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Tau Charm Factory Physics*

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Abstract

Physics from a Tau Charm Factory is presented.

INTRODUCTION

Tau Charm Factories proposed for future machines will provide powerful and unique facilities to study a variety of physics topics: the tau lepton, charm mesons, charmonium and the J/ψ decays. These topics cover the physics of the members of the first and second quark doublets and the third lepton doublet. The number of events produced in a running year of 5,000 hours is shown in table 1. This represents a factor 100-1000 increase over previous data samples. A workshop held at Stanford Linear Accelerator Center[1] reviewed the physics,[2] the machine[3] and the detector[4] for such a facility. In this paper, highlights of this meeting will be

Table. 1 Tau Charm Factory particle yields at 10^{33}

e+e−	Particle	Produced events
J/ψ	J/ψ	10^9/month
3.680	ψ'	5×10^8/month
$2m(\tau)$+2 MeV	$\tau^+\tau^-$	4×10^6 pairs/year
3.67 GeV	$\tau^+\tau^-$	4×10^7 pairs/year
ψ'' (3.77)	$D^\circ\bar{D}^\circ$	4×10^7 pairs/year
ψ'' (3.77)	D^+D^-	5×10^7 pairs/year
4.03 GeV	Ds^+Ds^-	10^7 pairs/year
4.14 GeV	Ds Ds*	2×10^7 pairs/year

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reviewed. We will begin with a short sketch of the machine issues and then briefly describe topics in tau, charm and charmonium-J/ψ physics.

STORAGE RING

The machine for the Tau Charm Factory was studied extensively by accelerator physicists.[3] The main conclusion was; the machine is difficult to build but well within present day technologies. The schematic layout is shown in Fig. 1. The general layout plan is to have separate rings, a dedicated e^+ and e^- injector and probably a single interaction region. The operating range was chosen in the energy range 3-4.2 GeV. The peak luminosity to be obtained is $\mathcal{L}=10^{33}$ cm^{-2}s^{-1} at E=4.0 GeV and at lower energies the luminosity should scale quadratically downward. It is expected to achieve high integrated luminosity with frequent filling of the rings, "topping off", which would occur every 30-60 minutes. The start up luminosity is expected to a few times 10^{33} cm^{-2}s^{-1} and in a few years achieve routine 10^{33} running.

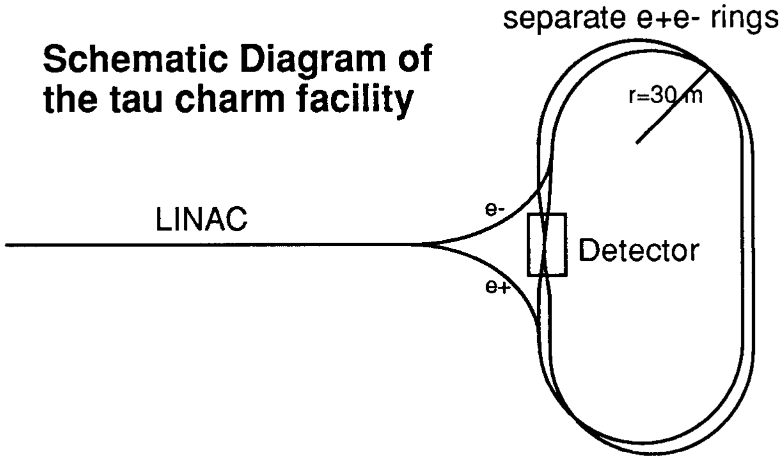

Fig. 1 Layout of a Tau Charm Factory

The design parameters considered were 24 bunches per beam, a current of 0.5 ampere and beta values of β_x^*=20 cm and β_y^*=1 cm to achieve a luminosity of 10^{33} cm^{-2}s^{-1}. The main technical challenges to handle ampere sized currents include the vacuum system design and beam loading. The only technical hurdles for the detector are the requirements of close in mini-beta quad magnets, a 50 ns beam crossing and up to a 1 Khz signal rate for the J/ψ decays.

TAU PHYSICS

Tau physics in a Tau Charm Factory has several important advantages:

- Well defined low energy kinematics for tagging
- Low momentum tracks for high resolution mass measurements
- Small backgrounds (no charm nor beauty decays)
- Possibility to run below $\tau^+\tau^-$ threshold to study backgrounds

In the following physics examples,[5] the data sample is based on two years of running at the design luminosity. The branching ratio measurements and Michel parameter measurements were studied very near threshold to take advantage of tau's being almost at rest. The tau neutrino measurement was done at a center mass energy of 4.2 GeV.

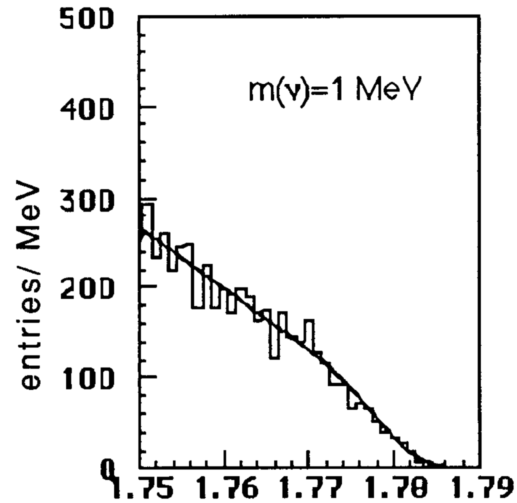

Fig. 2 Five pion endpoint mass

Tau neutrino mass

The tau neutrino mass may be measured from the decay $\tau \rightarrow 5\pi\nu$. The basic technique is to measure the end point mass spectrum of the five pions. The key benefits are the very high statistics and the excellent mass resolution attainable due to the low momentum (~300 MeV/c) of the pions from a tau which is nearly at rest in the lab. The end point spectrum for a one MeV tau neutrino mass is shown in Fig. 2. For a two year run at a center mass energy of 4.2 GeV, there will be ~1000 events near the end point, $m(5\pi)>1750$ MeV. This limit will approach 3 MeV which will improve the current limit of 35 MeV by a factor of ten .

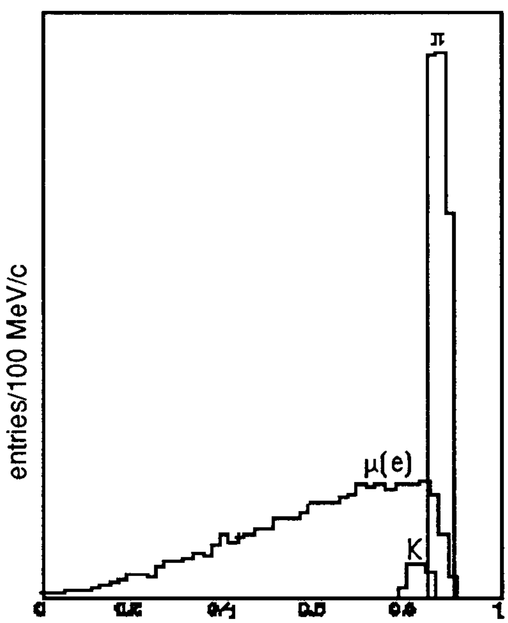

Fig. 3 One prong momentum spectrum

Tau absolute branching ratios

The precise determination of absolute tau branching ratios are important to study the one prong problem.[6-8] A unique advantage of the measurement of the tau branching ratios near threshold is the ability to separate by kinematics the one prong tau decays of $\tau \rightarrow \pi\nu$ and $K\nu$ from the $\tau \rightarrow e\nu\nu$ and $\mu\nu\nu$. Near threshold, the momentum spectrum of the pion and the kaon in the one prong tau decay, appears as a narrow peak near the kinematic limit. This enables a useful separation from the leptonic decays where the electron and the muon momentum spectrum will be spread over the allowable momentum range. This is shown in Fig. 3. By measuring the number of events where both tau's decay into the $\pi\nu$ modes ("double tag") and the number of events where one of the two tau's decays into the $\pi\nu$ mode ("single tag"), we can obtain the total number of produced tau pairs in the sample and the branching ratio $B(\tau \rightarrow \pi\nu)$. Using a similar technique for the electron, muon and kaon modes we can achieve a fractional error of 0.4-0.5% on the leptonic modes and 1% on the kaon mode. This result is a factor ten better than the current fractional error on the pion modes which is 10%.

Michel Parameters

The Michel parameters[9], ρ and η, are the constants that determine the shape of the energy distribution of the electron or muon in the leptonic decay of the tau. These parameters are determined by fitting the energy spectrum of the electron or the muon. The measurement of these parameters from tau's produced near threshold is advantageous due to the tag selection of the pion mode. Selecting the e-π and μ-π decay modes will provide a clean sample. In particular, the low energy lepton energy spectrum will not be contaminated by the π–π mode which is the case when this is studied using tau's produced at higher center of mass energies. The resulting study indicates the fractional error on the ρ parameter will be 0.4% which is a factor ten improvement over current values and comparable to the measurement for the muon.

Other measurements not discussed here but included in the workshop are: study of the multiple photon decays,[10] effects of charged Higgs in tau decays,[11] anomalous magnetic moments,[12] search for 2nd class currents,[13] electric dipole form factors,[14] supersymmetry affects in tau decays,[15] precision measurement of the tau mass,[16] QCD tests in tau decays[17,18] and the search for rare tau decays[19].

CHARM PHYSICS

Charm physics in a Tau Charm Factory has several important advantages:

- Large well established D°, D^+ and Ds^+ cross sections
- Exclusive, associated production of charm meson pairs to provide uniquely defined kinematics and low background contamination

- Well understood light quark continuum backgrounds and the ability to run below $c\bar{c}$ threshold
- Hadronic calorimetry can be used to veto background events that feed into the event selections with a missing neutrino

The main limitations in further progress in understanding charm meson decays is limited statistics.[20] The Mark III obtained a combined tag sample of charged and neutral D mesons of less than 10^4. The Tau Charm Factory in two years of running will amass nearly 10^7 tags. This very high statistics plus the detector improvements in neutral calorimetry resolution for the η and π° modes and hadronic calorimetry to reject K_L backgrounds should provide a major improvement in charm meson physics. The following examples are based on two years of running on the ψ''.

Leptonic Decays

Measurement of the leptonic decays of the Ds and the D^+ will provide a measurement of the pseudoscalar decay constant which is related to the branching ratio in the following formula;

$$B(D^+ \to \mu^+ \nu) = \frac{G_F^2}{8\pi} f_D^2 \tau_D M_D m_\mu^2 |V_{cd}|^2 \left(1 - \frac{m_\mu^2}{M_D^2}\right)^2$$

The pseudoscalar decay constant has only been measured for the pion and the kaon. It is basically a measurement of the wavefunction overlap or the annihilation of the quark-antiquark pair. Its importance lies not only in testing various models[21] but also in the model extrapolation for f_B which is a parameter in the box diagrams from $B\bar{B}$ mixing. If the values of the heavy quark decay constants are found to be anomalously too large or small, our understanding of the top quark mass and $B\bar{B}$ mixing may change.

The measurement[22] of the D^+, $Ds^+ \to \mu^+ \nu$ requires the use of fully reconstructed events where the exclusive pair production is achieved and the only missing track is the neutrino. This allows the use of the constraint of the missing mass of the neutrino. In addition, hadronic calorimetry will be important to reject backgrounds with K_L decays that could feed down into this channel. Using the expected tag sample in a Tau Charm Factory, the measurement of f_D and f_{Ds} should be achievable with a few percent error. The $\tau\nu$ mode was also studied. Depending on the backgrounds, this mode could also provide a large rate and could provide another independent measurement. Thus far there is only an upper limit for f_D from the Mark III group.

Exclusive Semileptonic Decays

Measurement[23] of the semileptonic decays of D→Keν and D→πeν in all possible modes will provide important measurements of the KM matrix elements.[24] The relation between the KM matrix element and the partial semileptonic rate is;

$$\Gamma(D^o \to \pi^- e^+ \nu) = \frac{G_F^2 M_D^5}{192\pi^3} \left|V_{cd}\right|^2 \int \left|f_+^{\pi}(t)\right|^2 p_\pi^3 dt$$

The measurement will provide a measurement of the KM parameters, V_{cd} and V_{cs} and the form factor for the hadronic transition;

$$f_+^{K,\pi}(t) = f_+^{K,\pi}(0) \times \left[\frac{M^2_{D^*,F^*}}{M^2_{D^*,F^*} - t}\right]$$

The predicted number of detected events are at a few times 10^5 level for the Cabbibo allowed D decays and a few times 10^4 level for the Cabbibo suppressed modes. The measurement is performed by detecting a D decaying into a Keν or πeν recoiling against a D tag. An important technique in this analysis is the use of the exclusive nature of the measurement where all the tracks are measured except the missing neutrino. The missing mass of the neutrino is a powerful constraint that other non-exclusive measurements will not have. These measurements will provide a 1% determination of the KM parameters and a precise measurement of the form factors. In a Tau Charm Factory the projected number of πeν (Keν) events is 4×10^4 (3×10^5) whereas the current existing modest sample is 7 (55) from the Mark III.

$D^\circ \overline{D}^\circ$ Mixing

Mixing in the charm sector is predicted from the Standard Model to be;

$$2r_D = \left(\frac{\Delta m}{\Gamma}\right)^2 + \left(\frac{\Delta\Gamma}{2\Gamma}\right)^2$$

where r_D is the ratio of mixed to unmixed events and $\Delta\Gamma$ and Δm are the mass mixing parameters. Expected rates from the Standard Model are $r_D \sim 10^{-4}$-10^{-5} and any unexpected larger rates could be the case for new physics.[25] The mixing can be measured by comparing the charge of the leptons in events where $D^\circ\overline{D}^\circ$ is produced and both of the D°'s have semileptonic decays. The second but more problematical technique is to use the case where both of the D's have the non-leptonic hadronic decays and compare the strangeness by the sign of the charged kaon. This last case may be plagued by double Cabbibo suppressed (DCSD) decays[26] where one D has a Cabbibo suppression at each W connection with a quark line. Although this rate is small, $\sim\tan^4\theta_C$, these events cannot be separated by time evolution measurements in a Tau Charm Factory and they may mask the real mixing rate. It has been pointed out[27] that Bose statistics forbids the decay of both of the D's into identical hadronic states that are in a p-wave. Hence the decay $\psi' \rightarrow D^\circ\overline{D}^\circ \rightarrow K^+\pi^-K^+\pi^-$ is only possible from mixing and not from DCSD, whereas the decays $e^+e^- \rightarrow \gamma D^\circ\overline{D}^\circ \rightarrow \gamma K^+\pi^-K^+\pi^-$ or $\psi' \rightarrow D^\circ\overline{D}^\circ \rightarrow K^+\pi^-\pi^\circ K^+\pi^-$ may be attributed only to DCSD or in combination with mixing. By systematically measuring decays that are s-wave (DD^*) and p-wave (ψ') and several hadronic modes that decay into identical pairs the question of mixing and DCSD can be disentangled and it is possible to measure $\Delta m/\Gamma$ and $\Delta\Gamma/2\Gamma$ separately. The studies[28] indicate that mixing may be detected to a level of $r_D \approx 10^{-4}$ and by measuring several modes in different techniques the level of $r_D \approx 10^{-5}$ may be obtained.

Other charm physics topics covered in the workshop included a measurement of the absolute branching ratios of the D^+, D° and Ds mesons by use of the double tag method, measurement of inclusive semileptonic branching ratios,[29] search for CP violation by measuring differences in the $D/\overline{D}$ rates[30,31] and the search for rare D decays[32] such as ee, $\mu\mu$, μe,[33] penguin decay modes[34] and CP violating decays.[31]

J/ψ AND CHARMONIUM PHYSICS

J/ψ and charmonium physics in a Tau Charm Factory will benefit enormously from the ultra statistics and improvements from better detector capabilities which include;

- High resolution electromagnetic calorimetry
- Uniform charged and neutral track acceptance
- Very large solid angle and very forward angle acceptance

The very high statistics enables precise measurements of branching ratios of the J/ψ by use of the decay mode $\psi' \to \pi^+\pi^- J/\psi$ where the J/ψ events can be tagged by detecting missing mass recoil of the $\pi^+\pi^-$ system. One third of the ψ' decays into this mode. Another major improvement will be the inclusive photon capability that a high resolution crystal calorimeter will allow. This resolution will enable "Crystal Ball" like inclusive photon resolution. This permits precise measurements of absolute branching ratios of radiative decays such as the η_c, iota, and theta as the luminosity errors will cancel out when the exclusive and inclusive

rates are measured in the same experiment.

Charmonium decays

Among the charmonium decays, several measurements[35,36] can really put the model to a more confining test. These include the two photon decay of the η_c and the three photon decay of the J/ψ. They are simply the two(three) photon diagram divided by the two(three) gluōn diagram of the $\eta_c(J/\psi)$.

$$\frac{\Gamma(J/\psi \to \gamma\gamma\gamma)}{\Gamma(J/\psi \to e^+e^-)} = \frac{4\alpha e_q^4(\pi^2-9)}{3\pi} \qquad \frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(\eta_c \to gg)} = \frac{8}{9}\left(\frac{\alpha}{\alpha_s}\right)^2\left(\frac{e_q}{2/3}\right)^4$$

The three photon decay of the J/ψ can be measured via the transition $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to \gamma\gamma\gamma$. This channel is not affected by the $e^+e^- \to \gamma\gamma\gamma$ background. This decay channel can be easily normalized as the total J/ψ events can be counted from studying the missing mass from the $\pi^+\pi^-$ tags. The η_c decays can be measured in $J/\psi \to \gamma\eta_c$, $\eta_c \to \gamma\gamma$. The normalization can be obtained by use of the inclusive photon measurement of the radiative photon from the η_c. Because the inclusive measurement is performed in the same experiment the luminosity errors will cancel out. This of course will enable precise measurements of the branching ratios $B(\eta_c \to K\bar{K}\pi)$ and $B(\eta_c \to p\bar{p})$ which are needed to normalize two photon and antiproton gas jet production of the η_c and the χ states. These relations predict a rate of 10^{-5} for the three photon decay of the J/ψ and 10^{-3} for the two photon decay of the η_c. In a Tau Charm Factory there will be 2,550 detected three photon decays of the J/ψ and 4,500 detected two photon decays of the η_c from a radiative decay of the J/ψ. From the existing world data there is a limit for the J/ψ decays and for the η_c there are all combined 150 events so far detected and a wide range of branching ratio values from the two photon experiments.

Search for Glueballs and Hybrids

The central prediction of the QCD lattice gauge theories is the existence of the lowest lying scalar glueball. The radiative decays of the J/ψ are the seminal hunting ground for these particles. Thus far the search in $J/\psi \rightarrow \gamma\pi\pi$, $\gamma\eta\eta$ and γKK has been negative. The possible explanations include a small branching ratio and/or the signal is hidden by overlapping $q\bar{q}$ resonances. Recent theory[37] has suggested that the scalar mass may be near 1.5 GeV instead of of 1 GeV and that the tensor mass is a factor 1.5 higher. If this is correct the glueball may be hidden among the backgrounds of $\rho\pi$ and f(1270) in the $\pi\pi$ mode and the f(1525) in the $\eta\eta$ and KK modes. To disentangle[38] [39] the signal from other resonances these channels requires a partial wave analysis requiring high statistics and a uniform and very forward acceptance. The current samples from the Mark III and DM2 are based on 5-10 million events and the forward acceptances of these detector were limited to $|\cos\theta|<0.8$. The proposed Tau Charm Factory will produce 10^9 J/ψ events in a month of running and the acceptance is designed to achieve $\cos\theta$ measurements up to 0.95. These measurements will allow a careful search for underlying resonances but also a complete measurement of many decay modes to verify the flavor decay of the candidates which are important tests of the glueball predictions.

Rare decays

The ultra high number of J/ψ events allows the possibility of observing weak decays. We can estimate the rate from the ratio of the lifetime of the D mesons and the width of the J/ψ;

$$\frac{2\hbar/\tau(D)}{\Gamma(J/\psi)} = 5 \times 10^{-7}$$

This rate is could easily be enhanced by non-spectator effects such as exchange diagrams. These decays[40] could appear either as a spectacular signature in the direct decay into a charm meson, $J/\psi \rightarrow Ds+X$, or into C or CP violating decays such as $J/\psi \rightarrow KsKs$ or $\phi\phi$. These rare decays follow similar physics proposed for very high statistics machines such a super LEAR or SATURNE[41] which are proposed to study rare decays of light quark mesons which are expected at the level of 10^{-13} because of their wide widths. The OZI suppressed nature of the J/ψ causes a relatively narrow width and this provides an advantage in terms of the larger branching ratios of these rare decays. What is interesting in the Tau Charm case is the possibility of observing these decays is within reach and the decay modes are striking and unmistakable.

Other studies not discussed here include the study of light quark spectroscopy,[42] search for the η_c' and the $^1p_1$,[35] study of the iota[43,44], E and theta[45] mesons, search for hybrids and 4-quark states[37,46], study of the $\rho\pi$ puzzle in ψ' decays[47] and study of η_c hadronic decays[48].

SUMMARY

The main conclusions of the Tau Charm studies from the workshop were;

- Precision tau and charm measurements testing the Standard Model are possible with a very high luminosity, $\mathcal{L}=10^{33}$ cm^{-2}s^{-1} machine
- Machine designs understudy, capable of this luminosity, are challenging but well within present technologies
- Detector designs[49] for Tau Charm physics are easily within present daytechnologies and represent substantial improvements in physics capabilities over previous detectors.
- The scope and breath of the physics is very broad, a Tau Charm Factory represents a major facility studying a wide range of particles: tau leptons, charm mesons, J/ψ and ψ' decays and their secondaries.

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