Physics Summary
τ-Charm Factory Workshop

ABRAHAM SEIDEN
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, CA 95064

I. INTRODUCTION

The Standard Model leaves us with at least two major questions:

(*a*) What is the source of electroweak symmetry breaking (i.e., what is the Higgs sector)?

(*b*) Why do we have fermion families? In particular:

(1) Why are there several (at least three) families?

(2) Why do these have the mass pattern we see?

(3) Why, for the quarks, are the weak and mass eigenstates different? Why is the Kobayashi Maskawa (K.M.) matrix what it is?

(4) How does CP violation fit in?

We can also ask a third question:

(*c*) How do the solutions to (*a*) and (*b*) relate? For example, since no intrinsic masses are allowed by the electroweak theory, are the masses in (*b*) simply related to (*a*)?

To study these issues we can

– Go up in energy scale and search for new particles, or

– Study the known quarks and leptons very carefully, looking for evidence for mechanisms which are presently not understood. This has so far led us to the K.M. matrix, but no hint of underlying dynamics beyond the exchange of left-handed W's, for the case of fermion decay.

Unlike the gauge theory couplings which are universal and prescribed for particles in a given group multiplet, there is substantial uncertainty in what to expect for new physics. Thus one can have mass dependent couplings, new/different K.M. matrices, flavor dependent couplings, different quark and lepton sector behavior and non-trivial phases needed to explain CP violation. The spectrum of the family members has not yet provided enough clues to fit the puzzle together.

The proposed τ-charm factory, the focus of this workshop, would allow a careful study of the second generation quark family and the third generation lepton family. It would provide a large variety of channels in which to search for surprises, since:

(a) The τ is the only lepton with a wide variety of channels for decay (with many having Standard Model contributions which are calculable to high precision). It has leptonic, Cabibbo allowed, and Cabibbo suppressed hadronic decays.

(b) Charm is the only quark with Cabibbo allowed, Cabibbo suppressed, and doubly suppressed decays (if we ignore the top quark, which is not accessible for experimentation). Indeed charm is probably our only way to look for special physics in the decay of the up-like quark sector.

In the discussion below, I will try to emphasize examples of the most important and unique physics topics for the τ-charm factory. I will assume that a year of data-taking corresponds to an integrated luminosity of 10^{40} cm^{-2}. Detailed analysis of the signal rates and backgrounds has been done using a detector approximately similar to the one worked out at the workshop.[1] Effects of resolution and particle decays are usually included in the simulation. More subtle sources of systematics have not yet been fully studied.

The range of energy to be covered by the τ-charm factory and the measured R (in this case the hadronic plus $\tau\bar{\tau}$ cross-section normalized to $\mu^+\mu^-$) value in

Physics Range of Tau-Charm Factory

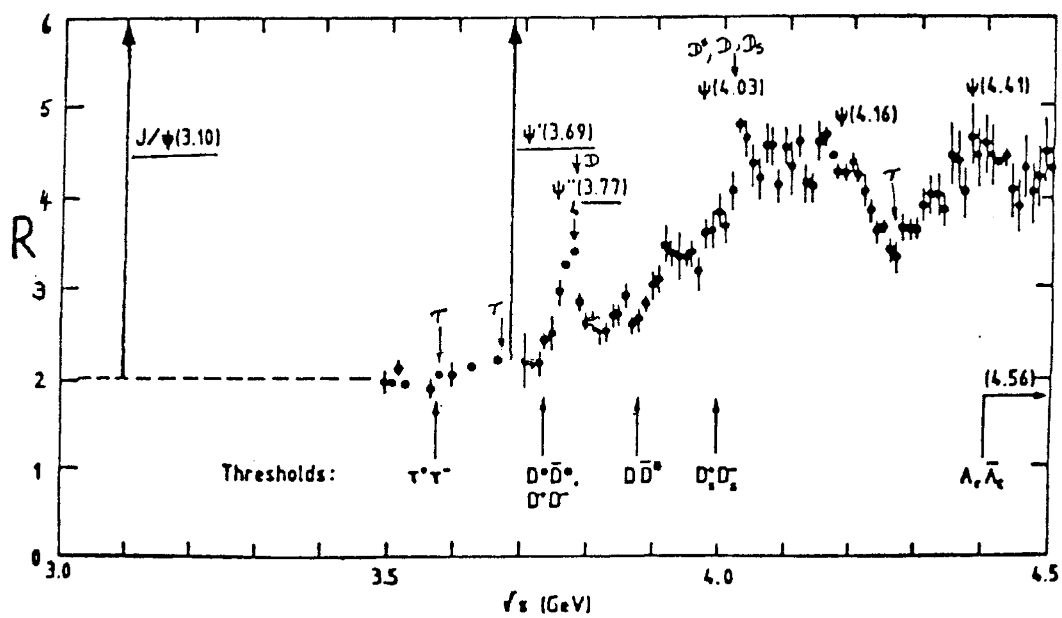

Fig. 1. R value versus the center of mass energy in the τ-charm energy range.

this range are shown in fig. 1. Several special running energies are indicated in the figure.

(1) For charmonium studies the J/ψ and ψ' resonances.

(2) For τ studies:

  (a) 3.57 GeV—very close to threshold allowing for maximum particle identification and final state separation in τ decays,

  (b) 3.68 GeV—for high rate and minimum hadronic background,

  (c) 4.25 GeV—for the maximum τ cross-section, with low background, and large $\tau\bar{\tau}$ polarization correlation.

(3) For charm studies:

  (a) the ψ'' resonance at 3.77 GeV which decays into a p-wave $D\overline{D}$ state,

  (b) 4.03 GeV for production of $D_S\overline{D}_S$ and $D\overline{D}^*$ final states,

  (c) 4.14 GeV for production of $D_S\overline{D}_S^*$ and $D\overline{D}^*$ final states.

These will be the running energies discussed below. They allow a long term, very rich, physics program of high precision measurements.

Finally, fig. 2 shows the $\tau\bar{\tau}$ Born cross-section (which is valid except near threshold or at a very narrow resonance) which indicates that the τ-charm factory provides the highest rate for τ's at a given integrated luminosity in e^+e^- production.

II. τ PHYSICS

The τ provides a third generation lepton family, and one of the goals of the τ-charm factory is to allow a better measurement of the masses of the family members. By an energy scan, we expect to be able to measure m_τ with an error of about 0.3 MeV. This can be checked by a very careful scan right near threshold. The threshold cross-section approaches a constant[2] (unlike the Born cross-section

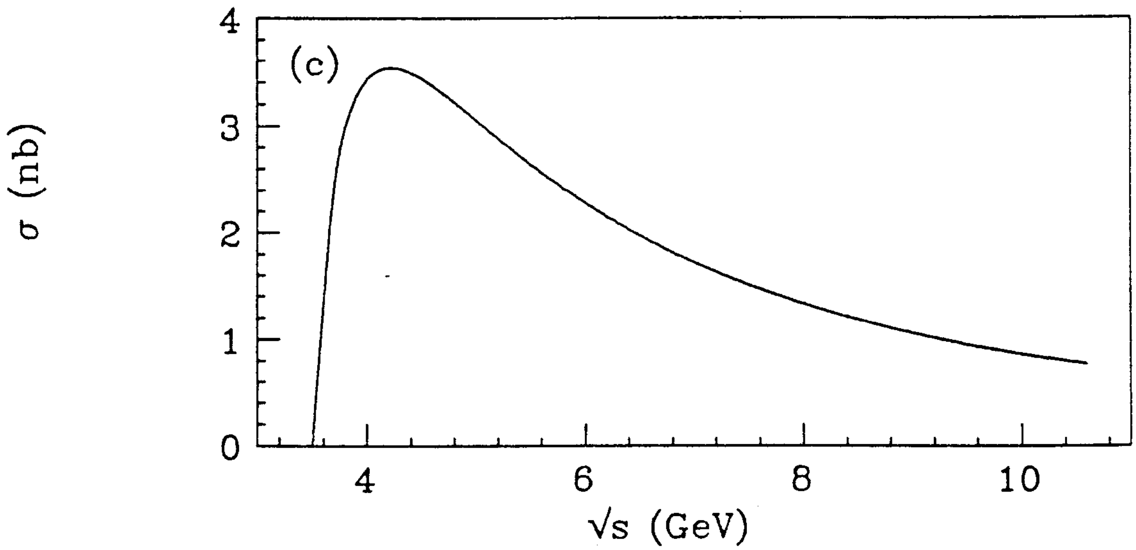

Fig. 2. Born cross-section for $\tau^+\tau^-$ production in e^+e^-.

in fig. 2) of about 0.22 nanobarns, which is reasonably large. The disappearance of τ pair production, signals that we are below threshold.

Of importance is a search for a finite neutrino mass. This can be accomplished, once m_τ is known, by a study of the endpoint of the invariant mass spectrum of five charged pions in the decay $\tau \to 5\pi\nu_\tau$.[3] If no mass is found, a limit can be set at $m_{\nu_\tau} \lesssim 3$ MeV.

A large fraction of τ decays are fully calculable in the Standard Model. These provide a good test of the model, including even the electroweak corrections which contribute at the few per cent level. The most precisely predicted decay widths are those for the final states: $e\bar{\nu}\nu$, $\mu\bar{\nu}\nu$, $\pi\nu$, $K\nu$. The branching ratios for these should be measurable at the τ-charm factory with a fractional accuracy, $\delta B/B \sim \frac{1}{2}$ to 1%.[3] This should be good enough to get to the level of the electroweak corrections. Table 1 shows these branching ratios normalized to that of the electron, as presently measured and as predicted, with and without the electroweak corrections.

Table 1: Ratio of Branching Ratios for Accurately Predicted τ Decays

Ratio	Present Values	No Electroweak Corrections[4]	With Electroweak Corrections[5]
μ/e	1.02 ± 0.03	0.973	0.973
π/e	0.62 ± 0.04	0.607	0.601
K/e	0.038 ± 0.011	0.0395	0.0399

Besides these branching ratios, many detailed final state distributions are predictable for τ decay because of the simplicity of the weak matrix elements. Figure 3 shows the variables describing a final state particle for the decay of a τ of fixed helicity, in its rest frame.

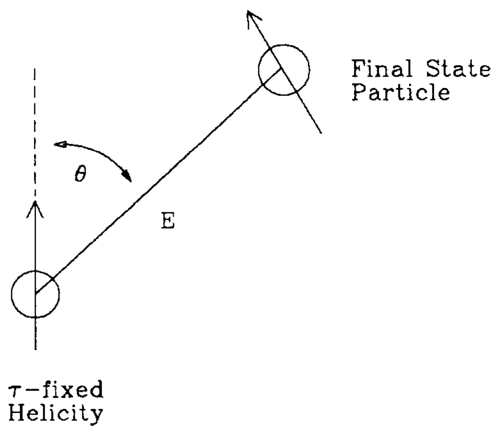

Fig. 3. Variables describing distribution for a particle produced in τ decay.

The energy distribution, the angular distribution, and final state polarization all provide tests of the Standard Model. For the charged leptons from $e\bar{\nu}\nu$, $\mu\bar{\nu}\nu$ decays, these distributions are specified in terms of the Michel parameters. However, even quantities like the polarization of the ρ meson in the $\rho\nu$ final state, or the ω meson in the $\omega\pi\nu$ final state, provide detailed tests of the Standard Model.

As an example, the energy distribution for the charged lepton in the $e\bar{\nu}\nu$ and $\mu\bar{\nu}\nu$ final states is determined by the ρ Michel parameter, with $\rho = 3/4$ for current couplings of fixed chirality. The present values are

$$\rho_e = 0.65 \pm 0.09$$

$$\rho_\mu = 0.84 \pm 0.11$$

In μ decay, $\rho = 0.752 \pm 0.0026$. At the τ-charm factory, this should be measurable with a statistical error of about 0.001.[6]

We look at some of these measurements and the experimental questions in a little more detail below as a function of the collision center of mass energy.

A. τ Run at $E_{c.m.} = 3.57$ GeV

This run could be the extension of a very careful scan near threshold and has some special advantages. The event numbers for a run of a little more than half a year are given in table 2.

Table 2. Event Numbers for a τ Run Very Near Threshold

	$N_{\tau\bar{\tau}} =$	2.5×10^6
Inclusive All Charged Single π Decays =	$2N_{\tau\bar{\tau}}B_\pi =$	5×10^5
All Charged Double	$\pi + \pi$	2.5×10^4
One Prong Events	$\pi + e$	1.0×10^5
	$\pi + \mu$	1.0×10^5
	$\pi + K$	3.0×10^3
	$e + K$	6.0×10^3
	$\mu + K$	6.0×10^3

From these event numbers we can determine the absolute branching ratios for all charged single prong modes with a fractional error, $\delta B/B$, of

$$\left.\begin{array}{c} e \\ \mu \\ \pi \end{array}\right\} \sim \tfrac{1}{2}\% \text{ fractional error}$$

$$K \quad \sim 1\% \text{ fractional error.}$$

This measurement would proceed as follows:

(1) Measure all events of the type e–π, μ–π, K–π, e–K, μ–K, π–π. The number of events depends on the number of τ pairs and the product branching ratios as $2N_{\tau\bar{\tau}}B_iB_j$ (except for π–π, which is $N_{\tau\bar{\tau}}B_\pi^2$).

(2) Using these events, which are extremely clean, establish the shape of the π spectrum from τ's for the running energy.

(3) Measure number of π's from τ's inclusively, using fixed spectrum from (2), in events with $\gtrsim$ 800 MeV missing energy. This measures

$$2N_{\tau\bar{\tau}}B_\pi.$$

Combining this with the measurements of $2N_{\tau\bar{\tau}}B_iB_j$ in (1) above, we can get each B_i value independent of $N_{\tau\bar{\tau}}$.

The advantage of doing this very near threshold is shown in fig. 4. The π spectrum is a narrow spike which separates well from the other particles. It can be found inclusively allowing the absolute branching ratio measurement independent of $N_{\tau\bar{\tau}}$. The K and π spectra don't overlap at all, allowing much better K identification, since we need separate only K–μ–e. At lower energies in the spectrum the π cannot contaminate the e or μ distributions. This can be contrasted with the spectra at a small increase in energy, $E_\tau = 2.250$ GeV, shown in fig. 5, where all the particles are mixed together. The kinematic separation near threshold is equivalent to an extra factor of about 10 in background rejection.

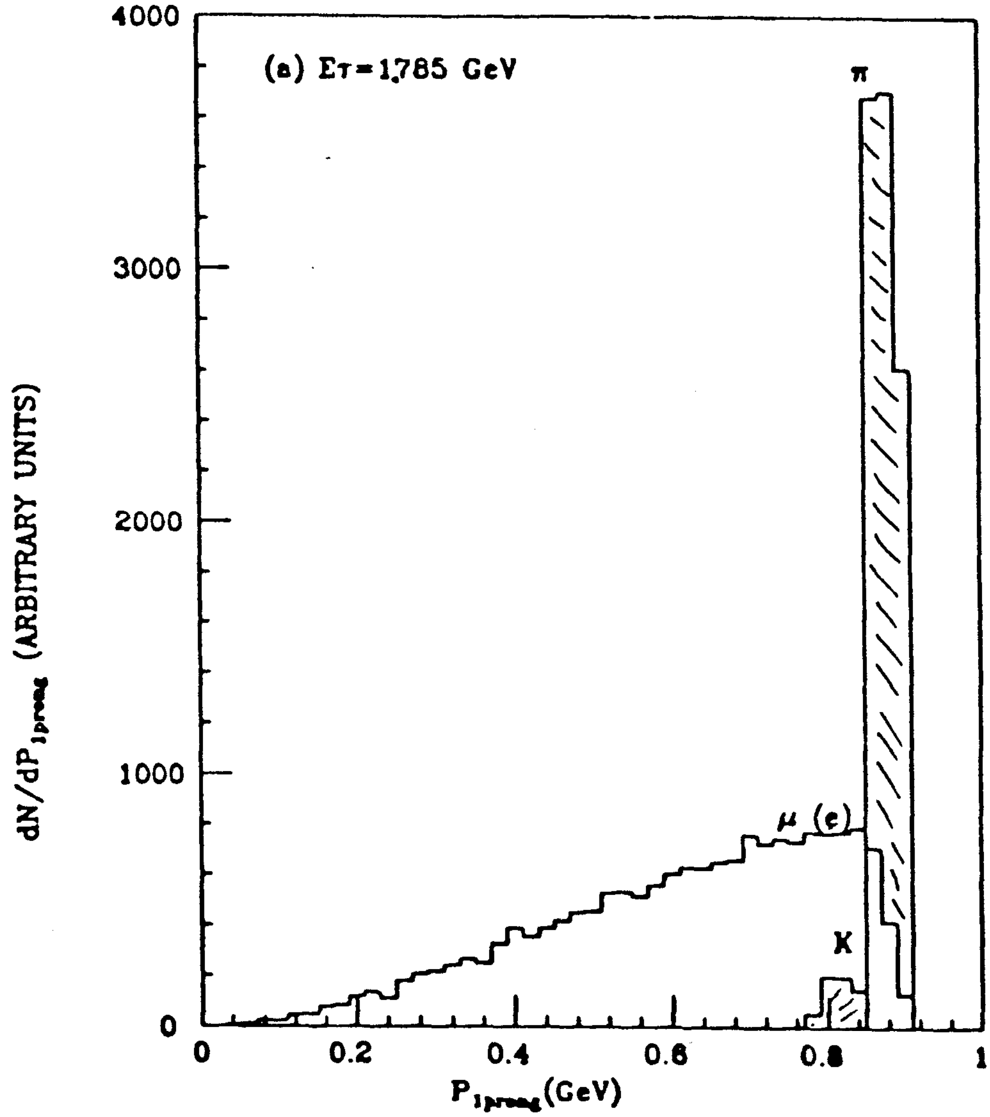

Fig. 4. Momentum spectra for particles in 1-charged prong τ decay at an energy $E_\tau = 1.785$ GeV.

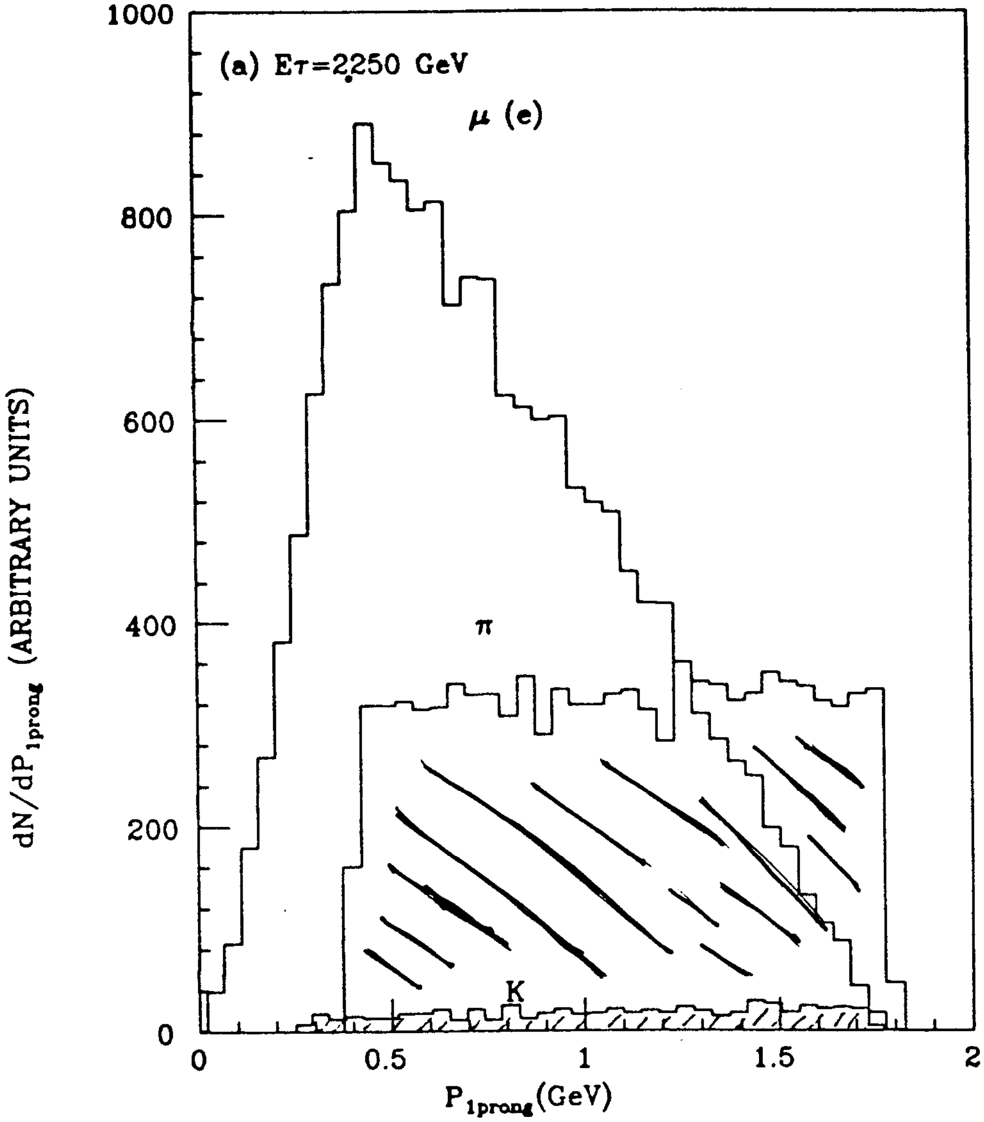

Fig. 5. Momentum spectra for particles in 1-charged prong τ decay at an energy E_τ = 2.250 GeV.

These distributions have some direct implications on the detector:

(1) One must have a hermetic detector to tell that we have neutrinos in the final state—near threshold, there is always lots of missing energy ($> \frac{m_\tau}{2}$) in real τ events for decays into $\mu\nu\bar{\nu}$, $e\nu\bar{\nu}$, $\pi\nu$, $K\nu$.

(2) Using missing energy, we can eliminate non-τ background, however measurements are still limited by confusion of one τ decay with another. To avoid this, one needs very good particle identification. However, the kinematic region of interest is limited to $p \leq 1$ GeV; a region where several good, well established, techniques exist to separate

$$e - \mu - \pi - K.$$

Can use: dE/dx, TOF

Shower shapes, E/P match (to select e).

Range and Tracking in Calorimeter (to select μ).

Because of the very excellent particle separation near threshold, this is an excellent place to measure in an unbiased way the spectra for e and μ over nearly the full momentum range in τ decay. These are described, for example, by the ρ Michel parameters discussed earlier. At this energy one can achieve a statistical error on these parameters of about 0.003, comparable to the error on the lepton spectrum in μ decay.

B. τ Run at Higher Energies

Running at higher energies one can get an order of magnitude more data than near threshold. This is then the place to make the most precise measurements, particularly for measurements not limited by particle misidentification. Running just below the ψ' would give $N_{\tau\bar{\tau}} \simeq 2.5 \times 10^7$/year, with minimal hadronic background. Running at $E_{\rm c.m.} = 4.25$ GeV would give $N_{\tau\bar{\tau}} \simeq 4 \times 10^7$/year with reasonably large polarization correlations between the decaying τ and $\bar{\tau}$, since the τ velocity $\beta = .5$.

This would probably be the best place to measure correlations of the final state angular and polarization variables with the τ helicity.

Examples of some of the physics goals at these energies are described below. The selection of τ events would be based on an energetic leptonic tag, with significant missing transverse momentum. This would give tagged samples of about 10^7 events. With these we could:

(1) Measure m_{ν_τ}, or lower limit down to about 3 MeV. What has been investigated in some detail is the decay channel $\tau \to 5\pi^{\pm}\nu_\tau$.[7] Including all efficiencies we can expect about 1500 events of this type per year of running. A finite value of ν_τ is then searched for through its effect on the endpoint of the $5\pi^{\pm}$ invariant mass spectrum. Background from hadronic events has been searched for using Monte Carlo simulations of the hadronic events at 3.68 GeV energy. No events were found, implying a signal to background ratio > 50. Simulations of the endpoint spectrum we could expect to see for various neutrino masses are shown in fig. 6.

(2) Search for rare or forbidden decays. Examples are:[8]

$$\begin{aligned} \tau^- \to\ & e^- e^+ e^- \\ & e^- \mu^+ \mu^- \\ & \mu^- e^+ e^- \\ & \mu^- \mu^+ \mu^- \\ & \mu^- \pi^0\ . \end{aligned}$$

We can expect to get limits which depend on the inverse of the total number of produced $\tau\bar{\tau}$ events. Thus we expect limits $\sim 10^{-7}$. This would represent a reduction by a factor of about 100 to 1000 compared to the present limits.

(3) Measure decay distributions with high statistics. For example, the Michel parameters ρ_e and ρ_μ in $e\bar{\nu}\nu$ and $\mu\bar{\nu}\nu$ can be measured with a statistical error of 0.001. Measurements such as these can be made with errors which

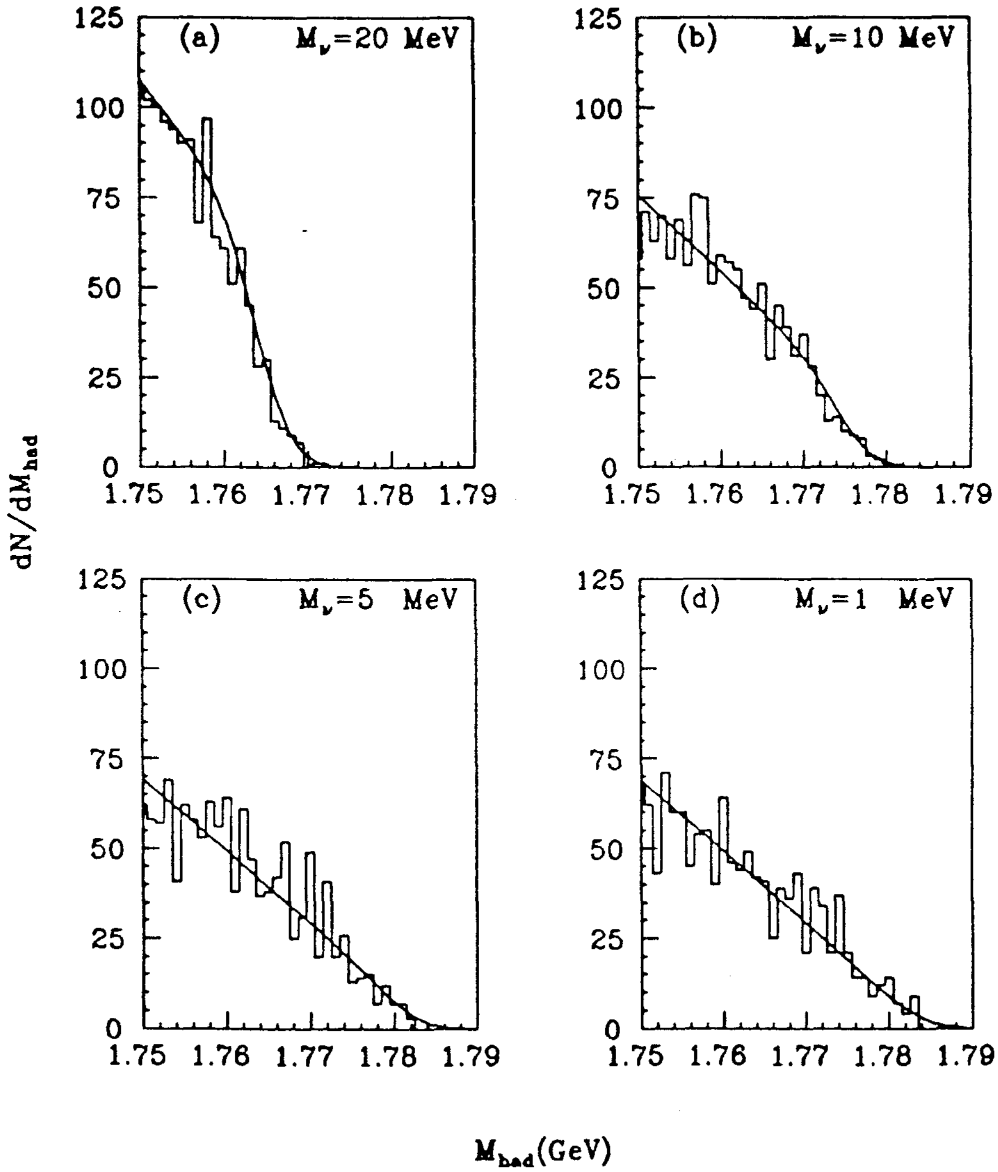

Fig. 6. Endpoint spectra for the five pion invariant mass for various values of m_{ν_τ}. Distributions come from an initial $5 \times 10^7 \tau\bar{\tau}$ Monte Carlo data sample.

are typically in the 0.1% to 1% range if systematic errors are minimized. This is controlled by the statistics available. From the approximate 10^7 tagged $\tau\bar{\tau}$ decays, a typical branching ratio $\sim 10\%$ yields $\sim 10^6$ events of a given type. For a distribution described by a small number of parameters we can expect a best fit for the parameters to have an error in the 0.1% to 1% range. Thus distributions in τ decays (like the absolute branching ratios discussed earlier) will be tested within this range of accuracy at the τ-charm factory.

Very qualitatively, we can also ask what scale is being probed by these measurements. As an example, we can imagine a new interaction adding incoherently to the normal weak decays and changing a distribution by about 1/2%. Assuming the same coupling as for the normal weak interactions, the propagator factor of $1/m^4$ in the rate implies that we are sensitive to a mass scale $4 \times m_W$. For a forbidden decay, the 10^{-7} limit that can be set implies that a mass scale of about 4 TeV is being probed for this case. For a case of new physics which adds coherently to the normal weak interactions the scale being probed is somewhere between the two scales above.

C. Possibilities for New Physics

Several examples of new physics were discussed at the workshop. Although none are presently compelling, they provide interesting examples of effects that could happen.

The simplest example is, of course, the Standard Model with one neutral physical Higgs scalar. For a heavy Higgs, we would not expect to see any effects in τ decays, as is the case for most searches at low energy. For τ decay, the same is true typically for the simplest supersymmetric extension containing five physical scalar particles.[9] A possibility that exists, however, is that there are different Higgs scalars in the lepton and quark sectors. If the leptonically coupled Higgs is light compared to the τ, then a Higgs Bremsstrahlung process exists providing a rate for $\Gamma(\tau \to H + X) = x^2 6.4 \times 10^{-6} \ln(m_\tau/m_H)\Gamma(\tau \to X)$, where x is a relative coupling squared.[10]

The above models have all had Higgs doublets only. Models with $SU(2)_L$ singlet charged scalars also exist and are consistent with all present data. Such models can increase the $\tau \to \mu\bar{\nu}\nu$ branching ratio relative to $\tau \to e\bar{\nu}\nu$ by a few per cent.[10] This would be measurable at the τ-charm factory.

A final example discussed was the case of three Higgs doublets, with CP violation stemming from this sector.[11] Such models generate electric dipole moments for the fermions, which violate CP. The size of the electric dipole moment grows like the mass cubed of the fermion, making measurements for the τ potentially a more sensitive test than those for the other leptons. The present experimental limits are:

$$d_e < 3 \times 10^{-24} \text{ ecm for the electron,}$$

$$d_\mu < 10^{-18} \text{ ecm for the muon.}$$

These numbers are consistent with a τ electric dipole moment as large as $d_\tau \sim 10^{-15}$ ecm, if we scale from the muon value using $(m_\tau/m_\mu)^3$.

Such a moment yields a CP violating interference through the diagrams shown in fig. 7.

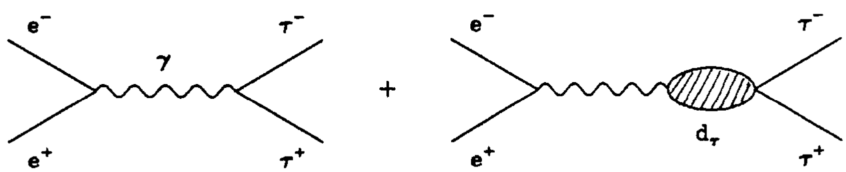

Fig. 7. $\tau^+\tau^-$ production through the normal current and through an electric dipole coupling.

If we look at a decay such as $\tau^+\tau^- \to \pi^+\bar{\nu}_\tau + \pi^-\nu_\tau$, we can construct a CP violating observable through which d_τ can be measured. An example is the symmetric tensor constructed from the pion directions and charges

$$(\hat{q}_+ - \hat{q}_-)_i \, (\hat{q}_+ \times \hat{q}_-)_j + (i \leftrightarrow j) \; .$$

Assuming a year's run at $E_{\text{c.m.}} = 4.25$ GeV, a preliminary estimate for the limit on d_τ that can be achieved is

$$d_\tau \lesssim 10^{-16} \text{ e.c.m.}$$

III. D PHYSICS

The plan for doing D physics involves running choices of at least two and probably three energies. At each energy one produces exclusive simple final states, which allow strong mass and momentum constraints for background elimination. In addition, the final state produced leads to a quantum coherent $D\overline{D}$ state which can be used to great advantage in mixing and CP violation studies. The energies of interest for D physics are:

3.77 GeV, leading to $D^0\overline{D^0}$ and D^+D^- only,

4.03 GeV, leading to $D_S^+D_S^-$ and DD^* mainly,

4.14 GeV, leading to $D_SD_S^*$ and DD^* mainly.

The number of events expected are

$$4 \times 10^7 \; D^+D^-$$
$$5 \times 10^7 \; D^0D^0$$
$$1.2 \times 10^7 \; D_S^+D_S^-$$

and comparable, or somewhat larger, numbers of DD^* and $D_SD_S^*$. From these, one can get clean, tagged samples, containing $\sim 10^7$ events. In this case a tag corresponds to fully reconstructing one D or D_S of a decay pair using momentum and mass constraints. The other D decay can then be examined for interesting or rare decays.

Note that extremely little is known about D_S decays and this machine would dramatically improve this situation. In particular, no absolute D_S branching ratio is known at all.

The D physics program is outlined in the table below.

Table 3: D Physics to be Done

---

(1) Systematics of Decays

  (a) Cabibbo allowed

  (b) Singly Cabibbo suppressed

  (c) Doubly Cabibbo suppressed

  (d) Study of form-factors in semileptonic decays

  (e) Study of Penguin contributions.

(2) Measurement of K.M. matrix elements V_{cd}, V_{cs}.

(3) Measurement of meson structure constants in leptonic decays, using for example

$$D^+ \to \mu^+\nu \quad \sim V_{cd} f_D$$
$$D_S^+ \to \mu^+\nu \quad \sim V_{cs} f_{D_S}$$

(4) Search for rare decays—flavor violating or family number violating.

(5) D^0-$\overline{D^0}$ mixing measurement.

(6) CP violation search–direct or in mixing.

Of the topics in the table, I will not discuss decay systematics which should be partly done by the machine in Beijing. I will also not discuss the search for rare decays. In general decays such as $D^0 \to e^+\mu^-$ can have limits set at the 10^{-7} level, as for analogous τ decays.

A. K.M. Matrix Elements

The present range of values for these matrix elements and the expected values are:[12]

	Present Values	Expect for 3 Generations
V_{cd}	0.16–0.23	0.22
V_{cs}	0.65–0.98	0.975

The strategy to measure these is to use semileptonic decays recoiling against fully reconstructed, tagged D decays. The process is thus:

$$D^0\overline{D^0} \rightarrow \text{ Fully Reconstructed Decay .}$$
$$\hookrightarrow K \text{ (or } \pi)e(\text{ or } \mu) + \nu \ .$$

These events are therefore only missing a neutrino and should have zero missing mass. Figure 8 shows the signal and background expected for one of the harder modes. It is very clean.

The measured rate is proportional to, taking $D \rightarrow Ke\nu$ as an example:

$$|f_+(t)|^2 \ |V_{cs}|^2 \ ,$$

where $f_+(t)$ is a vector current form factor. Table 4 lists the processes that can be measured and the expected rates after all efficiency and tagging cuts. There are a large number of redundant measurements. The final result for the K.M. elements will depend on how good the calculation of $f_+(t)$ can be made. A large data sample will allow a good measurement of the shape of $|f_+(t)|^2$ and will help constrain the theory. Perhaps, ultimately, this will allow a 5% measurement.

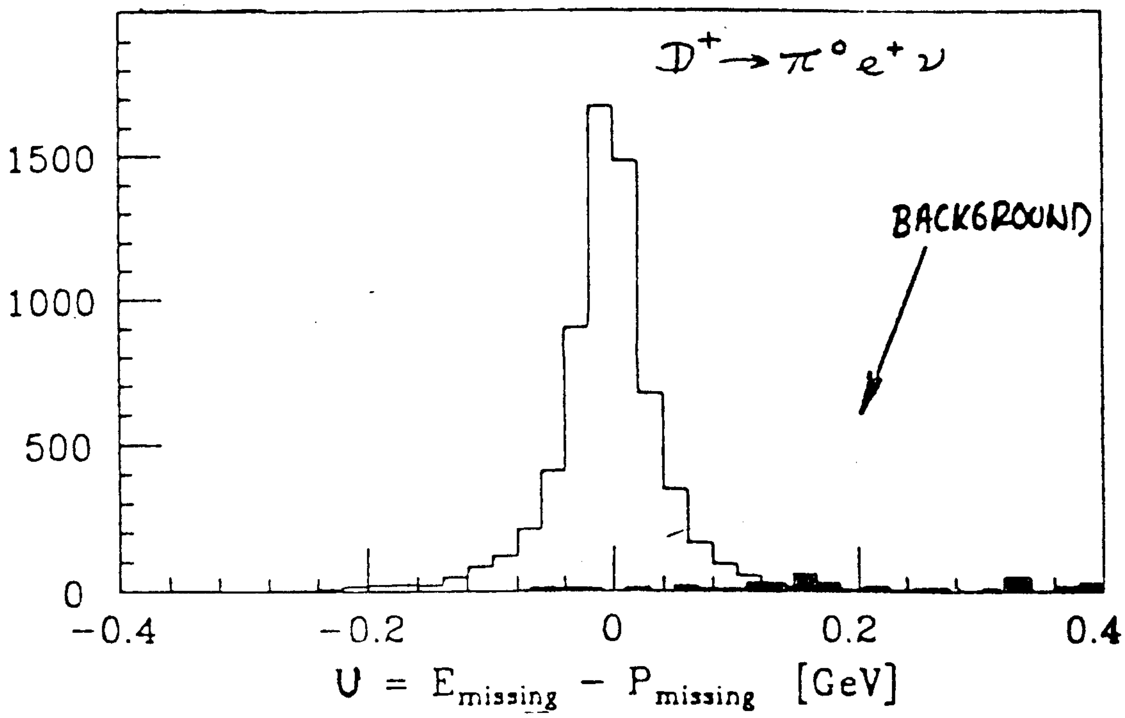

Fig. 8. Signal for D semileptonic decay in tagged D events. $U = 0$ for all particles detected except one neutrino.

Table 4: Rates for Measurement of K.M. Matrix Elements

Process	Number of Measured Events	Element Measured
$D^0 \to K^- e^+ \nu$, $K^- \mu^+ \nu$	3.3×10^5	$\lvert V_{cs}\rvert^2$
$D^0 \to \pi^- e^+ \nu$, $\pi^- \mu^+ \nu$	3.8×10^4	$\lvert V_{cd}\rvert^2$
$D^+ \to \overline{K^0} e^+ \nu$, $\overline{K^0} \mu^+ \nu$	1.6×10^5	$\lvert V_{cs}\rvert^2$
$D^+ \to \pi^0 e^+ \nu$, $\pi^0 \mu^+ \nu$	2.0×10^4	$\lvert V_{cd}\rvert^2$

B. Measurement of Meson Decay Constants f_D, f_{Ds}.

For this measurement one looks at leptonic D decays in fully reconstructed single tag events. The process is thus, for example:

$$
\begin{aligned}
&D^+D^- \rightarrow \text{Fully Reconstructed Decay.}\\
&\hookrightarrow \mu^+\nu\ .
\end{aligned}
$$

Again, isolation of the signal requires excellent missing mass resolution. The processes of interest are:

$$
\begin{aligned}
D^+ &\rightarrow \mu^+\nu \quad \sim f_D^2|V_{cd}|^2\\
D_S^+ &\rightarrow \mu^+\nu \quad \sim f_{Ds}^2|V_{cs}|^2\\
D_S^+ &\rightarrow \tau^+\nu \quad \sim f_{Ds}^2|V_{cs}|^2\ .\\
&\qquad \hookrightarrow \mu^+\nu\nu\\
&\qquad \hookrightarrow e^+\nu\nu\ .
\end{aligned}
$$

Given $|V_{cd}|^2$ and $|V_{cs}|^2$, we can calculate f_D and f_{Ds}. These can be used to estimate f_B in meson structure models, providing important input to mixing calculations for the B system. Alternatively, we can use the fact that the ratio of f_D/f_{Ds} does not vary too strongly in models to check the ratio of $|V_{cd}/V_{cs}|^2$.

The signals and background for these measurements are shown in fig. 9. Typical expected rates (after all selection cuts) are given in table 5.

Table 5: Rates for Measurement of Meson Decay Constants

Process	Number of Measured Events	Element Measured
$D^+ \rightarrow \mu^+\nu$	1100	$\lvert f_D\rvert^2$
$D_S^+ \rightarrow \mu^+\nu$	2000	$\lvert f_{Ds}\rvert^2$
$D_S^+ \rightarrow \tau^+\nu$ $\hookrightarrow \mu^+\nu\nu$	2000	$\lvert f_{Ds}\rvert^2$
$D_S^+ \rightarrow \tau^+\nu$ $\hookrightarrow e^+\nu\nu$	2400	$\lvert f_{Ds}\rvert^2$

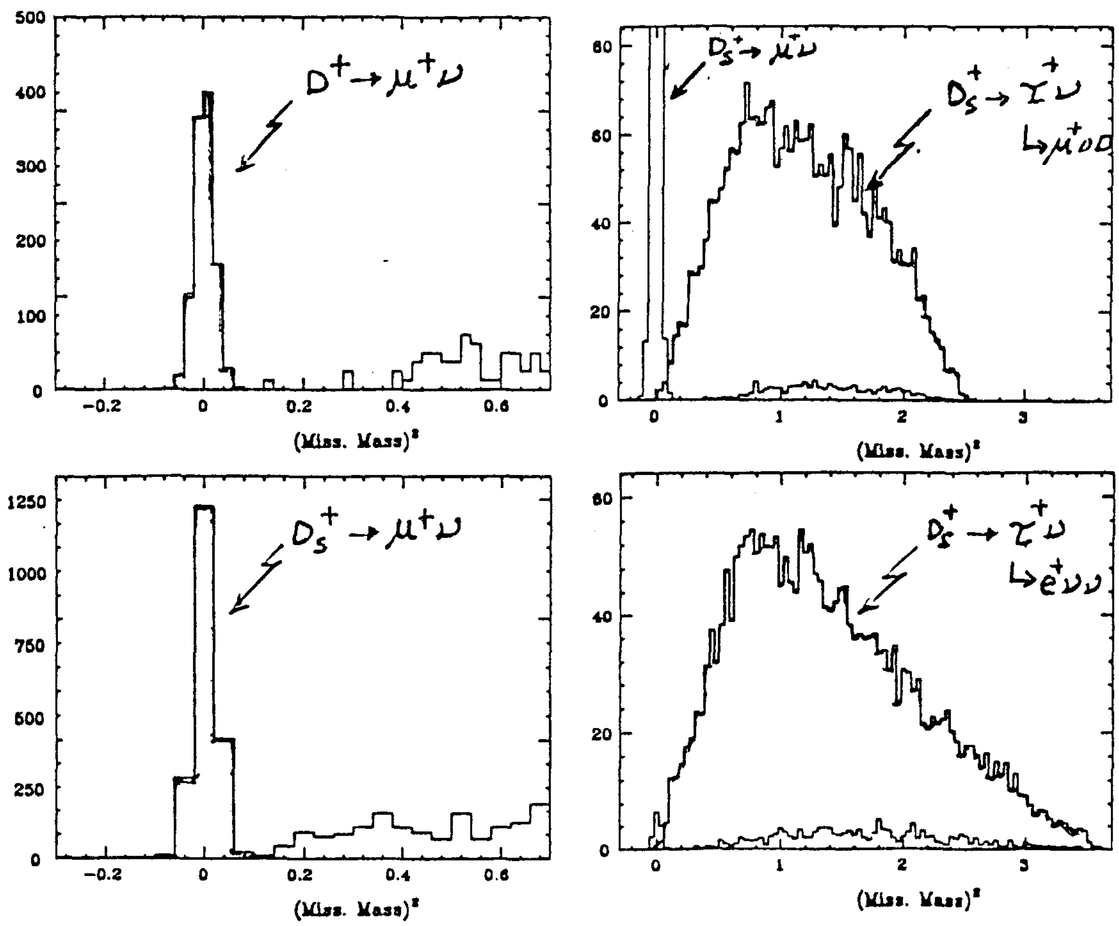

Fig. 9. Signals and background for channels used to measure D^+, D_S^+ leptonic decay. Note, what is a signal becomes a background and vice-versa for the $D_S^+ \to \mu^+\nu$ and $D_S^+ \to \tau^+\nu$ measurements.

Note, these measurements allow a search for new physics which does not exhibit the usual helicity suppression in pseudoscalar meson decay or which has mass-dependent couplings since we measure the ratio $\Gamma(D_S \to \mu^+\nu)/\Gamma(D_S \to \tau^+\nu)$. Also the absence of $e^+\nu$ final states at this level of statistics provides a similar test.

C. D^0–$\overline{D^0}$ Mixing

There are several advantages in the D system in searching for mixing and CP violation.[13] These are:

(1) D branching ratios into interesting states are still reasonably large.

(2) Thus we can cross check observations in several ways.

(3) Quantum statistics yields (different) correlations in decay for $D\overline{D}$ from the ψ'' and from $D\overline{D}^* \to \gamma\overline{D}D$ or $\pi^0\overline{D}D$, providing a nice analyzer.

We will look at mixing first. The mixing parameter is defined as

$$r_D = \frac{x^2 + y^2}{2} \ ,$$

where $x = \Delta m_D/\Gamma_D$, $y = \Delta\Gamma_D/2\Gamma$ come from mixing in the mass and decay matrices, respectively. To look for mixing, we can look for

$$D^0 \to \ell^{\pm} + X \ , \quad \overline{D^0} \to \ell^{\pm} + X'$$

With mixing, get same sign leptons.

Also can look for

$$D^0 \to K^{\pm}\pi^{\mp} \ , \quad \overline{D^0} \to K^{\pm}\pi^{\mp}$$

Can come from mixing or
doubly Cabibbo suppressed decays .

We can use the effect of quantum statistics to sort out the possibilities and make sure we have a signal. What we expect to see for various channels is given in table 6.

Table 6: Expectations for Mixing Rates for Various Exclusive Channels

Reaction	If Due to Mixing $\#\ell^\pm\ell^\pm/\#\ell^+\ell^-$	If Not Due To Mixing
$e^+e^- \to D^0\overline{D^0}$	r_D	0
$e^+e^- \to D^0\overline{D^0}{}^*$, $\hookrightarrow \overline{D^0}\gamma$	$3r_D$	0
$e^+e^- \to D^0\overline{D^0}{}^*$, $\hookrightarrow \overline{D^0}\pi^0$	r_D	0
	$\#(K^+\pi^-)(K^+\pi^-)/\#(K^+\pi^-)(K^-\pi^+)$	
$e^+e^- \to D^0\overline{D^0}$	r_D	0
$e^+e^- \to D^0\overline{D^0}{}^*$, $\hookrightarrow \overline{D^0}\gamma$	$3r_D$ + Doubly Cabibbo Suppressed + y (interference Term)	Doubly Cabibbo Suppressed
$e^+e^- \to D^0\overline{D^0}{}^*$, $\hookrightarrow \overline{D^0}\pi^0$	r_D	0

From the table we see that we can even perhaps measure x and y separately. We expect $x \gg y$ for new physics, otherwise the relative sizes are unclear. From the Standard Model, a best guess for r_D is $\sim 10^{-4}$. We expect to be able to measure r_D down to about 10^{-5} to 10^{-4}. Thus we should be able to bring the limit down to where we can expect to see an effect even in the Standard Model. The unmixed event numbers are given in table 7, after event selection criteria for a ψ'' run. These should be multiplied by r_D to yield numbers of mixing events.

Table 7: Event Numbers for Mixing Study

Final State from $D^0\overline{D^0}$	Number of Events
$K\pi + K\pi$	37,500
$Ke\nu + Ke\nu$	21,600
Sum of $K\mu\nu + K\mu\nu$ $Ke\nu + K\mu\nu$	60,000

Finally, we can employ a technique to search for mixing which does not involve only neutral D's. For example we can look at D^+D^{*-} final states, with a decay chain

$$\begin{array}{ll} D^+ & D^{*-} \rightarrow \pi^- D^0 \\ \hookrightarrow K^-\pi^+\pi^+ & \quad\hookrightarrow \ell^\pm + X \,. \end{array}$$

In these decays we have only one missing neutrino and should have a very nice clean signal. The rates are comparable to those in table 7.

D. CP Violation

CP violation could show up either in the mixing matrix or directly in final state decays. These are analogs of ε and ε', respectively, in the K system. We look at CP violation in mixing first.[13] Again, quantum statistics will allow a useful check of an effect. What we look at is a final state having one D decay into a CP eigenstate and the other into a state which tells D^0 and $\overline{D^0}$ apart. As an example, we choose

$$\begin{array}{llll} \text{(a)} & D^0 \rightarrow K^+K^- & \text{or (b)} & D^0 \rightarrow \ell^+ + X \\ & \overline{D^0} \rightarrow \ell^- + X & & \overline{D^0} \rightarrow K^+K^-. \end{array}$$

CP violation will give a rate difference depending on the quantum state of the $D^0\overline{D^0}$ system. This is described in terms of an asymmetry parameter, A, for the difference of rates for (a) and (b), divided by the sum. If the asymmetry comes from a phase angle in the mass matrix and $x \gg y$, then A can be written as $\sin(2\phi)$.

Table 8: CP Asymmetry for Various Reactions

Reaction	CP Asymmetry
$e^+e^- \to D^0\overline{D^0}$	0
$e^+e^- \to D^0\overline{D^0}^*$ $\hookrightarrow D^0\overline{D^0}\gamma$	$2\sqrt{2r_D}A$
$e^+e^- \to D^0\overline{D^0}^*$ $\hookrightarrow D^0\overline{D^0}\pi^0$	0

Table 9: Estimate of Semileptonically Tagged CP-Eigenstates

Eigenstate	CP	BR(%)	Efficiency	Events
$K_S^0\rho^0$	-1	0.3 ± 0.2	0.42	460
$K_S^0\eta$	-1	0.6 ± 0.3	0.12	290
$K_S^0\phi$	-1	0.27 ± 0.14	0.05	60
$K_S^0\pi^0$	-1	0.72 ± 0.15	0.26	770
$K_S^0\omega$	-1	1.3 ± 0.7	0.06	320
$\rho^0\pi^0$	-1	1.0 ± 0.5	0.70	3140
$\pi^+\pi^-$	+1	0.14 ± 0.05	0.80	460
K^+K^-	+1	0.5 ± 0.06	0.50	1040
$K_S^0K_S^0$	+1	0.20 ± 0.04	0.26	30

$\Rightarrow$ 6570 fully-reconstructed events.

Assuming 5000 hrs at 4.14 GeV and $L = 10^{33}$ cm^{-2}sec^{-1} and search for semileptonic tagged events ($D^0\overline{D^0}$ in $\ell =$ even state) with only a missing neutrino. Production cross-section $\sigma(D^0\overline{D^0}^*) = 0.9 \pm 0.2$ nb. Assume $K(\pi)e\nu$ and $K(\pi)\mu\nu$ tags only. Assume $D^* \to D^0\gamma$ is 0.37.

The expected asymmetry is given in table 8. Note that even for fairly small r_D, $2\sqrt{2r_D}$ is not so small. Again the measurement for $e^+e^- \to D^0\overline{D^0}$ and $D^0\overline{D^0}\pi^0$ provides a check for systematics.

The experimental isolation of the final states involved should be quite straight forward at the τ-charm factory. We look for example at the decay chain

$$\begin{array}{l} e^+e^- \to D^{0*}D^0 \to K^-e^+\nu \\ \qquad\qquad \hookrightarrow (\gamma \text{ or } \pi^0)D^0 \\ \qquad\qquad\qquad\qquad \hookrightarrow K^+K^- \,. \end{array}$$

Figure 10 shows the reconstructed $D^0 \to K^+K^-$ decay via the K^+K^- invariant mass. Figure 11 shows the subsequent D^* reconstructed from γK^+K^-, after selecting the D^0. This figure also shows the mass distribution for $D^* \to \pi^0K^+K^-$ after arbitrarily throwing away a photon. We see that the two D^* decay channels are very nicely separated. Finally, fig. 12 shows the missing mass in the event centered at zero, since we are missing just one neutrino from the D^0 semileptonic decay.

Table 9 gives the expected rates for a variety of CP eigenstates combined with a semileptonic decay. The CP asymmetry is then this rate times $2\sqrt{2r_D}A$. We see that a limit on A of about 0.3 could be set if r_D is $\sim 10^{-4}$. For new physics r_D could be much larger allowing a search for smaller A values.

We turn next to the case of direct CP violation. To simplify the discussion we assume no mixing at all. It would increase some rates if present. We will use quantum statistics at the ψ'' as a CP analyzer.

We imagine a ψ'' which decays into $D^0\overline{D^0}$. These can then subsequently decay into a CP eigenstate and a second state of the same CP as the first or a state which only D^0 or $\overline{D^0}$ can decay to, e.g., a semileptonic decay. We call the decay amplitudes for the initial CP decay A_D for D^0 decay and $A_{\overline{D}}$ for $\overline{D^0}$ decay. $A_D = \pm A_{\overline{D}}$ if CP is conserved. CP violation corresponds to these being unequal in magnitude, or having an extra phase difference. For simplicity we assume the

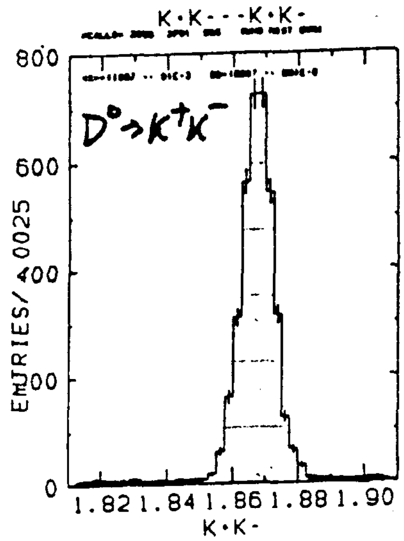

Fig. 10. Reconstructed D^0 from K^+K^- mass combinations.

$A_D = \pm A_{\overline{D}}$ if CP is conserved. CP violation corresponds to these being unequal in magnitude, or having an extra phase difference. For simplicity we assume the first CP decay occurs first, although the final result does not depend on this. At the time of the first decay, the second D is projected onto a state orthogonal to the first. It is thus projected onto $\frac{A_{\overline{D}}D^0 - A_D\overline{D^0}}{\sqrt{|A_D|^2+|A_{\overline{D}}|^2}}$. This is not simply $\frac{D^0 \pm \overline{D^0}}{\sqrt{2}}$ if CP is violated. For no mixing this state will propagate and subsequently decay. A semileptonic decay will analyze the amount of D^0 versus $\overline{D^0}$ in the propagating state. We thus get an asymmetry

$$\frac{(\ell^+ + \text{CP Eigenstate}) - (\ell^- + \text{CP Eigenstate})}{(\ell + \text{CP Eigenstate}) + (\ell^+ + \text{CP Eigenstate})} = \frac{|A_D|^2 - |A_{\overline{D}}|^2}{|A_D|^2 + |A_{\overline{D}}|^2} \,.$$

This is sensitive to the magnitude difference in the amplitudes only. However, we can also choose a CP eigenstate, of the same CP as the initial decay, as the analyzer. This is now sensitive to the magnitude and phase difference. Assuming the second decay conserves CP, the rate to this kind of final state is proportional to $\frac{|A_D - A_{\overline{D}}|^2}{|A_D|^2+|A_{\overline{D}}|^2}$. More generally, we can get a contribution to the CP violation from

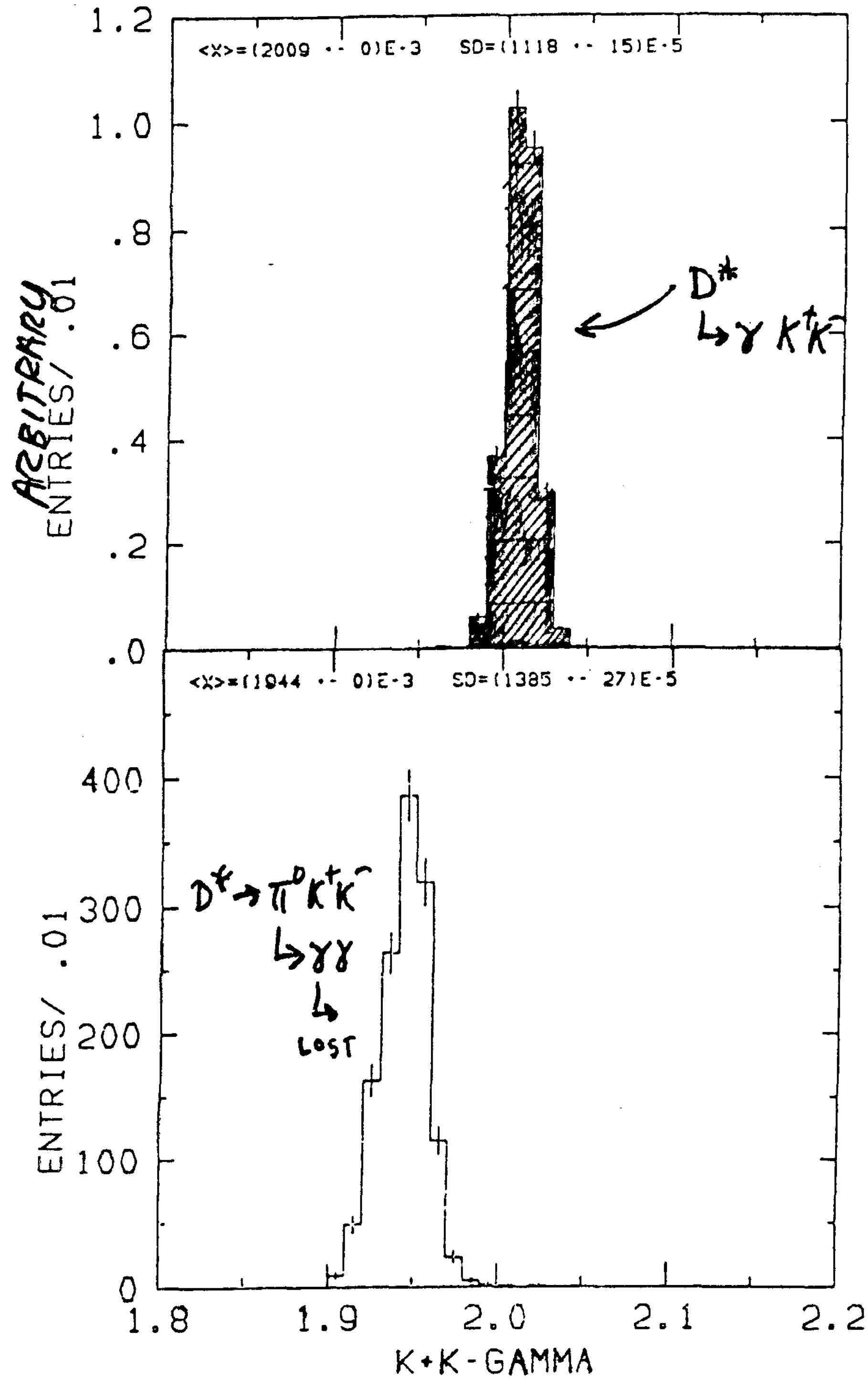

Fig. 11. D^* reconstructed from γK^+K^- (top), mass of γK^+K^- from $D^* \to \pi^0 K^+K^-$ with one photon arbitrarily thrown out (bottom).

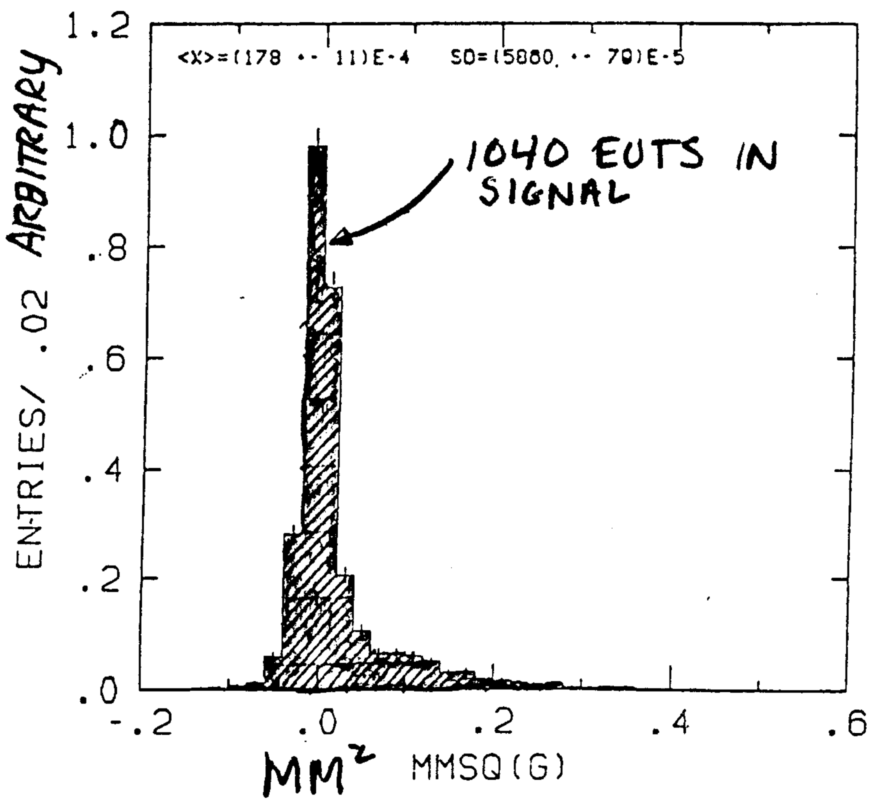

Fig. 12. Missing mass in final state: $\gamma K^+K^- + K^-e^+\nu$, showing peak at zero.

each of the decays. Table 10 shows the event rates expected for the two search methods discussed. Note the latter method has the advantage that we should get no events at all, and thus limits from it improve as $1/N$ instead of $1/\sqrt{N}$ where N are event rates.

Finally, for a direct CP violation search, one can compare a very large variety of partial widths for conjugate decays, e.g., $D^+ \rightarrow f$ versus $D^- \rightarrow \bar{f}$. Since many decays exist yielding $\sim 10^6$ events, these tests can be made at $\sim 10^{-3}$ level, provided systematics which treat positive and negative particles differently can be minimized. As with the previous methods, we see that the τ-charm factory allows a CP violation search at the level of 10^{-3}–10^{-2}.

Table 10: Rates for Direct CP Violation Measurement

Case 1: $\ell^- +$ CP eigenstate versus $\ell^+ +$ CP eigenstate. Rates are for sum. Difference is asymmetry times rates in the table.

CP Eigenstate	Number of Events
K^+K^-	15,000
$\pi^+\pi^-$	10,000
$K_S^0K_S^0$	4,000
$\rho^0\pi^0$	5,000

Case 2: Two CP eigenstates of the same CP.

State 1	State 2	Number of Events for 100% CP Violation
K^+K^-	$\pi^+\pi^-$	300
K^+K^-	$K_L^0\pi^0$	3,000
$\pi^+\pi^-$	$K_L^0\pi^0$	1,000

IV. QCD STUDIES

The τ and D systems provide several interesting topics in QCD. For example, the rate for τ hadronic versus leptonic decay $\frac{R(\tau \to \nu_\tau + \text{ hadrons})}{R(\tau \to \nu_\tau + \bar{\nu} + e))}$ is an interesting test of QCD, having an expression in terms of a perturbative QCD expansion with small non-perturbative corrections.[14] Similarly, the matrix elements into hadrons in τ decay $\langle H| J_\mu^V |0\rangle$ and $\langle H| J_\mu^A |0\rangle$ are quite interesting and for the vector current related to other measurable quantities.[15] In the D system, we have seen that we are interested in the matrix elements $\langle K| J_\mu^V |D\rangle$ and $\langle 0| J_\mu^A |D\rangle$, which are important for calculating $D \to K + \mu\nu$ and $D \to \mu\nu$, respectively.

However, the richest system for QCD studies comes from the charmonium states J/ψ, ψ', η_c. These yield interesting topics which can be broken into:

(1) Issues of the $c\bar{c}$ wave function and mass spectrum. Examples are the rates for $\psi \to 3\gamma$ and $\eta_c \to \gamma\gamma$. These are not well measured at present.

(2) Issues involving gluons in charmonium decay. Decays of interest are $J/\psi \to gg\gamma$, $J/\psi \to ggg$, $\eta_c \to gg$. What should we really do to calculate these, since gluons interact strongly and also don't appear in the final state?

(3) Issues in hadronization, where we really focus on the hadronic final states from the above decays.[16] Thus we can study the processes shown in fig. 13.

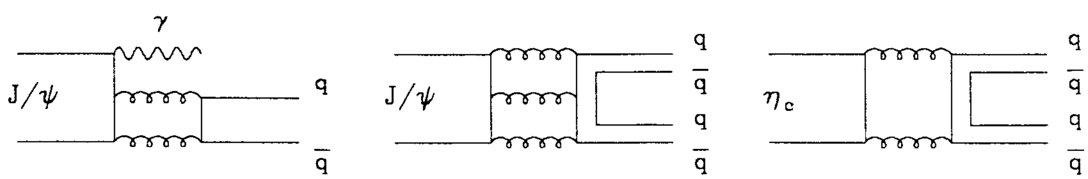

Fig. 13. Decay diagrams for various ψ, η_c decays.

There are several advantages to using the J/ψ for such light quark spectroscopy studies. These are as follows:

(*a*) J/ψ has well defined initial quantum numbers, $J^{PC}I^G = 1^{--}0^-$. Its helicity $= \pm 1$ when produced in e^+e^- annihilation. It's an SU(3) singlet with no hidden light quarks.

(*b*) It is produced with almost no background in e^+e^-.

(*c*) We can get many events. In fact the τ-charm factory could easily provide 10^9 such decays.

(*d*) The mass is ideal for studying mesons in the 1–2.5 GeV mass region. Rates are reasonable for exclusive decays into two body final states which can be looked at in terms of simple models and spin analyzed using small numbers of contributing amplitudes.

(e) The related perturbative decay diagrams prominently involve gluons, providing a good laboratory to search for gluonic bound states (glueballs) or states involving quarks and gluons (hybrids) which may be obscured in other production processes.

(f) By comparing rates for $J/\psi \to \gamma + M_1$ to those for $J/\psi \to M_1 + M_2$ or $\eta_c \to M_1 + M_2$, where M_2 is a well understood meson (for example a light pseudoscalar or vector meson), we can try to determine the quark and/or gluon content of the meson M_1. Note for M_2 we can choose a whole nonet of related mesons, allowing a search for a nonet structure for mesons of type M_1 (if it is an ordinary $q\bar{q}$ state) or a different structure (if it is not simply $q\bar{q}$).

We look at a few examples of physics from charmonium below. Perhaps the most important issue is the status of glueballs.[16] The most recent lattice calculations still indicate that the lightest glueball should be a 0^{++} state with mass ~ 1.5 GeV. Such a state has still not been seen in J/ψ decays. However, there are still several possibilities:

(1) The θ which is favored to have $J^P = 2^+$ could be a mix of 0^+ and 2^+ states. The 0^+ might then be a glueball.

(2) The 0^+ glueball could decay primarily into $\eta\eta$ and/or $\eta\eta'$ and therefore no experiment at the J/ψ has been good enough to find it.

These type of questions should be resolvable with large data samples plus good neutrals detection.

In general, the 1–2.5 GeV mass region is very rich with structures and we can expect to resolve quite a few in several simple channels, such as

$$\pi\pi,\ \eta\eta,\ \eta\eta',\ KK,\ \eta\pi$$
$$KK\pi,\ \eta\pi\pi$$
$$\text{Vector} + \text{Vector}$$
$$\gamma + \text{Vector}\ .$$

Present data at the J/ψ in any potential resonance contain ~ 100 to a few hundred events. With the τ-charm factory, we could get many thousands of events in each channel. As discussed earlier, it is critical to discern a pattern, since one state alone is not easily interpretable. Even among the simplest states, 0^+ and 1^+, it is presently not clear what the correct particle assignments and interpretations should be.

As a further example, we mention the status of scalars other than the glueball. We can study these in the channels

(a) $J/\psi \to \gamma +$ Scalar

(b) $J/\psi \to$ Vector + Scalar
$\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi\pi, KK, K\pi, \eta\pi$, etc.

(c) $J/\psi \to \gamma + \eta_c$
$\qquad\qquad\qquad \hookrightarrow$ Pseudoscalar + Scalar.

An interesting additional channel is $D_S^+ \to$ Scalar $+\pi^+$, which has been seen
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \hookrightarrow \pi^+\pi^-$

with very low statistics.[17] The scalar here should originate from $s\bar{s}$ quarks $\to \pi^+\pi^-$ below $K\overline{K}$ threshold, providing a specific flavor selection for looking at scalars.

Rates for these processes are quite good with product branching ratios for (b) of a few $\times 10^{-3}$ and for (c) of a few $\times 10^{-4}$. Thus 10^8 to 10^9 J/ψ decays would yield very large data samples. By looking for flavor correlations between the scalar and vector or pseudoscalar combinations, as expected approximately from the OZI rule, we could hope to discern a full multiplet pattern among the scalars. At present the choices for substructure for the scalars includes for some of these states, $K\overline{K}$ molecules, normal $q\bar{q}$ states with strong threshold effects, or four-quark states.[16]

Figure 14 shows some of the structures seen in presently available data for $J/\psi \to \phi + \pi^+\pi^-$ or K^+K^-. We expect naively to be seeing objects containing $s\bar{s}$ quarks decaying to $\pi^+\pi^-$ or K^+K^-. The data in the 1 GeV region are overlayed by various coupled channel solutions for the $\pi^+\pi^-$ and K^+K^-spectra. However,

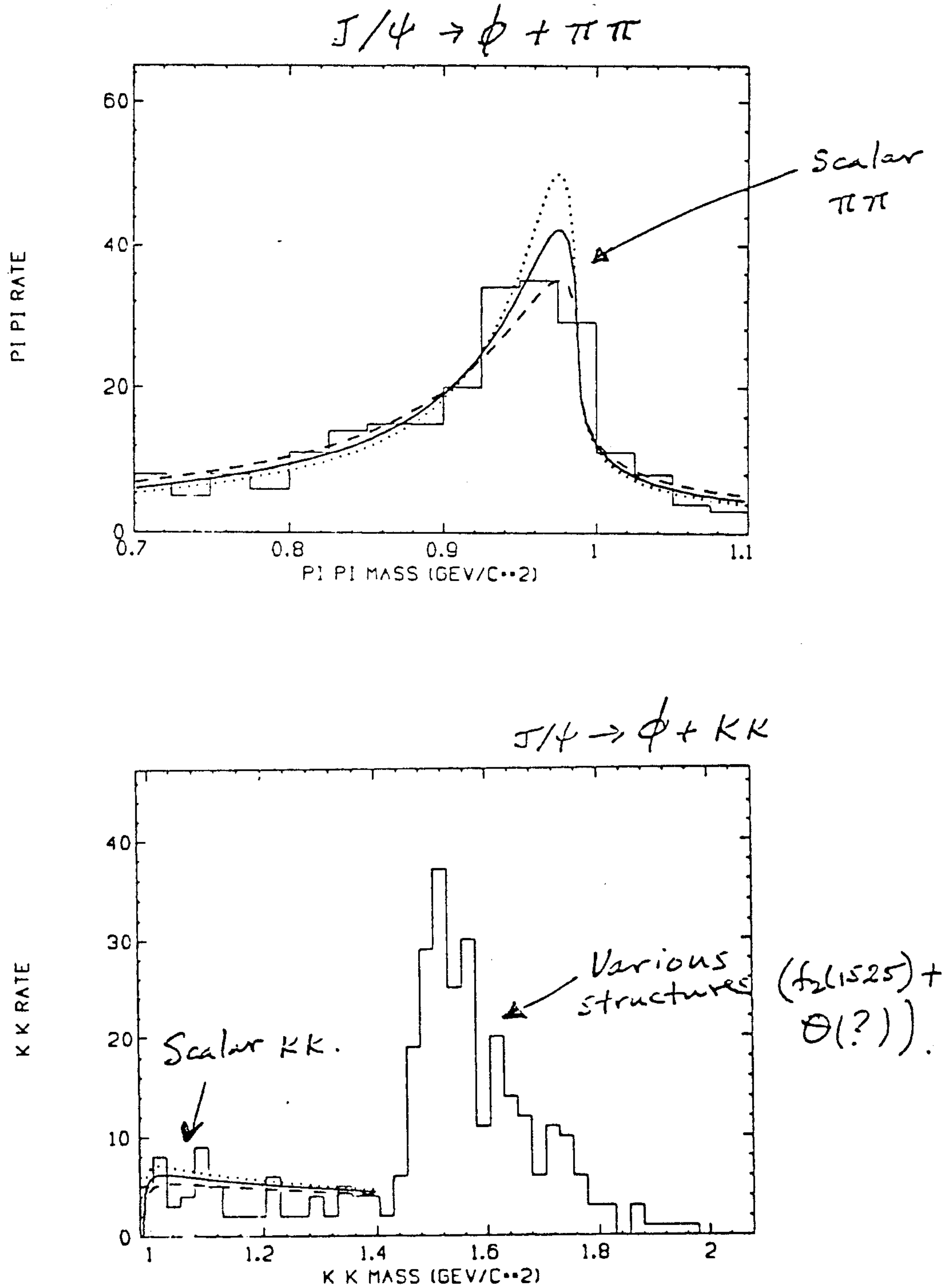

Fig. 14. Mass distributions for $\pi^+\pi^-$ and K^+K^- seen in $J/\psi \to \phi + \pi^+\pi^-$ or K^+K^-.

the data do not involve enough statistics to allow one to be sure what the spectral shapes are or even whether more than one state is present. Finally, the K^+K^- data show various interesting but poorly resolved structures in the region about 1.4 GeV. The $\pi^+\pi^-$ spectra (not shown) also show interesting, but different, structures in this higher mass region. Substantially larger data sets should allow measurements which can resolve these structure.

Finally, we expect a τ-charm factory to allow the remaining questions in the charmonium system to be answered. We list a few of these below.[18]

(1) Measure mass of the remaining states, ${}^1P_1$ and η_c'.

(2) Determine better the η_c properties.

(a) Check the $J/\psi \to \gamma\eta_c$ branching ratio.

(b) Measure the full width, Γ_{η_c}.

(c) Measure the two photon width, $\Gamma(\eta_c \to \gamma\gamma)$. For 10^8 J/ψ decays, we get 990 events of $\eta_c \to p\bar{p}$. The mass resolution of 5 MeV in this channel should allow us to measure Γ_{η_c} to better than 1 MeV. We also get 650 events of $\eta_c \to \gamma\gamma$. From the above two channels we can measure the product branching ratios

$$B(J/\psi \to \gamma\eta_c)\ B(\eta_c \to p\bar{p})$$
$$B(J/\psi \to \gamma\eta_c)\ B(\eta_c \to \gamma\gamma)$$

We expect that at Fermilab, the product branching ratio

$$B(\eta_c \to p\bar{p})\ B(\eta_c \to \gamma\gamma)$$

will be measured in an upcoming $p\bar{p}$ experiment. Combining with the above measurements, we can calculate each of the three branching ratios involved.

V. CONCLUDING SUMMARY

To summarize, we have collected together the primary physics goals of the τ-charm factory.

$\underline{\tau}$

Measure m_τ, $\delta m_\tau \simeq 0.3$ MeV and $m_{\nu_\tau} < 3$ MeV.

Interesting absolute branching ratios to $\frac{\delta B}{B} \sim \frac{1}{2}\%$

Parameters describing calculable distributions in Standard Model $\sim 1\%$.

Flavor violating decays $\sim 10^{-7}$ (same for D's).

Can calibrate backgrounds by moving below $\tau\bar{\tau}$ threshold.

$\underline{D}$

Measure $|V_{cd}/V_{cs}| \sim 5\%$, limited by theoretical uncertainties.

f_D, $f_{D_S} \sim$ similar accuracy.

Mixing value for $r_D \sim 10^{-5}$, if $r_D \gg 10^{-4}$ implies new physics.

CP violating asymmetries $\sim 10^{-3}$ to 10^{-2}.

Can check effects by using quantum statistics.

<u>QCD</u>

Finish measuring charmonium properties (e.g. $\psi \to 3\gamma$, $\eta_c \to 2\gamma$).

Continue (hopefully complete) glueball hunt!

Light quark spectroscopy: 0^+, 1^+ states, search for non-standard (non-$q\bar{q}$ states).

QCD for $\tau \to \nu_\tau +$ Hadrons; for D decays via $f_+(t)$ form factors, f_D and f_{D_S} values.

REFERENCES

1. J. Kirkby, "Issues of Tau-Charm Detector Design," these Proceedings.
2. M. Voloshin, talk given at workshop.
3. J.J. Gomez, these Proceedings.
4. F. Gilman and S.-H. Rhie, *Phys. Rev.* **31**, 1066 (1985).
5. W.J. Marciano and A. Sirlin, *Phys. Rev. Lett.* **61**, 1815 (1988).
6. These are discussed by Y.S. Tsai, W. Fetscher, J.J. Gomez, these Proceedings.
7. J.J. Gomez, these Proceedings.
8. B. Barish, these Proceedings; C. Heusch, these Proceedings.
9. H. Haber, these Proceedings.
10. M. Voloshin, talk given at workshop.
11. W. Bernreuther and O. Nachtmann, these Proceedings.
12. R. Schindler, these Proceedings.
13. See I. Bigi, these Proceedings; G. Gladding, these Proceedings; and U. Karshon, these Proceedings.
14. E. Braaten, these Proceedings; and A. Pich, these Proceedings.
15. B. Barish, these Proceedings; and A. Pich, these Proceedings.
16. These issues were discussed in the talks of W. Toki, N. Isgur, and F. Close, these Proceedings.
17. J.C. Anjos *et al., Phys. Rev. Lett.* **62**, 125 (1989).
18. R. Mir, these proceedings.