branching ratio B = 0.53% [12]) with the other decaying leptonically ($\tau^- \rightarrow e^-\nu_\tau\bar{\nu}_e$ with B = 17.84% or $\tau^- \rightarrow \mu^-\nu_\tau\bar{\nu}_\mu$ with B = 17.36%). If our selection criteria are fully efficient, we should select approximately 0.37% of the total τ events; however, our selection criteria are not fully efficient.

Requiring one of the two τ's to go through a leptonic decay channel will help eliminate some of the background, such as multi-hadronic events ($ee \rightarrow q\bar{q}$). Therefore when we consider events with four charged tracks, one of the tracks should be on one hemisphere (the tag hemisphere) and the other three on the other hemisphere (the signal hemisphere). Such an event is said to have a 1-3 topology (see Fig. 3). The "tagged" track indicates that the event is indeed a $\tau\bar{\tau}$ event as well as indicating whether the lepton decaying on the signal side is a τ or a $\bar{\tau}$.

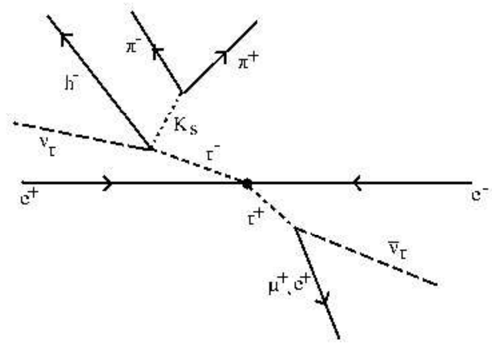

Figure 3: Signal and tag hemispheres in a $\tau\bar{\tau}$ event

To reduce background from non-τ events and other τ decays, we apply selection criteria to both the signal and tag hemispheres:

Signal Hemisphere Requirements

We require that there is only one $K_S \to \pi^+\pi^-$ candidate in the signal hemisphere. The mass of the $\pi^+\pi^-$ must be close to the K_S mass. In Fig.4, the invariant mass constructed for the K_S is plotted. Note that outside the mass window of 0.488 and 0.508 GeV/c^2 $q\bar{q}$ background makes up a larger fraction of the total signal, so cuts are imposed there to eliminate those events.

Furthermore, the decay point of the K_S must be displaced from the initial e^+e^- initial point. Fig.5 shows the distribution of the decay length of the K_S, $L(K_S)$, in the detector. The Monte Carlo shows that most of the background is found in the region of $L(K_S) <$ 2.5, so those events are cut out. The result of this cut is a relatively clean sample.

We also require that none of the oppositely charged tracks are from a photon conversion ($\gamma \to e^+e^-$). This reduces background from $\tau^- \to \pi^-\pi^-\pi^+ (\geq 1\pi^0)\,\bar{\nu}_\tau$ (charge conjugation implied) decays where one of the γ's from the $\pi^0 \to \gamma\gamma$ undergoes a conversion $\gamma \to e^+e^-$.

The following features of the signal hemisphere help maximize the selection efficiency and reduce the statistical errors in the measurements:

1. No particle identification (PID) will be used to identify the hadron (h^-) in $\tau^- \to K_S h^- \nu$, where h^- may be a π^- or a K^-. This is to prevent introduction of PID errors and to increase statistics which reduces statistical uncertainty;

2. Any number of π^0's in the decay is allowed. π^0's are not a source of CP asymmetry according to the Standard Model. This will increases the number of events, which in turn reduces the corresponding statistical errors. This also eliminates any systematic uncertainties associated with the π^0 reconstruction.

Tag Hemisphere Requirements

In the tag hemisphere, we require that the charged track be identified as an e or μ. We reduce the background from multihadron events by requiring that there are few low energy, neutral particles in this hemisphere. In addition, the momentum of the tagged particle in the centre-of-mass (CMS) frame must be less than 4 GeV/c to reject dimuon ($e^+e^- \to \mu^+\mu^-$) and bhabha scattering ($e^+e^- \to e^+e^-$). Fig. 6 shows a graph of the tag's momentum in the CMS frame. A significant discrepancy between the Monte Carlo simulation and the data points occurs for the region $P_{cms,tag} > 4$. This deviation is due to the fact that Monte Carlo does not include dimuon and Bhabha scattering.

At the end of the selection, 101 885 Monte Carlo events remain. After normalizing the Monte Carlo luminosity with respect to real data, there are 56443.1 events in the Monte Carlo, of which only 1063.28 events come from background signals. This means that 98% of the sample is composed of signal events, in contrast with a 61% purity before the selection cuts.

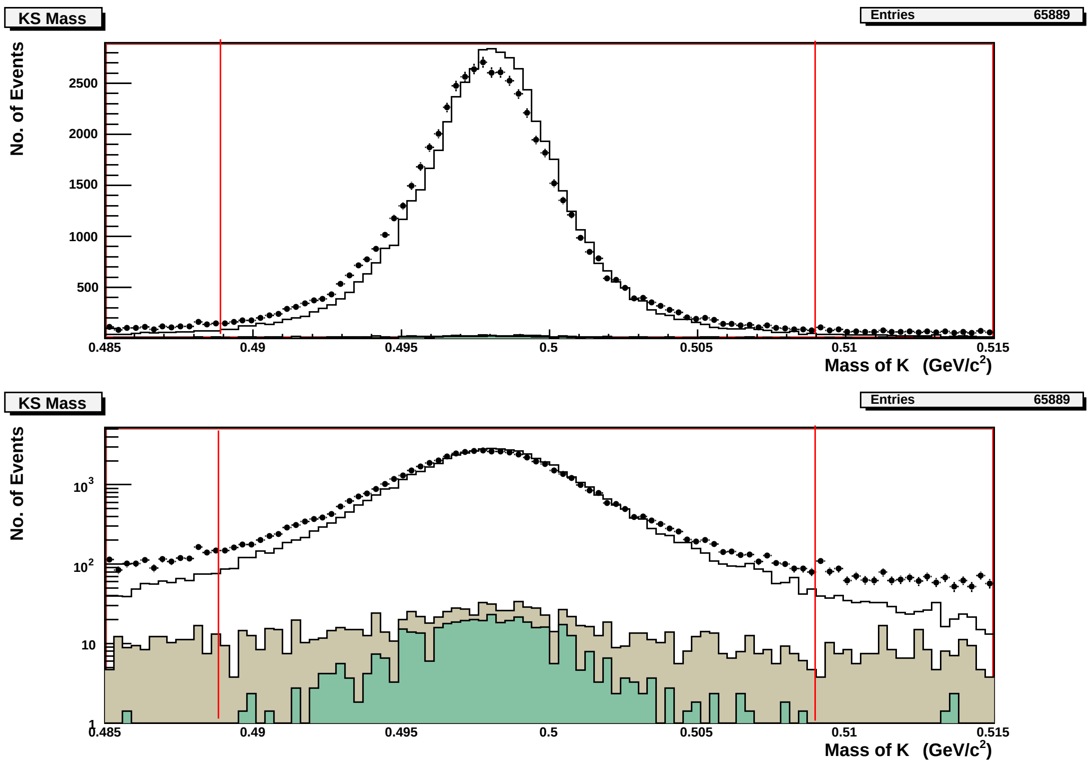

Figure 4: The invariant mass of $\pi^+\pi^-$ pairs. The large peak corresponds to the K_S meson. The lines indicated the region (0.488-0.508 GeV) to select K_S mesons. In this graph, events passing through all the cuts in Table B except for the mass cut are plotted. Points with error bars represent data points, the white histogram represents events generated by Monte Carlo simulation, green backgrounds from other τ decay modes, and beige $q\bar{q}$ backgrounds.

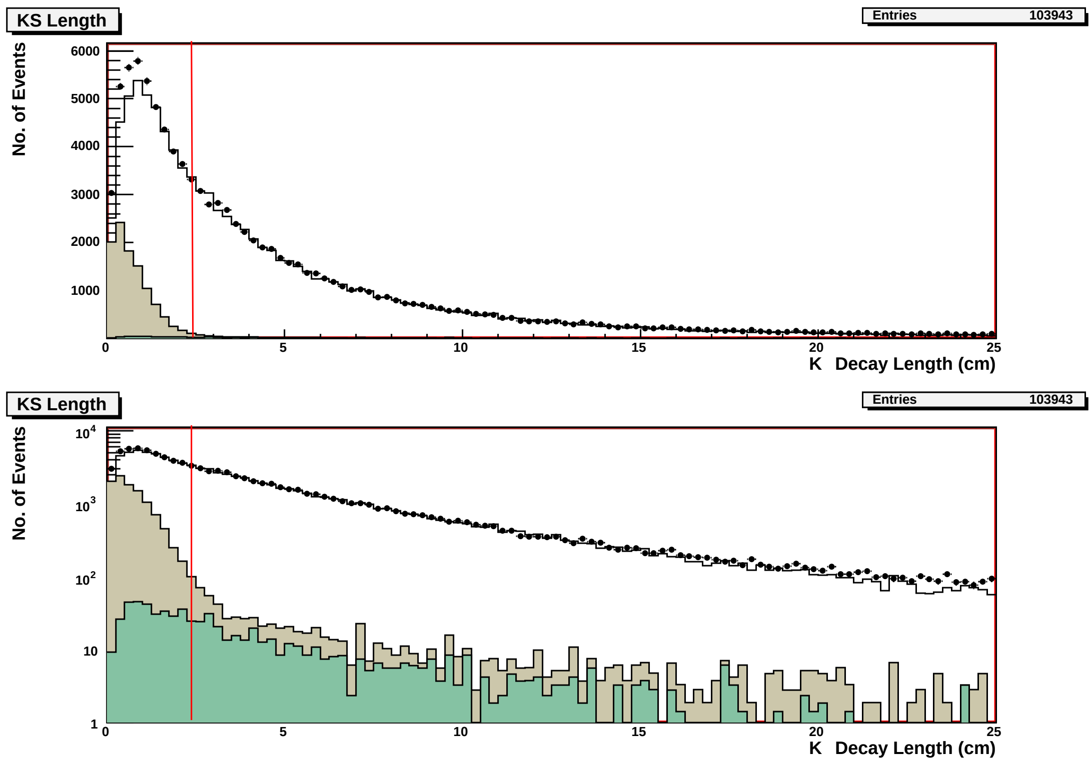

Figure 5: The decay length of the reconstructed K_S meson. Using the same colour scheme as Fig. 4, this histogram demonstrates that most of the background from $q\bar{q}$ are cut out after imposing a cut at the K_S decay length > 2.5.

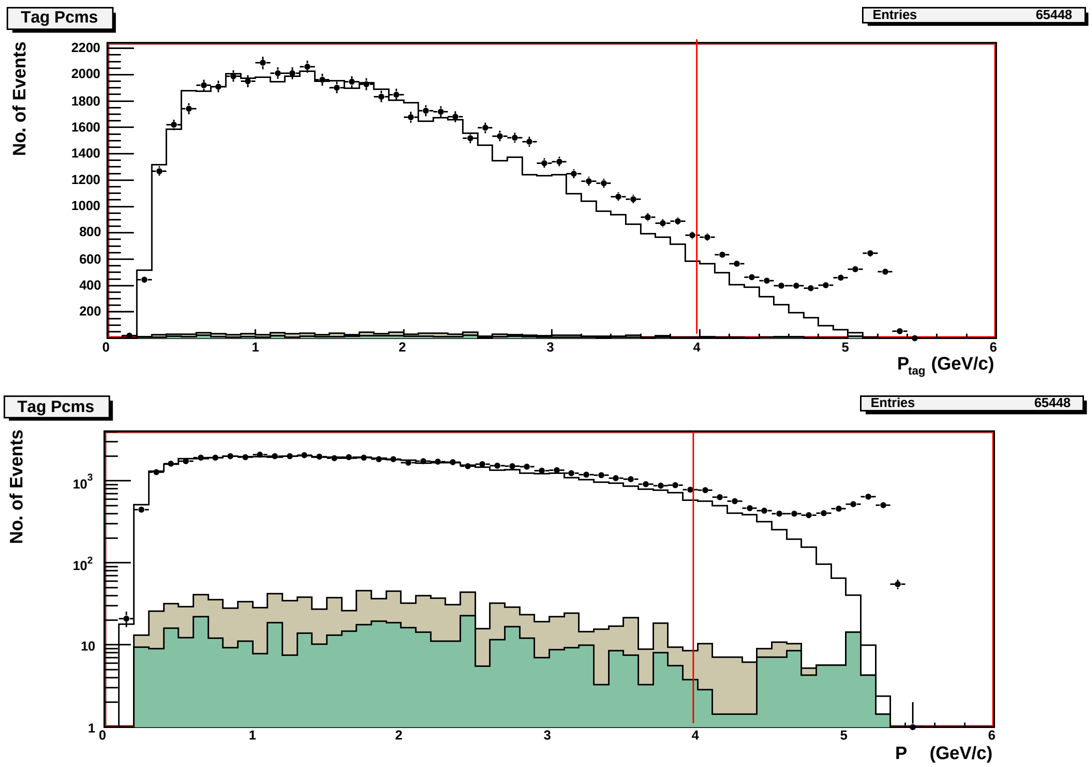

Figure 6: The momentum of the charged lepton in the centre-of-mass frame in the tag hemisphere. The top plot is using linear scale whereas the bottom plot is drawn with a logarithmic scale. This plot shows events after all cuts in Table B except for the $P_{cms,tag}$ cut; the momentum cut is marked by the red line in the graph. The colour scheme for the histograms is the same as Fig. 4.

6 Preliminary Studies

It is anticipated that a "blinded" analysis will be performed. This means that the selection criteria and systematic errors will be evaluated using Monte Carlo and "control data" samples. Only when this is complete will we examine the data. The "control data" sample consists of real data taken from the particle detector without a K_S. In both samples, no CP violation is expected. If a charge asymmetry occurs in either of the analysis, it may be evidence of biases introduced by the cuts used, and biases can be removed before starting the analysis. This will help eliminate some of the sources that may give false signals contributing to CP violation.

The CP asymmetry is determined using:

$$A = \frac{N(\tau^+) - N(\tau^-)}{N(\tau^+) + N(\tau^-)} \tag{6}$$

where $N(\tau^+)$ and $N(\tau^-)$ are the number of τ^+ and τ^- reconstructed from the 3-prong signal side respectively.

The error in A is given by (see Appendix A for detailed calculations):

$$\sigma_A = \frac{2N_+N_-}{(N_+ + N_-)^2}\sqrt{\frac{1}{N_+} + \frac{1}{N_-}} \tag{7}$$

6.1 Monte Carlo Studies

The Monte Carlo (KK2F) simulates 3-prong τ decays containing one K_S. A total of 270 million τ pair events have been generated. This number, corresponding to an integrated luminosity of $\sim$300 fb^{-1}, is based on all the events before implementation of any selection criteria. With the selection criteria as described in Section 5, the following asymmetries are measured with e and μ tags:

Tags	Asymmetry	Number of Events	
		Positive tag	Negative tag
e-tag	(-0.38±0.41)%	29 915	29 690
μ-tag	(0.63±0.49)%	21 007	21 273
either tag	(0.04±0.31)%	50 922	50 963

We observe no asymmetry in the Monte Carlo sample with a precision approaching 0.3%. We have varied a number of the selection criteria (see Appendix) and it may be possible to reduce this statistical uncertainty to 0.2%.

6.2 Preliminary Studies on Control Sample

We are fortunate to have a "control sample" to study the selection criteria and estimate the systematic errors. We use $\tau^- \rightarrow \pi^-\pi^-\pi^+ \,(\geq 0\pi^0)\, \nu_\tau$ decays where none of the two $\pi^-\pi^+$ combinations have a mass near the K_S mass. This is a large sample with approximately ten times more statistics than our nominal sample. Without K_S in the control sample, no CP violation is expected to be observed in the decays unless some new physics dynamics are involved.

The control sample is the first opportunity to look at real physical events (as opposed to Monte Carlo simulated events). One can look at any biases introduced by the cuts, since a charge asymmetry observed in the control sample indicates that there are biases introduced by the cuts on CP-preserving events. The real K_S data can be examined only after studies on the control sample are completed.

Initially, the same cuts are applied on the control data sample and the CP asymmetry is calculated. To further ensure that the sample is free from contamination with K_S, events with pairwise π's whose invariant mass is in the K_S mass window (0.488 GeV $< m_{K_S} <$ 0.508 GeV) are cut out from the analysis. We have begun to analyse the control sample but no results are available at this time.

7 Systematic Uncertainties

In addition to the statistical uncertainty, there are also systematic uncertainties in the charge asymmetry:

- K_S identification: The source of Standard Model CP violation in τ decays is from a K_S. If a K_S is mis-identified, errors will be introduced to the analysis. The chances of mis-identifying a K_S can be reduced by cutting out events containing neutral hadrons with mass lying outside the mass window.

- Tracking efficiency: This should not be a dominant error, as the tracking efficiencies are expected to be the same for a positively and a negatively charged track. The control sample will determine if the tracking efficiency does indeed contribute towards the systematic error of the experiment.

Many of the systematic uncertainties (e.g. luminosity uncertainty) cancel in the asymmetry. Initial studies on the Monte Carlo find no charge-dependent systematic errors; however, further work is required.

8 Feasibility of the Project

The statistical uncertainty can be calculated using Eq. (13). After some algebra, one arrives at:

$$\sigma_A = \frac{1-A^2}{2}\sqrt{\frac{1}{N_+}+\frac{1}{N_-}} \tag{8}$$

The asymmetry is expected to be 3.27×10^{-3} according to the Standard Model. Having obtained a 0.2-0.3% statistical uncertainty from the Monte Carlo sample with luminosity

$\mathcal{L} \sim 300 fb^{-1}$, one can expect that the statistical error is reduced approximately by a factor of $\sqrt{3}$ at the end of 2008, where an integrated luminosity of $\sim 1000 fb^{-1}$ is anticipated. As a result, a precision of $\sim$ 0.1-0.16% is expected. There are ways to increase statistics in the dataset, such as modifying the K_S decay length cut or loosening the $E_{neutral}$ cut. More studies are needed to ensure that no biases are introduced in the measurement after varying the cut.

Note that the statistical uncertainty obtained from an inclusive analysis (i.e. events with any number of π^0 or any hadron as one of the charged tracks) is greatly reduced. In other words, one of the merits of performing an inclusive analysis on the sample is that the statistics have been maximised. However, the inclusive analysis has the disadvantage of not having the ability of detecting angular distribution of decay products. Studying the angular distribution can be useful in CP violation analysis.

9 Conclusion

The Standard Model predicts that a charge asymmetry of 0.3% will be observed in the decay studied. Observation of this asymmetry signal is significant because this is the first example of CP violation observed outside the K and B meson systems. Any major deviation from the Standard Model prediction is an indication of new physics. Our initial studies on the Monte Carlo and the control sample suggest that we should be able to measure the charge asymmetry with an accuracy of 0.1-0.16% by 2008. Our measurement will be able to test the predictions of the Standard Model.

Appendix

A Calculation of σ_A

To calculate the error on the asymmetry, the following assumptions are made [13]:

1. The errors σ_{N_+} and σ_{N_-} are uncorrelated. This is valid in the case that the total number of tagged particles is not predetermined and fixed.

2. The probability of counting the number of tagged particles follows a Poisson distribution

The error on the asymmetry A is then calculated as follows [13]:

$$\sigma_A^2 = \begin{pmatrix} \frac{\partial A}{\partial N_+} & \frac{\partial A}{\partial N_-} \end{pmatrix} \begin{pmatrix} \sigma_{N_+}^2 & 0 \\ 0 & \sigma_{N_-}^2 \end{pmatrix} \begin{pmatrix} \frac{\partial A}{\partial N_+} \\ \frac{\partial A}{\partial N_-} \end{pmatrix} \tag{9}$$

Since $A = \frac{N_- - N_+}{N_- + N_+}$, one obtains:

$$\frac{\partial A}{\partial N_+} = \frac{-(N_- + N_+) - (N_- - N_+)}{(N_- + N_+)^2} \tag{10}$$

$$= \frac{-2N_-}{(N_- + N_+)^2}$$

$$\frac{\partial A}{\partial N_-} = \frac{2N_+}{(N_- + N_+)^2} \tag{11}$$

Substituting back, and remembering for Poisson statistics $\sigma_x^2 = x$ for distribution x, one obtains the following result:

$$\Rightarrow \sigma_A = \frac{2N_+N_-}{(N_+ + N_-)^2}\sqrt{\frac{1}{N_+} + \frac{1}{N_-}} \tag{12}$$

In the case of small asymmetry, $N_+ \approx N_- = N_\pm$, and so σ_A will scale like $\frac{1}{\sqrt{N_\pm}}$, which means that the greater number of statistics, the smaller statistical uncertainty in the measurement of asymmetry.

B Monte Carlo Studies: Effects of Selection Cuts

In the studies for Monte Carlo generated events, the cuts are varied and effects on the asymmetry are observed. The results are as follows (for e-tag):

Original Cut	New Cut	Asymmetry Measured
$P_{cms,tag} < 4.$	$P_{cms,tag} < 3.$	-0.59±0.45%
$E_{neutral,tag} < 1.$	$E_{neutral,tag} < 1.5$	-0.21±0.41%
KsLength>2.5	KsLength>3.	-0.48±0.43%
KsLength>2.5	(Cut removed)	+0.37±0.31%
0.488< m_{K_S} <0.508	0.485< m_{K_S} <0.510	-0.40±0.41%

When the cuts are applied one by one, the number of events will be reduced at each stage. The exact number of event after each successive cut, as well as the remaining fraction, is summarised in the table below:

Cut	# of Events After Cut	Fraction
None	782 660	100%
# Conv = 0 and $\Sigma q = 0$	718 739	92%
$P_{cms,tag} < 4.$	666 943	85%
$E_{neutral,tag} < 1.$	450 006	57%
$N_{neutral} < 2$	375 099	48%
K_S Cuts (# of K_S, decay length and m_{K_S})	180 217	23%
e/μ PID	101 885	13%

References

[1] Peacock, J. *Cosmological Physics* Cambridge: Cambridge University Press, 1999.

[2] Peskin, M. and Schroeder, D. *An Introduction to Quantum Field Theory*. Westview Press, 1995.

[3] Barr, S. et al. *Magnitude of the Cosmological Baryon Asymmetry*. Phys. Rev. D **20** 10, 1979.

[4] Bigi, I.I. and Sanda A.I. *A 'Known' CP Asymmetry in τ Decays* arXiv:hep-ph/0506037, 2005.

[5] Griffiths, D. *Introduction to Elementary Particles*. Wiley-VCH: Germany. 2004.

[6] Kleinknecht, K. *Uncovering CP Violation: Experimental Clarification in the Neutral K Meson and B Meson Systems*. Springer Tracts in Modern Physics **195**, 2003.

[7] Heeger, K.M. *Evidence of Neutrino Mass: A Decade of Discovery*. hep-ex/0412032.

[8] Bilenky, S.M. et al. *Long-Baseline Neutrino Oscillation Experiments and CP Violation in the Lepton Sector*. Phys. Rev. D **58** 033001, 1998.

[9] Delepine, D. et al. *Supersymmetry and CP violation in $|\Delta S| = 1$ τ decays*. hep-ph/0608008.

[10] BaBar Collaboration. *The BaBar Physics Books*. SLAC-R-504.

[11] PEP-II Official Website. URL: http://www.slac.stanford.edu/grp/ad/ADPEPII/ADPEPII.html

[12] Kirkby, D. and Nir, Y. *CP Violation in Meson Decays*. Physics Letters B: Review of Particle Physics (PDG Data Book), 2006.

[13] Lyons, L. *Statistics for Nuclear and Particle Physicists*. Cambridge University Press, 1992.

[14] Lewczuk, M. and Sobie, R. *Measurement of the Branching Fraction of* $\tau \rightarrow 3\pi\eta\nu$ *and* $\tau \rightarrow f_1\pi\nu$. BAD Note 1596.

[15] Kühn, J.H. and Mirkes, E. *CP Violation from Charged Higgs Exchange in Hadronic Tau Decays with Unpolarized Beams*. hep-ph/9711364.