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DOE RESEARCH AND
DEVELOPMENT REPORT

TAU AND CHARM PHYSICS PROSPECTS AT CESR/DORIS AND B FACTORIES*

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Abstract

We review some of the recent results in tau and charm physics from ARGUS and CLEO, outline the tau and charm physics program at proposed asymmetric B Factories, focus on a few interesting measurements, and point out the some of the pros and cons of doing tau and charm physics at B Factories as opposed to threshold tau-charm factories.

1 INTRODUCTION

The high-statistics, high precision measurements of the properties of tau leptons and charmed mesons which are part of the τcF program will face stiff competition from B Factories, high-luminosity e^+e^- colliders operating in the region of the Υ resonances (*i.e.*, at $\sqrt{s} = 9 - 11$ GeV).

The main focus of B factories will be the study of decays of the B mesons produced via $e^+e^- \to \Upsilon(4S) \to B\bar{B}$, in particular, the observation of CP violation in B decays (which requires asymmetric energy beams, so that the $B\bar{B}$ system is moving in the laboratory). However, the high luminosity, precise detectors, and clean e^+e^- environment will also afford a rich program in tau and charm physics. Indeed, the only existing (symmetric) B Factory, the Cornell Electron-Positron Storage Ring (CESR), is already a major player in these fields.

The asymmetric B Factories (ABFs) now being planned are already in advanced design stages, and many workshops have been held around the world to establish their physics goals. This talk will provide a brief overview of these goals (in tau and charm physics), with some emphasis on a few particularly interesting measurements.

2 STATUS OF PROJECTS

It was announced last spring that the DESY Directorate had decided to discontinue data taking for the ARGUS experiment at DORIS, citing conflicts with HERA. ARGUS is still producing physics results with the data they have in hand, but we can no longer look forward to a steady stream of papers. That leaves only the CLEO detector at CESR as the remaining experiment studying e^+e^- collisions in the Υ resonance region.

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CESR is a true B Factory: in typical CLEO running, CESR delivers a peak luminosity $\mathcal{L} \geq 2 \times 10^{32}/cm^2/sec$, yielding $\sim$ 10 pb^{-1}/day or $\geq$1 fb^{-1}/year.

CESR is in the midst of an adiabatic upgrade of its facilities, including new RF cavities, better optics, injector upgrade, and new feedback systems. They hope to double the luminosity by the end of 1994. Later plans call for an increase in the number of bunches from 7 to 27 or 45, the addition of transverse feedback systems and superconducting RF cavities. The luminosity could approach 10^{33} by 1996.

2.1 Asymmetric B Factory Progress

There are active efforts proposing high luminosity B Factories (with the ultimate goal of observing CP violation in the B system) at SLAC (3/nb/s) [1], Cornell (3/nb/s) [2], KEK (10/nb/s) [3], as well as other efforts at Novisibirsk, DESY and CERN-PSI. All are asymmetric, require 2 rings, and many bunches to achieve luminosities in excess of $10^{33}/cm^2/sec$. Detailed designs for the accelerator and detector are already in rather advanced stages.

In the US, a joint "non-comparative" review by the Dept. of Energy (DOE) and National Science Foundation (NSF) of the SLAC and Cornell proposals was made during June. At present, the final site-selection and request to Congress for funding is on hold pending the decision on the SSC. LATE BREAKING NEWS: The DOE has selected SLAC as the site for a B Factory.

In Japan, groups are working towards government approval and funding of TRISTAN-II at KEK in 1994, and commissioning in 1998. They are holding a series of planning meetings in KEK.

Table 1 gives a comparison of B Factory design parameters (Ref. [4]).

3 CROSS SECTIONS AND RATES

At $\langle E_{cm} \rangle = 10.6$ GeV, the cross-section for $\tau^+\tau^-$production is $\sigma_{\tau\tau} = 0.92$ nb, and for $c\bar{c}$ production is $\sigma_{cc} = 1.30$ nb. CESR has been delivering >1/fb/year to the CLEO detector, corresponding to >0.9M $\tau^+\tau^-$, and >1.3M $c\bar{c}$ events per year. CLEO has already run for three years with this data rate.

We can crudely model the mix of "stable" charmed mesons and baryons from fragmentation of the $c\bar{c}$ jets as

$$D^+ : D^0 : D_s : \Lambda_c \sim 0.40 : 0.40 : 0.15 : 0.05 \tag{1}$$

Again crudely, 3/4 of all D's come from D^*'s, and 15% of all D's come from D^{**}.

With approximately 2 fb^{-1} of data analyzed (corresponding to 1.84 million produced $\tau^+\tau^-$ and 2.6 million produced $c\bar{c}$ events), CLEO-II reconstructs

Table 1: B Factory projects and design parameters.

Lab.	DESY	KEK	Novosib.	LBL-SLAC	CERN-PSI	Cornell
$\mathcal{L}$ ($10^{33} cm^{-2} s-1$)	3	10	5	3	1 - 10	3
Energy (GeV)	3 /9.3	3.5/8	4.3/6.5	3.1/9	3.5/8	3.5/8
$\beta^*(cm)$	1/2[1)]	1	1	1.5/3[1)]	1	1.5
Circumference (m)	2304	3018	714	2199	963	765
Emittance ϵ_x (nm)	50	19	5	50	90	130
separation plane	Vert.	Horiz.	Horiz.	Horiz.	Vert.	Horiz
Bunch dist. S_b (m)	3.6	0.6	4.2	1.3	3	3.3
I.P. elements[2)]	Q_1^*, Q_2^*, Q_3	B^*, Q_1^s	B^*, Q_1^s	B^*, Q_1^*, Q_2^*, Q_3^*	Q_1^s, Q_2^s, Q_3, Q_4	Q_1^s
Rings Position	Top	Side	Top	Top	Top	Side
Aspect ratio	flat	flat	flat	flat	flat	flat
Collision type	Head-on	Head-on	Head-on	Head-on	Head-on	Crab
Collision upgr.	none	Crab	Monochr.	Crab.	none	none
RF	n.c.	n.c.	n.c./s.c.	n.c.	s.c.	s.c.

1) *Different values of beta for low and high energy rings*

2) *Elements common to both beams; a * indicates a permanent magnet, a s a superconducting one*

- 6800 events $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$
- 3200 events $D^{*+} \to D^+\pi^0$, $D^+ \to K^-\pi^+\pi^+$
- 3000 events $D^{*+} \to D^0\pi^+$, $D^0 \to K^-l^+\nu$
- 1300 events $D_s \to \phi\pi^+$
- 6300 events $\Lambda_c \to pK^-\pi^+$
- significant signals for $D_1^{**}(2420)$, $D_2^{**}(2460)$, $D_s^*(2110)$, $D_{s1}^{**}(2536)$, $D_{s2}^{**}(2577)$
- significant signals for Ξ_c^0, Ξ_c^+, Σ_c^0, Σ_c^+, Σ_c^{++}

4 TAU PHYSICS PROSPECTS

Some of the interesting studies in the tau physics program at CLEO and future B Factories include:

- measurement of branching fractions at <1% level
- tau lifetime
- precision tests of Lorentz structure: ρ and η
- spin correlations and spin structure: ξ and δ
- tests of QCD from inclusive decays
- Cabibbo suppressed decays: $K(n\pi)\nu_\tau$

- rare decays, second class currents
- forbidden decays, lepton family number violation
- neutrino mass limit

This program is vast, and here we can only discuss a few select issues.

4.1 Tau Lifetime Measurement

The current world average on the tau lifetime [5] is $\tau_\tau = 296 \pm 3$ fs; *i.e.*, the error is about 1%. The world average is dominated by measurements done at LEP. It will be difficult to significantly improve on this at CESR, even with the new silicon vertex detector (SVD) that will be installed in CLEO in summer 1994, and even when employing all the various methods available [5]. The reason is simply that the average flight path is $\gamma\beta c\tau = 250\ \mu m$, while the e^+e^- interaction spot in the transverse (x and y) dimensions is $\sigma_{beam} \sim 500 \times 20\ \mu m$. In addition, the relatively low momentum of the tau decay products means that multiple scattering in the beampipe degrades impact parameter resolution significantly. Finally, methods using 3-prong decay modes are hampered by a significant hadronic background.

At an ABF, the situation will be somewhat better. A year of running would yield $N_{\tau\tau} = 30$M produced events; one expects to reconstruct some 6×10^5 events with the topology $l^\pm - vs. - 3\pi^\pm X$. The large boost will separate the 3-prong vertex from the lepton along the z axis. With an SVD consisting of both axial and z silicon microstrips, one could measure Δz with $\delta c\tau / c\tau \sim 0.2$, and the measurement would be independent of the e^+e^- interaction point. Monte Carlo studies [6] predict that one could measure τ_τ with a statistical error $< 0.2\%$ and with systematic errors from SVD geometry of $< 0.3\%$. The systematic errors from expected $q\bar{q}$ backgrounds are smaller still. Of course, these Monte Carlo estimates are probably idealized underestimates, but it may be realistic to expect $\sigma(\tau_\tau)/\tau_\tau < 0.5\%$ at an ABF.

4.2 Tau Branching Fractions

At present, the two of the most accurate single measurements of tau branching fractions are a 1.5% measurement of $\mathcal{B}(\tau \to e\nu\nu)$ [7] and a 2.2% measurement of $\mathcal{B}(\tau \to \rho\nu)$ [8] from CLEO, both of which are expected to improve shortly. Both of these measurements use the double-tagging technique, selecting events in which both taus decay to the signal mode. The branching fraction is determined from the square root of the number of events:

$$\mathcal{B} = \sqrt{(N_s - N_b) \,/\, (\mathcal{E}\mathcal{L}\sigma_{\tau\tau})} \tag{2}$$

so that many errors are halved. This same technique is now being applied at CLEO to the $\mu\nu\nu$ and $3\pi^\pm\nu$ modes.

CLEO also has the best measurements of the multi-π^0 modes $h^\pm\pi^0\pi^0\nu_\tau$, $h^\pm\pi^0\pi^0\pi^0\nu_\tau$, and $h^\pm\pi^0\pi^0\pi^0\pi^0\nu_\tau$, where $h^\pm$ stands for either a charged pion or kaon [9]. The $\pi^\pm n\pi^0$ mass distributions are shown in Fig. 1. Multi-π^0 modes will be discussed in greater detail below.

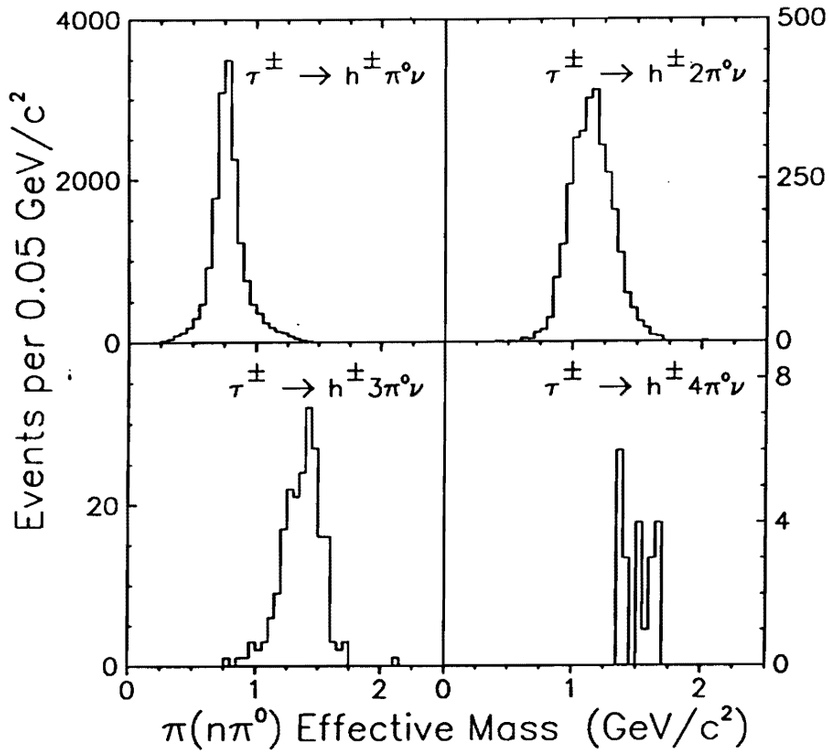

Figure 1: Invariant $\pi^\pm n\pi^0$ mass spectra, for $n = 1, 2, 3, 4$ from CLEO. The hatched histograms represent expected background.

Cabibbo-suppressed decays are most easily studied using events with well-identified charged $K^\pm$. Unfortunately, CLEO has poor $\pi^\pm/K^\pm$ separation over much of the momentum range of these particles in tau decay, so measurements of the particle-specific modes require model-dependent extrapolation. Thus, CLEO instead makes use of $K_S \to \pi^+\pi^-$ decays, or K^{*0} resonant peaks. This will change dramatically at B Factories; the CP violation physics there demands $\pi^\pm/K^\pm$ separation up to 4 GeV or more, and much work is being devoted to particle ID systems capable of that kind of performance.

The 1-2% errors on branching fractions for major modes at CLEO is entirely dominated by systematics; statistical errors are already less than 0.5%. These systematic errors, while not fundamental, are difficult to improve upon. One must rely on the accuracy of the Monte Carlo in simulating the decay kinematics, including all the radiative effects. The double-tag method depends on knowledge of the absolute cross-section, while the single-tag method measures products or ratios of branching fractions, not absolute branching fractions. But the most severe source of error is associated with extra showers in the crystal calorimeter which may come from beam-related backgrounds or interactions of the charged hadrons in the calorimeter. An example is the CLEO event shown

in Fig. 2. The presence of these showers makes it difficult to isolate an exclusive decay mode channel with well-defined efficiency and background rejection. No Monte Carlo at present will describe these extra showers with better than 1% precision.

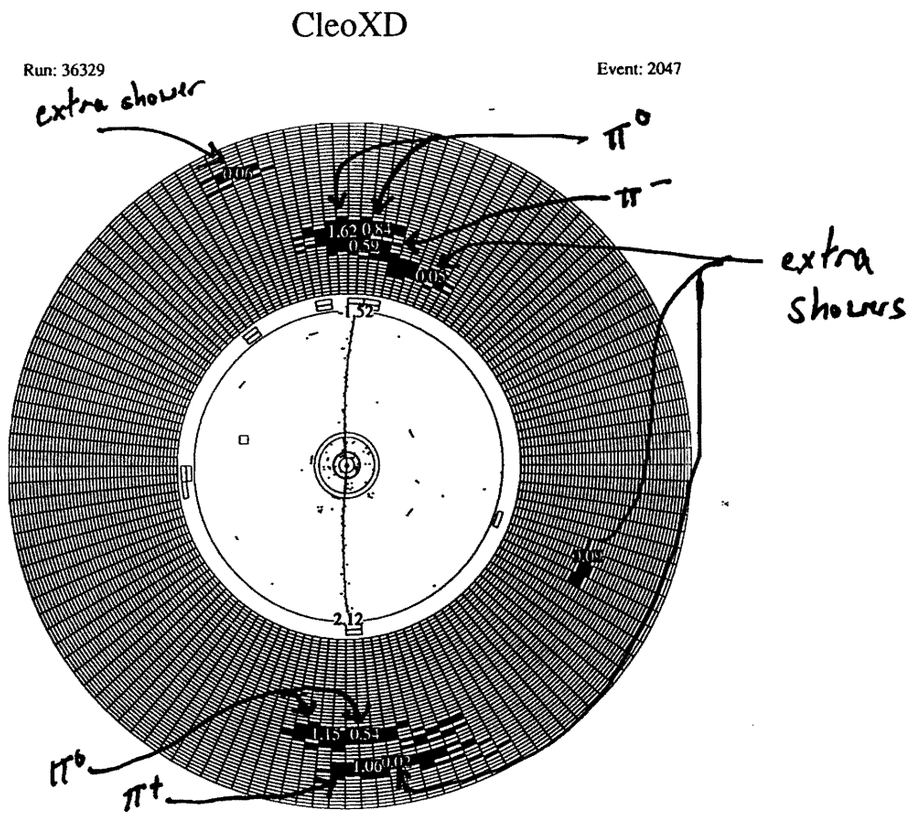

Figure 2: A $\tau^+\tau^-$ event from CLEO in which both taus decayed to $\pi^\pm\pi^0\nu_\tau$. The crystal calorimeter is shown in "tunnel" view: the outermost ring of boxes are the crystals at the $+z$ end of the calorimeter barrel, and the inner ring corresponds to the $-z$ end. Extra showers, produced most likely from the interaction of the charged pion in the calorimeter, are indicated.

4.3 Global Tau Branching Fraction Measurements

A particularly powerful and satisfying technique for measuring *all* tau decay branching fractions is to select an unbiased sample of tau decays (by tagging on the recoil tau decay) or $\tau^+\tau^-$ events, and then classifying the decay of each tau seen. These techniques have been employed by CELLO and Mark II in the $E_{cm} = 29-35$ GeV region and ALEPH at $E_{cm} = 91$ GeV.

Can such techniques be used at lower beam energies? Here is a partial list of pros and cons for doing global reconstruction at a τcF, a B Factory, an Asymmetric B Factory (ABF), or at LEP/SLC.

LEP + no bkgnd from non-$\tau^+\tau^-$, $\Rightarrow$ high efficiency unbiased sample

CLEO	$-$	lower trigger efficiency
CLEO	$-$	harder to separate $\tau^+\tau^-$ from backgrounds without bias
TCF	$-$	harder to separate $\tau^+\tau^-$ from backgrounds without bias
ABF	$+$	boost separates vertices: unbiased sample?
...		
LEP	$-$	lower statistics: $\sigma_{\tau\tau} = 1.5$ nb, $N_{\tau\tau} \simeq 50$K/expt and growing!
CLEO	$+$	high statistics: $\sigma_{\tau\tau} = 0.9$ nb, $N_{\tau\tau} \simeq 2$M and growing!
TCF	$+$	high statistics: $\sigma_{\tau\tau} \leq 4$ nb, or > 3 nb below ψ''
...		
TCF	$+$	below ψ'', isolated lepton or monochr. $\pi^\pm \Rightarrow$ unique tag
CLEO	$-$	always charm background, with fragmentation
ABF	$-$	boost, $\lvert\cos\theta\rvert < 0.95$ acceptance $\Rightarrow$ missing particles
...		
LEP	$-$	π^0's merge; hard to separate π^0 from $2\pi^0$
CLEO	$+$	high π^0 reconstruction efficiency, can separate π^0 from $2\pi^0$
TCF	$+$	high π^0 reconstruction efficiency *if* backgrounds permit
LEP	$+$	energetic π^0's stand out over noise, $h^\pm$ interactions
CLEO	$-$	π^0's not very energetic; γ's mix with noise, $h^\pm$ interactions
TCF	$-$	π^0's not very energetic; γ's mix with noise, $h^\pm$ interactions

The bottom line for doing global reconstruction at 10 GeV is that global analyses requiring unbiased samples are very difficult. To achieve the smallest errors, it is, at present, best to measure ratios of branching fractions, or normalize to $\sigma_{\tau\tau}$.

4.4 Tau Michel Parameter Measurements

The decay rate for the purely leptonic decays $\tau \to \nu_\tau l \nu_l$ can be described in terms of the Michel parameters, in direct analogy with muon decay. The shape of the charged lepton spectrum in the τ rest frame is governed by the Michel parameters ρ and η:

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx} = \frac{x^2\left[12(1-x) - \frac{4}{3}\rho(8x-6) + 24\eta\frac{m_l}{m_\tau}\frac{(1-x)}{x}\right]}{1 + 4\eta(m_l/m_\tau)} \tag{3}$$

with $x = E_l/E_{max}$ and $E_{max} = (m_\tau^2 + m_l^2)/(2m_\tau)$.

The precise values of the Michel parameters provide a test of the Lorentz structure of the decay. In the Standard Model, this structure is described by $V - A$ couplings at both the $\tau - \nu_\tau$ and $l - \nu_l$ vertices. In this case, $\rho = 3/4$ and $\eta = 0$. Small departures of the these parameters from their Standard Model value would be an indication of an admixture of $V+A$ structure from, *e.g.*, the right-handed $W^\pm$ of $L-R$ symmetric theories, or *scalar* structure from, *e.g.*, the charged Higgs of 2-Higgs doublet theories.

For example, a non-zero value for η could only come from some scalar or tensor coupling. The limit on η from muon decay is fairly stringent: $\eta = -0.007 \pm 0.013$; but if there is a charged Higgs, it will couple much more strongly to the more massive tau than to the muon, making the former a more sensitive test for its presence.

The best results on the ρ Michel parameter in leptonic tau decays comes from ARGUS 1990 [10]: $\rho_e = 0.747 \pm 0.045 \pm 0.028$ and $\rho_\mu = 0.734 \pm 0.055 \pm 0.027$. The data are shown in Fig. 3.

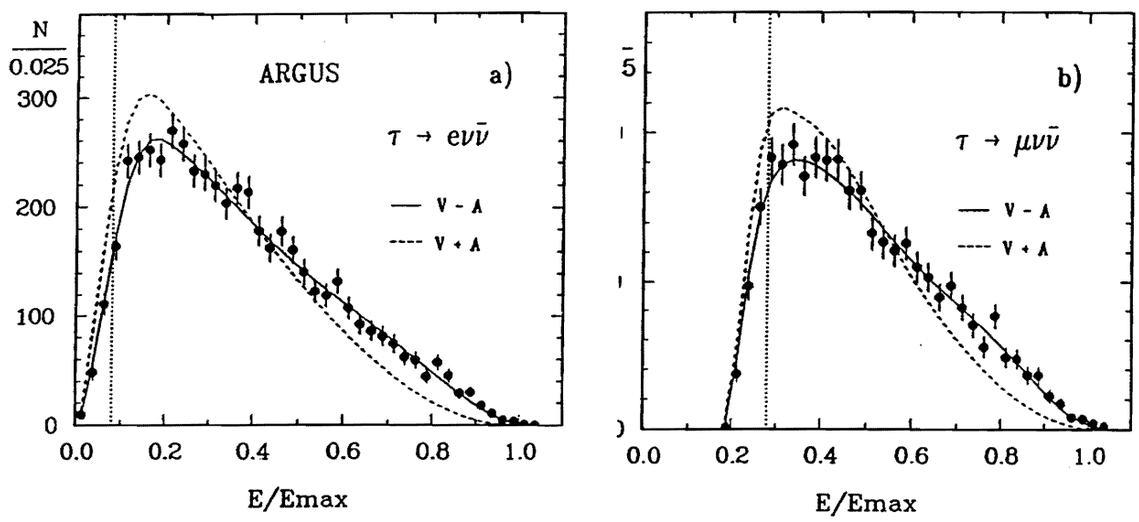

Figure 3: The spectra for the charged lepton in the decays (a) $\tau \to e\bar{\nu}_e\nu_\tau$ and (b) $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ (ARGUS data). The solid lines are fits to the spectra for the ρ parameter.

CLEO analyses are in progress, and we can expect statistical errors of half the ARGUS values with data already analyzed. Improvement on the systematic errors will be more difficult.

One can get a limit on η by considering the integral of Eqn. 3, *i.e.* the total branching fraction to $\nu_\tau\mu\nu_\mu$ and $\nu_\tau e\nu_e$. We have

$$\frac{\Gamma_\mu}{\Gamma_e} = \frac{0.9726}{1 + 4\eta(m_l/m_\tau)} \tag{4}$$

where the factor 0.9726 comes from phase space. World averages [11] give $|\eta| < 0.11$ at 95% C.L.

Measuring η directly is very difficult. The electronic decay $\nu_\tau e \nu_e$ is completely insensitive to η, so it must be measured in the $\nu_\tau \mu \nu_\mu$ mode. Most of the sensitivity comes from the low-momentum muons, which are difficult to distinguish from pions with current detectors. Furthermore, at $E_\tau = 5$ GeV, the Lorentz boosted lepton spectrum causes ρ and η to be strongly correlated.

Things will be a bit easier at an ABF, largely because a fine-grained hadron calorimeter will permit muon identification with high efficiency and low backgrounds down to low momenta; but the Lorentz boost will remain. A τcF will have a great advantage working near $\tau^+\tau^-$ threshold, where taus decay at rest in the lab. There will be no boost smearing the Michel spectrum, no backgrounds, near perfect particle ID, and good momentum resolution at low momentum.

4.5 Spin Polarization in τ Decays

Taus from Z^0 decay at LEP/SLC are polarized due to their different L, R couplings. Thus, tau decays have been used at LEP as "spin analyzers" to measure the Z^0 polarization, directly observing explicit parity violation on Z^0 pole. These beautiful measurements make use of the assumption that tau decays proceed via pure $V - A$ couplings.

Tau pairs produced via $e^+e^- \to \tau^+\tau^-$ below the Z^0 yields no net τ polarization, but QED predicts well-defined polarization (spin-spin) *correlations* [12]. At $E_{cm} = 10.6$ GeV, the spin polarizations of the tau pair are 95% *anti-correlated.* This fact has been used by ARGUS to test the $V - A$ "spin-analyzability" of tau decays.

The spin analyzing power of the decay charged lepton momentum spectrum in leptonic tau decays is described by the Michel ξ parameter. A generalization of Eqn. 3 gives

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx\,d\cos\theta} = \frac{x^2/2}{1+4\eta(m_l/m_\tau)}\left\{\left[12(1-x)+\frac{4}{3}\rho(8x-6)+24\eta\frac{m_l}{m_\tau}\frac{(1-x)}{x}\right]\right.$$
$$\left.\mp P\xi\cos\theta\left[4(1-x)+\frac{4}{3}\delta(8x-6)\right]\right\}, \qquad (5)$$

where ξ and δ are additional Michel parameters, P is the degree of polarization of the tau spin along its direction of motion in the lab, and $\cos\theta$ is the angle between the tau direction of motion and the daughter charged lepton direction. In semi-hadronic decay modes, the "spin-analyzer" parameter that plays the same role as ξ in leptonic decays is $h_{\nu_\tau} \equiv -\frac{2g_v g_a}{g_v^2+g_a^2}$, where g_v and g_a are the weak charged current vector and axial-vector couplings of the tau; in the $V - A$ theory, $h_{\nu_\tau} = 1$, corresponding to left-handed tau neutrinos.

At LEP, one *assumes* $\xi = 1$ and $h_{\nu_\tau} = 1$, then uses the daughter particle's x spectrum to measure P for taus from Z^0 decay. At ARGUS and CLEO, one *assumes* the P-correlations given by QED, and uses the correlated x spectra from the daughters of the two taus in each event to measure ξ and h_{ν_τ}.

ARGUS has used the momentum correlations in $\tau \to e\nu\nu$ versus $\tau \to \mu\nu\nu$ to measure [15]

$$\frac{d^3\sigma}{dp_e dp_\mu d\theta_a} = I(p_e, p_\mu, \theta_a) + \xi_{\tau\to e}\xi_{\tau\to\mu} \cdot A(dp_e dp_\mu d\theta_a) \tag{6}$$

Electron-muon universality requires the Michel parameter in both decays are equal: $\xi_{\tau\to e} = \xi_{\tau\to\mu} = \xi_\tau$. With this assumption, the ARGUS result is $|\xi_\tau| = 0.90 \pm 0.13 \pm 0.08$, in good agreement with the prediction from maximal parity violation in the leptonic weak charged current.

ARGUS has also directly measured h_{ν_τ} in semi-hadronic decays [13], demonstrating explicit parity violation in tau decays. Following a procedure outlined in Ref. [14], they exploited the interference in the decay $\tau \to \nu_\tau a_1$, $a_1 \to \rho\pi$ by forming the triple-product $\langle \hat{n}_{3\pi} \cdot \hat{p}_\tau \rangle = h_{\nu_\tau} A_{LR}(m^2_{3\pi})$, where $\hat{n}_{3\pi} = (\vec{p}_1 \times \vec{p}_2)/|\vec{p}_1 \times \vec{p}_2|$ is the normal to 3π decay plane, p_τ is τ direction in lab, estimated by $p_{3\pi}$, and A_{LR} is a function of $m^2_{3\pi}$ determined by the dynamics of the strongly-decaying $a_1 \to \rho\pi$. Combining data from both τ^+ and τ^- decays, shown in Fig. 4, they get $h_{\nu_\tau} = 1.25 \pm 0.23^{+0.15}_{-0.08}$, in good agreement with the $V-A$ prediction of $h_{\nu_\tau} = 1$.

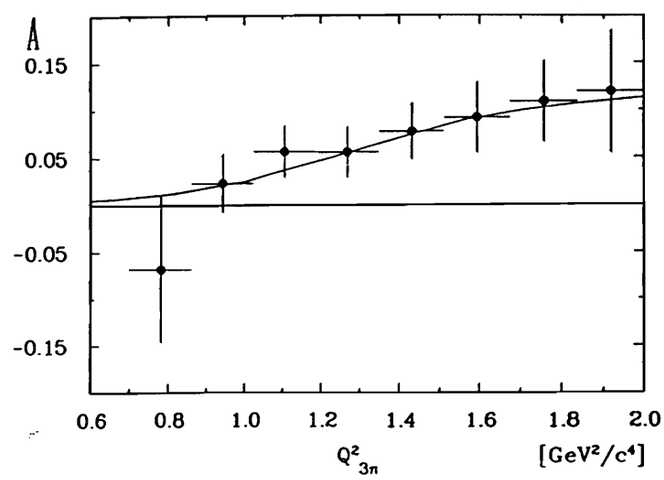

Figure 4: The parity violating asymmetry $A(m^2_{3\pi})$ for τ^- and τ^+ decays combined, measured in the ARGUS data. The solid line shows the predicted value for $h_{\nu_\tau} = 1.25$.

These are beautiful measurements, and they are direct confirmation of parity violation in tau decay; but they are not precise enough to restrict models! A more complete program is now being pursued by ARGUS and CLEO:

- use $e - v - \mu$ to measure $|\xi_{\tau\to e}\xi_{\tau\to\mu}|$
- use $e - v - \pi$, ρ, and a_1 to measure $\xi_{\tau\to e} h_{\nu_\tau}$
- use $\mu - v - \pi$, ρ, and a_1 to measure $\xi_{\tau\to\mu} h_{\nu_\tau}$
- use a_1 inclusive to measure h_{ν_τ}

This series of measurements is aimed at establishing the parity violating sign and magnitude of $\xi_{\tau\to e}$, $\xi_{\tau\to\mu}$, h_{ν_τ}, as well as δ_e and δ_μ, with sufficient accuracy to challenge models of physics beyond the Standard Model.

4.6 Neutrino Mass Measurement

The best limits on the mass of the tau neutrino have been obtained by studying the endpoint of the invariant mass distribution of the hadronic system X in the decays $\tau \to \nu_\tau X$, in particular systems for which the decay has small Q. Useful modes include $X = 5\pi^\pm$, $3\pi^\pm 2\pi^0$, and $KK\pi$. The present results are limited by statistics, since these small-Q modes have rather small branching fractions. The $KK\pi$ modes suffer both from low rate, and from low particle ID efficiency at CLEO.

The best limit is from ARGUS [16], which reconstructs 20 events in the decay $\tau \to \nu_\tau 5\pi^\pm$ and finds $m_{\nu_\tau} < 31$ MeV/c^2 at 90% C.L. CLEO II reconstructs 60 events in $\tau \to 5\pi^\pm\nu_\tau$ and 53 events in $\tau \to 3\pi^\pm 2\pi^0\nu_\tau$, using 1.7 fb^{-1} of data and very tight cuts to suppress background. Their result [17], shown in Fig. 5 is $m_{\nu_\tau} < 33$ MeV/c^2.

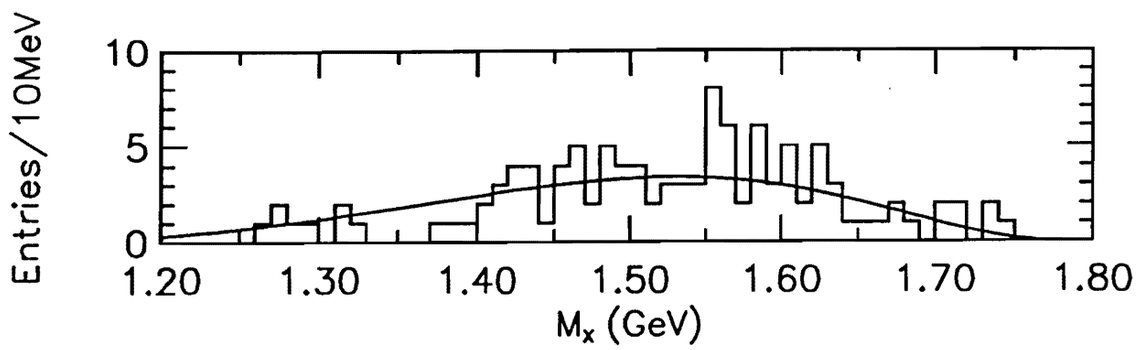

Figure 5: The invariant mass distribution for $5\pi^\pm$ and $3\pi^\pm 2\pi^0$ from $\tau \to 5\pi\nu_\tau$ in CLEO data. The curve is the prediction for $m_{\nu_\tau} = 0$.

The CLEO result can be extrapolated to what one might expect based on 30 pb^{-1} of data, using the $5\pi^\pm$ and $3\pi^\pm 2\pi^0$ decay modes. Barring one lucky event with $m_X \simeq m_\tau$, one can expect a limit on the order $m_{\nu_\tau} < 15 - 20$ MeV/c^2. A Monte Carlo study for the SLAC ABF projects a limit on the order of 5 MeV/c^2.

4.7 Rare Tau Decays

A most interesting class of tau decays forbidden in the Standard Model are decays that violate lepton family number, such as those which don't have a ν_τ amongst the decay products. This would be most easily seen in decays which have *no* neutrinos in the final state, so that all decay products are visible and reconstruct to the tau mass.

The decay $\tau^\pm \to \gamma\mu^\pm$ is a sensitive probe of physics beyond the Standard Model.

Such decays are predicted [18] in LR-symmetric models with Majorana neutrinos, and in superstring models. These models also predict rates for the decay $\mu \to \gamma e$, while recent results from PSI, TRIUMF and LAMPF give [19] $\mathcal{B}(\mu \to \gamma e) < 5 \times 10^{-11}$. This limit can be compared to the best limits from tau decays, from ARGUS 1992 [20]: $B(\tau \to \gamma\mu) \leq 3.4 \times 10^{-5}$, and CLEO II 1992 [21]: $B(\tau \to \gamma\mu) \leq 4.2 \times 10^{-6}$. Thus, the limits from tau decays are only competitive with the limit from muon decays if the models predict an enhancement for the more massive tau. In particular, models with mass-dependent couplings [22] predict an enhancement of order $(m_\tau/m_\mu)^5$, yielding $B(\tau \to \gamma\mu) \simeq 2 \times 10^5 B(\mu \to \gamma e) \leq 1 \times 10^{-5}$. The CLEO limit is already below this prediction.

Another important lepton family number violating decay is $\tau \to \ell\ell\ell$, where the final leptons are either $e^\pm$ or $\mu^\pm$. Decays like $\tau^- \to \mu^- e^+ e^-$ have FCNC at one vertex, while decays like $\tau^- \to \mu^+ e^- e^-$ have FCNC at two vertices. The best limit from muon decay is from SINDRUM 1985 [23]: $\mathcal{B}(\mu \to eee) < 2.4 \times 10^{-12}$. Once again, mass-dependent couplings give the interesting range for tau decays [24]: $\mathcal{B}(\tau \to \ell\ell\ell) \lesssim 3 \times 10^{-6}$. The newest results are beginning to probe this range: ARGUS 1992 [20] $\mathcal{B}(\tau \to \ell\ell\ell) < (15-20) \times 10^{-6}$; CLEO II 1993 [25] $\mathcal{B}(\tau \to \ell\ell\ell) < (3-8) \times 10^{-6}$, depending on mode, using 2M $\tau^+\tau^-$ events.

5 CHARM PHYSICS PROSPECTS

Some of the interesting studies in the charm physics program at CLEO and future B Factories include:

- measurement of D^+, D^0, D_s branching fractions at 1% level
- absolute branching fractions from $D^* \to D\pi$, $\quad D \to K\pi(\pi)$
- semileptonic decays of mesons and baryons, including measurement of heavy quark form factors and tests of HQET
- Cabibbo-suppressed and doubly suppressed decays
- non-spectator decay mechanisms
- leptonic decays $D^+, D_s^+ \to \mu^+\nu_\mu, \tau^+\nu_\tau$
- penguin annihilation $D^0 \to \mu^+\mu^-$
- $D^0 - \overline{D^0}$ mixing and CP violation
- charmed meson spectroscopy
- charmed baryon spectroscopy
- charmed baryon lifetimes
- rare and forbidden leptonic decays

- charm fragmentation at 10.6 GeV

5.1 Charmed Meson Absolute Branching Fractions

Some $\sim 60-80\%$ of all D^+, D^0, D_s^+ branching fractions are accounted for [11] in measured modes and easily predicted modes. Many poorly explored modes involve multiple π^0's, and $D_s \to \eta X$; thus good calorimetry is needed. Even for the simplest modes, the best precision on branching fractions is still at the $\sim 10\%$ level per experiment. Improvement requires both high statistics and techniques for making ***absolute*** measurements, as opposed to ratios of branching fractions. On the ψ'', one can measure absolute branching fractions by normalizing to luminosity times cross-section, neither of which are easy to understand at the few percent level. A better technique is to use double-tagging (*i.e.*, reconstructing both D's in $\psi'' \to D\bar{D}$), or forming an unbiased sample of single-tagged D decays.

CLEO is using a technique first used by HRS and ALEPH. D^0, D^+ mesons come more often than not from D^* decay. The slow pion π_s from $D^* \to \pi_s D$ has unique kinematics: for $p_{D^*} > 0.5 \times /E_{bm}$, $P_{\pi_s} \sim 250$ MeV/c, and small momentum with respect to the jet: $P_{t-jet} < 20$ MeV/c. Thus the angle α that the slow pion makes to the jet axis is strongly peaked at $\sin^2\alpha \simeq 0$. Pions from fragmentation rarely have both low momentum and very low $\sin^2\alpha$. These unique properties can be used to tag $D^* \to \pi_s D$ inclusively, giving a measure of the number of *produced* D^* mesons. One then exclusively reconstructs the D decay from a parent D^*, from which one obtains an absolute branching fraction.

This technique has been used at higher energy by HRS and ALEPH, but they have $b\bar{b}$ background; there is none at 10 GeV (D^*'s from B decays at the $\Upsilon(4S)$ have $p_{D^*} < 0.5 \times E_{bm}$ and $P_{\pi_s} \ll 250$ MeV/c). The largest systematic uncertainty comes from the momentum spectrum of the parent D^*'s, and the population of their polarization states. These must be known well in order to calculate the detection efficiency for the slow pion and the daughter D; but they can be measured with the data, leading to a systematic error on the order of $\sim 1\%$.

The latest CLEO result[26] is shown in Fig. 6, from which they obtain $\mathcal{B}(D^0 \to K^-\pi^+) = (3.91 \pm 0.08 \pm 0.17)\%$, *i.e.*, with 5% errors.

5.2 $D^0 - \overline{D^0}$ Mixing and CP Violation

The Standard Model predictions for $D^0 - \overline{D^0}$ mixing are strongly affected by non-perturbative QCD, and are not well determined. Defining

$$r_D \equiv \frac{D^0 \to \overline{D^0}}{D^0 \to D^0} = \frac{1}{2}\left[\left(\frac{\Delta M}{\Gamma}\right)^2 + \left(\frac{\Delta\Gamma}{2\Gamma}\right)^2\right] \tag{7}$$

the Standard Model predicts [27] $r_D \simeq 10^{-4}$.

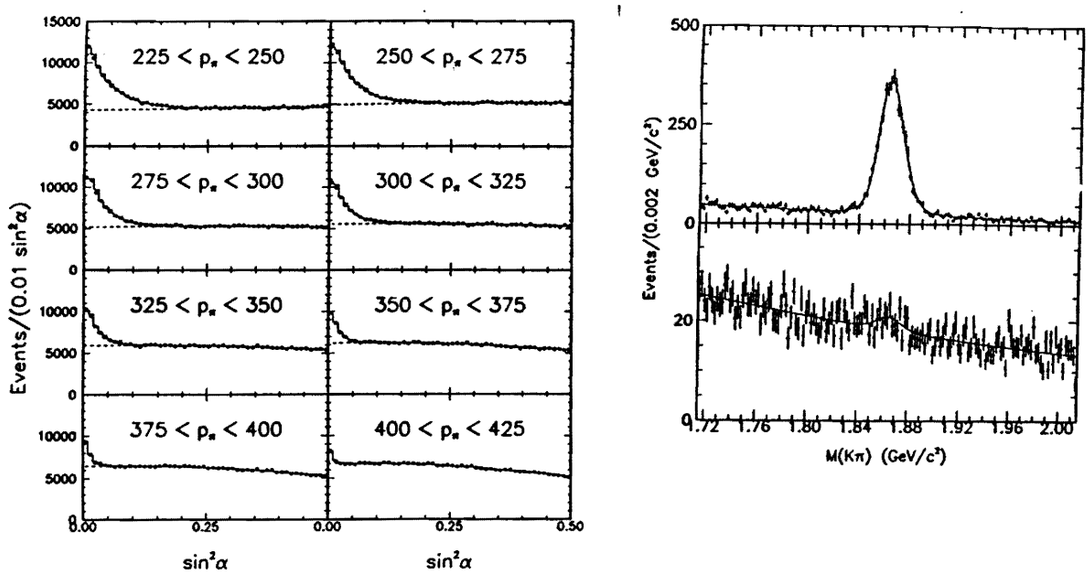

Figure 6: (a) The distribution of $\sin^2\alpha$ (see text) for pions in the indicated momentum ranges; the peak near zero is a measure of inclusive D^{*+} production. (b) The $K^-\pi^+$ mass peak for events with a slow pion π_s^+. and $M(\pi_s^+K^-\pi^+) \simeq M(D^{*+})$. (c) Same as (b), but $M(\pi_s^+K^-\pi^+) \neq M(D^{*+})$.

The cleanest signal for mixing is the observation of wrong-sign leptons from semileptonic D^0 decays, but wrong-sign kaons in hadronic decays are also useful. In that case, there is background from doubly-Cabibbo-suppressed decays (DCSD), but with different time dependence than in mixing. The time dependence of the decay rate is given by

$$I(D^0 \to K^+\pi^-) = e^{-\Gamma t}\left\{\frac{t^2}{4}\left[\Delta M^2 + (\frac{\Delta\Gamma}{2})^2\right] + \rho^2 + \rho t\frac{\Delta\Gamma}{2}\right\} \tag{8}$$

where ρ is ratio of amplitudes for the DCSD / Cabibbo-allowed decay.

At an ABF, one would use the decay $D^{*+} \to \pi^+D^0$ to tag the flavor of the daughter D^0, and then study the flight distance of D^0 to verify the expected time dependence and to separate mixing from DCSD. Monte Carlo studies [28] suggest that the precision tracking and vertexing of an ABF detector can be used to reduce backgrounds (in, *e.g.*, the $D^0 \to K\pi$ decay) to less than 1% of the signal. With 30 fb^{-1} of data, limits of $r_D < 6 \times 10^{-5}$ could be obtained. Using Eqn. 8, the study of the time dependent interference between DCSD and mixing will permit one to measure both ΔM and $\Delta\Gamma$.

Distinguishing $D \to K^-\pi^+$ from $K^+\pi^-$ requires good particle ID when the D decays at rest, since $m(K^-\pi^+) \simeq m(K^+\pi^-)$. At a B Factory, where D's are moving, the decay modes can be separated kinematically, at some level.

One can observe CP violation in D decays by measuring a difference in decay rates of the D^0 and $\overline{D^0}$ to CP eigenstates such as $\pi^+\pi^-$ or K^+K^-. Again using $D^{*+} \to \pi^+D^0$ tagging, with 30 fb^{-1} of data, we expect [29] 10,000 $D^0 \to \pi^+\pi^-$ decays and 20,000 $D^0 \to K^+K^-$ decays. Thus one can measure CP the violating asymmetry $\mathcal{B}(D^0 \to K^+K^-)/\mathcal{B}(\overline{D^0} \to K^+K^-)$ to 1%. Of course, the Standard Model prediction is $\ll$ 1%,

and hadronic corrections are large and uncertain. It is much easier to observe and interpret CP violation in B decay!

5.3 Charmed Meson Spectroscopy

The spectroscopy of charmed mesons and baryons is rich. An overview of the expected states is given in the Particle Data Book [11], pages III.68-71. Rates for reconstruction of various charmed mesons and baryons at CLEO and in one year of B Factory running are given in Table 2.

Table 2: Charmed meson (a) and baryon (b) reconstruction rates for CLEO 1.5, and projected for a B Factory.

		CLEO* 430 pb^{-1}		B Factory 30 fb^{-1}	
J^P	Decay Mode	S	S/B	S	S/B
2^+	$D^{**0}(2459) \to D^+\pi^-$	440	.15	15,000	.6
2^+	$D^{**+}(2471) \to D^0\pi^+$	§		7,000	. 3
1^+	$D^{**0}(2420) \to D^{*+}\pi^-$	300	.4	21,000	.4
1^+	$D^{**+}(2420) \to D^{*0}\pi^{+\dagger}$				
1^+	neutral $\to D^{*+}\pi^-$			21,000	.06
0^+	neutral $\to D^+\pi^-$			5,000	.02
2^+	D^0K^+, D^+K_s			22,000	5
1^+	$D_s^{**+}(2535) \to D^{*+}K_s$	30	5	2,100	5
1^+	$D^{*+}K_s$			22,000	.5
0^+	D^0K^+			670	.17

$1/2^+$ Charmed Baryons

	CLEO 430 pb^{-1}		B Factory 30 fb^{-1}	
Decay Mode	S	S/B	S	S/B
$\Lambda_c^+ \to pK^-\pi^+$	680	0.1	15,000	1
$\Lambda_c^+ \to pK_s$	122	0.5	9,000	.5
$\Lambda_c^+ \to \Lambda\pi$	90	0.7	6,000	.7
$\Lambda_c^+ \to \Xi^-K^+\pi^+$	33	3	2,000	3
$\Sigma_c^{++} \to \Lambda_c^+\pi^+$	54	0.6	1,500	~ 2
$\Sigma_c^0 \to \Lambda_c^+\pi^-$	48	0.4	1,200	~ 2
$\Sigma_c^+ \to \Lambda_c^+\pi^0$				
$\Xi_c^0 \to \Xi^-\pi^+$	18	4	1,300	4
$\Xi_c^+ \to \Xi^-\pi^+\pi^+$	24	1.2	1,700	1.2
$\Xi_c'^0 \to \Xi_c^+\pi^-$, $\Xi_c^0\gamma$				
$\Xi_c'^+ \to \Xi_c^0\pi^+$, $\Xi_c^+\gamma$				
$\Omega_c^0 \to \Omega^-\pi^+$			260	
$\Omega_c^0 \to \Xi^-\bar{K}^0\pi^+$			260	

The pseudoscalar D_s^+ meson is now seen in a dozen different modes by CLEO and ARGUS. The $L = 0$ vector mesons D^{*+}, D^{*0}, D_s^{*+}, are all well measured at 10 GeV; the D^* branching fraction world averages are completely dominated by the CLEO 1992 measurements [30]. The vector-pseudoscalar mass differences have been measured with high precision using CLEO's crystal calorimeter [31], including the recent result [32] $M(D_s^{*+}) - M(D_s^+) = 144.22 \pm 0.47 \pm 0.37$ MeV/c^2, and full width $\Gamma(D_s^{*+}) < 4.91$ MeV at 90% C.L.

The $L = 1$ mesons, D^{**}, D_s^{**}, are still being explored. There should be 12 states: $c\bar{u}$, $c\bar{d}$, $c\bar{s}$, each with $J_j^P = 0_{1/2}^+, 1_{1/2}^+, 1_{3/2}^+, 2_{3/2}^+$, where j is the total angular momentum of light quark. The mass splittings are due to the long-range (confinement) spin-orbit and tensor part of $c\bar{q}$ potential; it is of great interest theoretically to get accurate masses and spin assignments for these states. The $j = 3/2$ states are expected to be narrow (~ 20 MeV), while the $j = 1/2$ states are wide (> 50 MeV) and therefore difficult to distinguish

from non-resonant backgrounds. The $j = 3/2$ states have been seen by ARGUS [33] and CLEO [34] in $D^{**} \to D^{*}\pi$ with probable assignments $m(D_1^{**}) = 2420$, $m(D_2^{**}) = 2460$. Spin-parity analyses are just beginning [35].

ARGUS [36] and CLEO [37] observe $D_s^{**+} \to D^{*+}K_S^0$ and CLEO in $D^{*0}K^+$. The CLEO observation, shown in Fig. 7 yields $m = 2535.1 \pm 0.6$ MeV, $\Gamma < 2.3$ MeV, and J^P consistent with 1^+. We can expect to hear soon from CLEO on the D_s^{**+} $J^P = 2^+$ state.

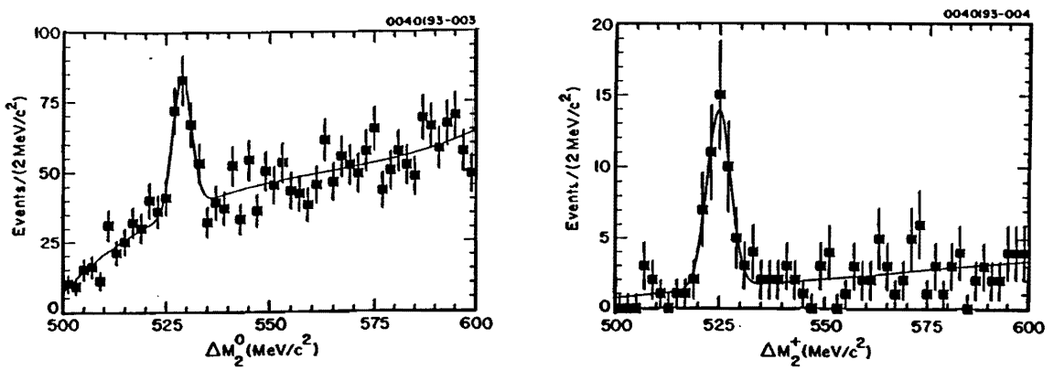

Figure 7: Evidence for the $D_s^{**+}(2535)$ in CLEO data. (a) The mass difference $M(K^+D^0\pi^0)-M(D^0\pi^0)$, when the $D^0\pi^0$ is required to be in the D^{*0} mass range; (b) The mass difference $M(K_S^0D^0\pi^+)-M(D^0\pi^+)$ when the $D^0\pi^+$ is required to be in the D^{*+} mass range. The D^0 is seen in the decay modes $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$. Charge-conjugate modes are included.

All these states are produced from $c\bar{c}$ and from B decay. To reduce combinatoric background, however, one usually requires high momentum D's coming from primary charm jets. In all cases, combinatoric backgrounds will be reduced at an ABF, where all decay vertices are separable, permitting reconstruction at lower momentum, *e.g.*, from B decay. In particular, one expects $B \to D^{**}l^+\nu$ to be very clean at an ABF.

5.4 Charmed Baryons

Of nine $J^P = 1/2^+$ singly charmed baryons, four decay weakly (Λ_c, Ξ_c^0, Ξ_c^+, Ω_c^0). Six have been observed by ARGUS and CLEO (Λ_c, Ξ_c^0, Ξ_c^+, Σ_c^{++}, Σ_c^+, Σ_c^0).

Many decay modes of the Λ_c have been observed by ARGUS [38] and CLEO [39]. Both experiments have measured parity violation in $\Lambda_c \to \Lambda\pi^+$, and CLEO in $\Sigma^+\pi^0$ decays. CLEO sees 14 modes, some of which are shown in Fig. 8, and the list is growing continuously. The semileptonic decays of the Λ_c are beginning to be explored, and parity violation has been measured there as well [40]. ARGUS and CLEO also see [41] the excited state $\Lambda_c^{*+}(2626)$.

$W^\pm$ annihilation (illustrated in Fig. 9) is not helicity suppressed in baryon decay, and it should dominate in $\Lambda_c^+ \to \Sigma^+K^+K^-$, Ξ^0K^+, $\Xi^{*0}K^+$, and $\Xi_c^0 \to \Omega^-K^+$ decays

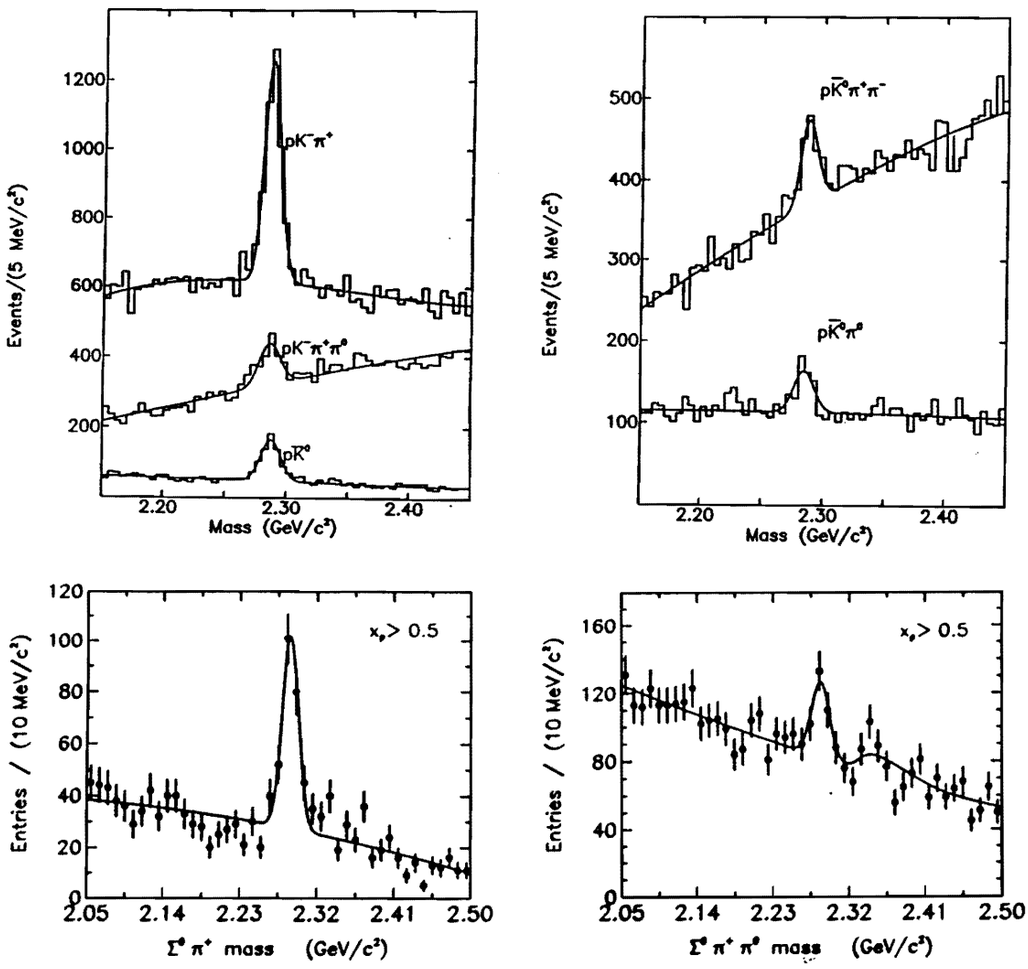

Figure 8: Some Λ_c^+ mass peaks from CLEO.

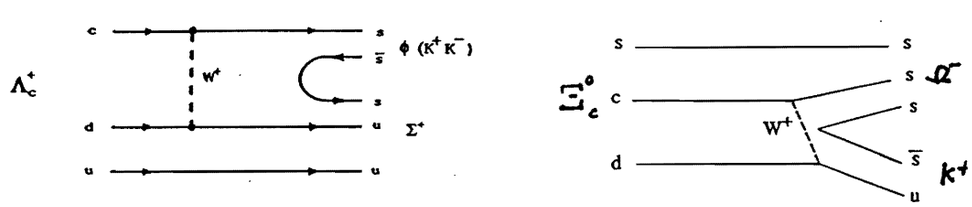

Figure 9: Feynman diagrams for charmed baryon decays mediated by $W^{\pm}$-annihilation. (a) $\Lambda_c^+ \to \phi\Sigma^+$; (b) $\Xi_c^0 \to \Omega^- K^+$. In both cases, the "spectator" d quark in the charmed baryon is not present in the decay products.

observed by CLEO and ARGUS.

All three Σ_c baryons have been seen, and their isospin mass splittings measured [42].

6 CONCLUSIONS

The tau and charm program at CLEO and at an ABF is very rich. The potential exists for several very precise measurements, stringent tests of the Standard Model, and the discovery of phenomena pointing beyond the Standard Model.

The techniques and capabilities are often complementary to those at a τcF, at LEP and SLC, and at fixed target experiments. With this multi-pronged "factory" approach, we can expect tremendous progress in tau and charm physics during the next decade.

7 ACKNOWLEDGEMENTS

I must first thank the hard working physicists of the CLEO and ARGUS collaborations for producing such a broad range of new measurements, making it easy to portray existing B Factories as successful tau and charm factories as well.

Secondly, I have drawn heavily from the proceedings of many B factory workshops at SLAC, Cornell, and KEK, and I thank all the participants in those workshops for their hard work and tenacity.

Finally, I must express my appreciation to the organizers of this Marbella workshop for providing us with incomparable surroundings to tempt us away from the workshop sessions.

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