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PHYSICS OF A HIGH LUMINOSITY COLLIDER OPERATED NEAR CHARM AND TAU PAIR THRESHOLDS

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The current plans for a high luminosity e^+e^- collider operated between 3.0 and 4.4 GeV/c^2 are described. Such a dedicated facility (The Tau-Charm Factory), operating near tau-pair and charm thresholds would allow studies of the decay of the third generation tau-lepton and the second generation c-quark with unprecedented precision and control of systematics. The charm physics of such a facility is discussed.

1. THE TAU-CHARM FACTORY

The Tau-Charm Factory design was first proposed by J. Jowett.[1] This design was the starting point for accelerator studies at the recent Tau-Charm Workshop.[2] Jowett's collider is a two ring machine operating between $\sqrt{(s)}$ = 3.0 and 5.0 GeV/c^2 and characterized by a high frequency (1.5 GHz) RF system driving 24 bunches with spacing $\sim 50ns$ and currents ~0.5 amps. Beams collide at a 0^0 crossing angle and are separated after the IP by 5 m long electrostatic plates. The β functions at the IP are $\beta_y^* = 1$cm and $\beta_x^* = 80$cm; with a vertical beam-beam tune shift ($\Delta\nu_y = 0.04$) the design achieves a luminosity L= 1.6×10^{33} sec^{-1} at about 5.0 GeV/c^2. Physics groups at the Workshop proposed a shift in the peak luminosity to 4.0 GeV/c^2. While optics, microbeta and separator schemes were verified or improved, the Workshop studies pointed to multibunch instabilities at high currents (associated with the "off the shelf" RF cavities chosen) and ion trapping in the e^- ring as problems. Emphasis was also placed on designs for dedicated injectors which allow operation with injection time optimized against beam lifetimes; this implies a collider with $L_{peak} \approx L_{avg}$.[3]

Table I. Charm and Tau Production

$\sqrt{(s)}$ (GeV/c^2)	Produced Species	Cross Section (nb)	Pairs Produced ($\times 10^{-7}$)
3.569	$\tau\bar{\tau}$	0.34	0.6
3.670	$\tau\bar{\tau}$	2.3	4.0
4.140	$\tau\bar{\tau}$	3.5	6.4
3.770	$D^0\bar{D}^0$	5.8	5.0
3.770	D^+D^-	4.2	4.0
4.028	$D_s\bar{D}_s$	0.7	1.2
4.140	$D_s\bar{D}_s^*$	0.9	1.6

2. CHARM AND TAU PRODUCTION NEAR THRESHOLD

Three distinct center of mass energies (3.770, 4.028, 4.140 GeV/c^2) are chosen for the study of charmed mesons and three energies for tau physics (3.569, 3.670, 4.14). We chose 5000 hours of fully efficient data taking as our definition of one running year.[4] Production rates are summarized in Table I.

The reasons for studying charm and taus at or near threshold are: the large and well measured σ_D, 5× to 10× greater than available at 10 GeV/c^2; the exclusive nature of production that *guarantees* low combinatorics backgrounds and production kinematics essential for background rejection and finally; the full knowledge of all physics backgrounds that is *independently* verifiable by small changes in $\sqrt{(s)}$. Running below threshold, provides information on backgrounds that otherwise introduce systematic uncertainties from the reliance on fragmentation Monte Carlos.

3. CHARM PHYSICS NEAR THRESHOLD

The second generation up-type quark, charm, may be the only quark for which Cabibbo allowed, singly Cabibbo forbidden, doubly Cabibbo forbidden and second order weak decays and perhaps even CP violation will be measurable.

The charm physics at the Tau-Charm Factory is organized along those lines, namely; weak hadronic decays (allowed thru doubly forbidden), pure and semi-leptonic decays (allowed and forbidden), rare decays and second order weak decays, and CP violating decays. *Only a*

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subset of these topics can be discussed here.

The unique kinematics of charm production near threshold coupled with detector improvements offers for the first time the ability to measure rare charm meson processes in a potentially background free environment. The primary technique employed is the ***single or double tagging*** method wherein one or both charmed mesons are *tagged* by reconstructing its mass; the recoil system is a-priori known to be another charmed meson with known charm and known 4-momentum, thus suppressing both non-charm and combinatorics backgrounds and allowing neutrinos to be *seen*.[5][6] Table II summarizes improved photon detection efficiency; a factor of two or more in D^0 and D^+ tagging may be possible. The D_s are so poorly known at this time, that major improvement over the 3% could be anticipated.

Table II. Established Single Tag Modes

Species	$\bar{\epsilon}$(%)	Tags/yr
D^0	12	1.2×10^7
D^+	7	5.5×10^6
D_s	3	8.3×10^5

3.1 Pure Leptonic Decays

Pure leptonic decays of the D are at present an unexplored area. The partial width for these decays is proportional to the product of the weak hadronic current (J_{had}) and the leptonic current (J_l). The axial vector current J_{had} is defined by the Van Royen - Weisskopf equation: $< 0 \mid J^{\alpha}_{hadronic} \mid D^+ >= iV_{cd}P^{\alpha} f_D$ in terms of the weak decay constant f_D. The weak decay constant f_D is thus a fundamental constant which characterizes the degree of overlap of the c and d quarks in the D and contains the QCD corrections which modify the $Wq\bar{q}$ vertex. To emphasize the interpretation, f_D can be written in terms of the wavefunctions of the heavy and light quarks: $f_D{}^2 \approx \frac{|\Psi(0)|^2}{M_D}$. A measurement of the leptonic decay of the D^+ or D_s provides an unambiguous determination of f_D or f_{D_s}:[7]

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

where M_D is the meson mass, m_μ the muon mass, V_{cd} the KM matrix element, G_F the Fermi constant, and τ_D the lifetime of the D^+.

Decay constants should scale like the square root of the inverse of the heavy quark mass (the $1/M_D$ term) times the reduced mass (μ_{cd}) to a power between one and two, ($\Psi(0)$ term). This $1/M_D$ dependence appears to be reproduced in Lattice calculations.[8] Thus, by measuring two distinct decay constants to adequate precision, say f_D and f_{D_s}, it should be possible to distinguish among models predicting their values, and reliably extrapolate to the B system for which precise measurements may never be obtainable. Table III summarizes the theoretical ranges.[9]

Table III. Estimates of Weak Decay Constants

Type	f_D	f_{D_s}	f_{B_d}	f_B/f_D
QCD SUM RULE	170-220	232-270	110-241	0.6-1.3
POTENTIAL	138-150	210-391	89-191	0.6-0.8
LATTICE	134-174	157-234	105-105	0.6-0.6
BAG	147	166	-	-

All the second order weak processes involving hadrons - such as $D\bar{D}$ and $B\bar{B}$ mixing involve box diagrams whose evaluation requires QCD corrections to J_{had}. The calculation of the B parameter is also related to the calculation of the f_D, since it amounts to the QCD corrections to the box diagram.

In a Tau-Charm Factory, the measurement of $D^+ \to \mu^+\nu$, and $D_s \to \mu^+\nu$ are simple.[10] Tagged events are sought containing only one additional muon, and with missing mass near zero. The pure leptonic decays $D_s \to \tau\nu$, with $\tau \to l\nu\nu$ or $\tau \to \pi\nu$ are also detectable although the monochromatic nature of the lepton and the missing mass constraint are lost. We rely on the tagging, hermeticity of the detector for photons, and the K_L^0 rejection. All neutral D_s decays are assumed to be *independently measured* before interpretation of the result.

Fig. 1 shows an estimate for the number of reconstructed events in the three charmed meson channels. We measure f_D and f_{D_s} to a few percent; $D_s \to \tau\nu$ can be reduced to a statistical error of about 1%.

3.2 Semileptonic Decays and KM Parameters

At the present time, knowledge of the KM matrix in the first two generations is restricted to precision measurements in the first row alone; V_{ud} and V_{us} are measured at the 0.1% and 1% level, respectively. Measurements in the charm row are only at the $\sim 20\%$ level now,

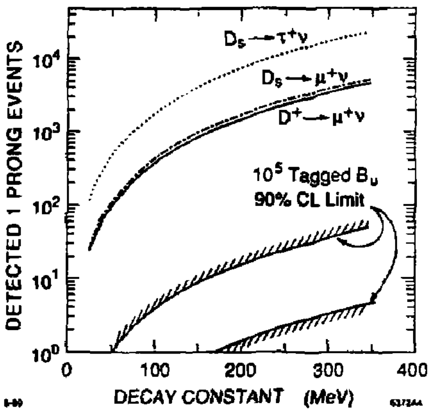

FIGURE 1

Detected pure leptonic events. Dotted ($D_s \to \tau\nu$), Dot-Dashed ($D_s \to \mu\nu$), Solid ($D^+ \to \mu\nu$), Limit region for $B \to \tau\nu$ based on 90% CL values of V_{bu}.

dominated by statistics systematics:

$$| V_{cd} |^2 = 0.058 \pm 0.014 \qquad \text{(CDHS)}$$

$$| V_{cs} |^2 = 0.530 \pm 0.080 \pm 0.060/f_+(0)^2 \text{(MKIII)}$$

$$| V_{cs} |^2 = 0.590 \pm 0.070 \pm 0.090/f_+(0)^2 \text{(E691)}$$

$$| \frac{V_{cd}}{V_{cs}} |^2 = 0.057^{+0.038}_{-0.015} \pm 0.005 \qquad \text{(MKIII)}$$

After leptonic decays, the Dl_3 decays are the next level of difficulty for theoretical interpretation. The partial width for Dl_3 decays involves two form factors $f_+(q^2)$ and $f_-(q^2)$. The latter, multiplied by m_l^2 is normally dropped, leaving: $\Gamma_l \approx \frac{G_F^2}{16\pi^3} M_D{}^5 | V_{cs} |^2 \int | f_+(q^2) |^2 (2x_e - 2x_K x_e - x_e{}^2 - 1 - \lambda^2)$. In the simplest picture, $f_+(q^2)$ is represented as a simple pole, with one normalization constant $f_+(0)$: $f_+(q^2) = f_+(0)\{\frac{M^2_{pole}}{M^2_{pole} - q^2}\}$.

Measuring Dl_3 decay rates and the q^2 dependence of the f_+ in D and D_s it is possible to extract $V_{cd} \times f_+(0)$ and $V_{cs} \times f_+(0)$. Because SU(4) is a badly broken symmetry, $f_+(0)$ deviates strongly from unity (unlike in the kaon system). Reliance on theory is imperative to extract the KM parameters. Ratios of rates will yield ratios of KM parameters with the form factor uncertainty reduced to the SU(3) breaking level only ($\approx 5\%$). The theoretical values for $f_+(0)$ come from potential models, QCD sum rules, and lattice calculations and range from 0.58 to 0.75.[11] Fig. 2 shows the power of kinematics to isolate Cabibbo allowed and suppressed decays with missing mass.

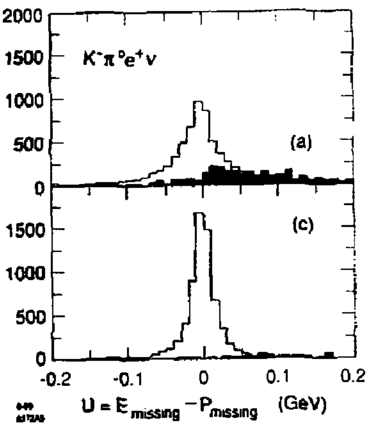

FIGURE 2

(a,c) Cabibbo allowed semileptonic decay. (Low and high resolution calorimeters)

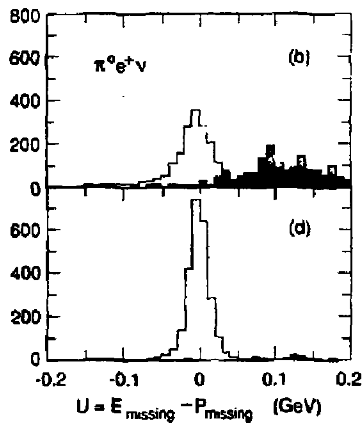

FIGURE 2

(b,d) Cabibbo suppressed semileptonic decay. (Low and high resolution calorimeters)

In Dl_4 decays four form factors appear; another vector ($V(q^2)$) and three axial vector ($A_0(q^2), A_1(q^2)$, and $A_2(q^2)$). One, $A_2(q^2)$, is inaccessible, being multiplied by m_l^2. If adequate statistics ($\sim 10^5$) are obtained, measuring the Dl_4 rates and the q^2 dependence of the form factors allows one to determine their relative values and hence V_{cd} or V_{cs} up to a single constant.

In Table IV estimates of the expected rates for the numerous channels in the spectator type semileptonic decays that are accessible to a Tau-Charm Factory.[12]

Table IV. Detection of Semileptonic Decays

$D^0 \to$	BR	# DET/yr
$K^- e^+ \nu$	0.034	0.29×10^6
$K^{*-} e^+ \nu$	0.060	1.53×10^5
$\pi^- e^+ \nu$	0.004	0.37×10^5
$\rho^- e^+ \nu$	0.004	0.16×10^5
$D^+ \to$		
$\bar{K}^0 e^+ \nu$	0.07	0.11×10^6
$K^{*0} e^+ \nu$	0.05	1.99×10^5
$\pi^0 e^+ \nu$	0.004	0.14×10^5
$\rho^0 e^+ \nu$	0.0025	0.13×10^5
$\omega e^+ \nu$	0.0025	0.55×10^4
$D_s \to$		
$\eta e^+ \nu$	0.02	0.67×10^4
$\phi e^+ \nu$	0.034	0.44×10^4
$K^0 e^+ \nu$	0.002	0.47×10^3
$K^{*0} e^+ \nu$	0.0013	0.45×10^3

In the next generation of experiments before Tau-Charm, the KM parameters may be driven down below the 10% level by improved statistics. It remains unclear that a sufficiently systematic and background free set of measurements will become available to resolve theoretical uncertainties significantly beyond their present values, thereby preventing truly precise determinations at the level of $\sim 1\%$; the goal of the Tau-Charm experiments.

With the sensitivity suggested in Table VI, it is clear that the Tau-Charm Factory can also provide information on states not accessible through semileptonic spectator graphs (see Fig. 3) such as $D \to gg l \nu$ and resonant $D \to (\text{glueball}) l \nu$. The couplings to the $\eta \prime$, the θ and the iota, in a semileptonic decay may provide new insights into their gluonic makeup. Branching fractions as small as $\sim 10^{-3}$ will produce 10's of detected (background free) events in these channels.

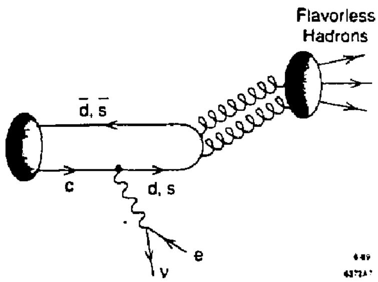

FIGURE 3

Examples of non-spectator semileptonic decay.

3.3 Rare D Decays

Experimental tests of extensions to the Standard Model (SM) require the observation of new particles or their manifestations. Bigi argues[13] that such extensions with new scalars or vector bosons (**Y**) (Fig. 4), have

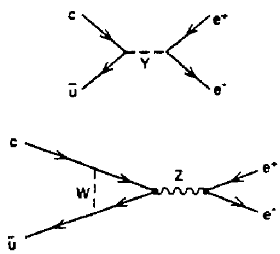

FIGURE 4

Examples of flavor changing neutral currents involving new scalars or vectors.

rates scaling like: $B(D \to l^+ l^- X) \propto \frac{g_{qY}^2 \times g_{lY}^2}{M_Y^4}$. Flavor changing neutral currents in the SM (ie: lepton family number violating decays, LFNV), are forbidden to all orders. Any observed non-zero rate signals the onset of New Physics. Examples are D^0 or $D^+ \to e^+ \mu^- X$, where X is a light hadron. Lepton family number conserving decays (LFNC) can be simulated by effective FCNC, allowed in the SM *only* through higher order weak and/or electromagnetic processes. The simplest examples of such are D^0 or $D^+ \to l^+ l^- X$. These one-loop induced

FCNC are most susceptible to New Physics. They compliment all searches in the down quark sector because the couplings to new particles may *a priori* be flavor dependent, either through mass-dependent couplings or through mixing angles.

All of these classes of decays are expected to occur at rates $\leq 10^{-7}$ in the SM.[14] This occurs because of the need for quark annihilation ($\sim f_D^2/M_D^2$) in the D, and in the case of two body decays, a reduction from the helicity suppression ($\sim M_l^2/M_D^2$) associated with the lepton chirality. Estimates are that long range effects may bring the SM allowed processes up in rate to 10^{-6} to 10^{-7}. If that is so, then sorting New Physics from Old requires the measurement of the full pattern of rare decays.

When helicity suppression is factored out of current limits, (all are at the few $\times 10^{-4}$ level[15]) the mass reach of these is ~0.2 TeV (choosing unit couplings for g_{qY} and g_{Yl}). The Tau-Charm factory brings these into the TeV range for the helicity suppressed class decays. The non-helicity suppressed channels will provide sensitivity to the ~ 20 to 200 TeV scale (see Table V).[16]

Table V. Sensitivity to Rare Decays

Channel	Estimated Background	Limit at 90% CL	Signal at 5σ
$D^0 \to e^+e^-$	$\leq$0.2 evts	3×10^{-8}	6.0×10^{-8}
$D^0 \to \mu^+e^-$	$\leq$1.3 evts	5×10^{-8}	1.2×10^{-7}
$D^0 \to \mu^+\mu^-$	$\leq$10. evts	8×10^{-8}	2.9×10^{-7}
$D^0 \to \rho^0e^+e^-$	$\leq$1.6 evts	4×10^{-8}	1.3×10^{-7}
$D^0 \to K^0e^+e^-$	$\leq$1.5 evts	2×10^{-7}	7.3×10^{-7}
$D^0 \to \nu\bar{\nu}$	$\leq$22. evts	-	8.0×10^{-6}

In addition to rare decays in the previous class, there are also ordinary radiative decays and Penguin - type hadronic and radiative decays. The hadronic decays lead to ordinary Cabibbo suppressed final states, and thus present a problem in untangling them from much larger "ordinary" physics.[17] The electromagnetic Penguins are GIM suppressed[18] to a level of $O(10^{-8})$: $A \sim \frac{(m_s^2-m_d^2)}{M_W^2}$. Rescattering processes (long range effects) may however enhance the electromagnetic graphs to a level of $O(10^{-5})$. Furthermore, a number of recent calculations suggest that QCD radiative corrections may enhance the Penguin graph even further.[19] At a level of 10^{-5}, decays like $D^+ \to \gamma\rho^+$ should be easily detectable in the Tau-Charm Factory.[20] The importance of seeking Penguins in charm decay where the tree graph is very small is to establish the strength of long range rescattering and QCD radiative corrections. Both these "corrections" must exist for B decay, and in fact may *dominate* the more interesting t-quark contribution. Thus, if the class of Penguin decays is found in D decay to be large ($O(10^{-5})$), it may be impossible to unambiguously resolve the t-quark contribution to electromagnetic-penguin B decay.

3.4 Mixing and Doubly-Suppressed Decays

In the SM, $D^0\bar{D}^0$ mixing is a second order weak interaction occurring either through the box diagrams or through long distance effects.[21] The mixing parameter r_D is defined as the ratio of the number of events exhibiting mixing to the number of events not exhibiting mixing. In an experiment not measuring time-evolution, but integrating over time, r_D is related to the mass matrix parameters ΔM, $\Delta\Gamma$ and Γ: $r_D = \frac{(\frac{\Delta M}{\Gamma})^2+(\frac{\Delta\Gamma}{2\Gamma})^2}{2}$. Box contributions to r_D are expected to be small $r_D \leq 10^{-6}$ because of GIM cancellation. Long range contributions to r_D, which are also second order weak, from ΔM and $\Delta\Gamma$ may be equal in magnitude and each as large as $\sim$ few $\times\ 10^{-2}$.

At this large a level, one of the main experimental backgrounds leading to "mixing like" final states comes from doubly Cabibbo suppressed decays (DCSD). Having branching fractions of $O(\tan^4\theta_c) = 0.003$), these decays may dominate a mixing signature. In the absence of time-evolution information, it has been suggested by Bigi[18] that a set of measurements at two or more energies can be used in conjunction with quantum statistics, to sort out mixing from doubly Cabibbo suppressed decays or New Physics. It is also possible using the interference term, to measure $\frac{\Delta M}{\Gamma}$ and $\frac{\Delta\Gamma}{\Gamma}$ separately. This is illustrated in Table VI where two sets of measurements are made. First, final states where both D^0 mesons decay semileptonically (thereby eliminating DCSD background), and second, where both decay hadronically, but to identical final states. In that case, Bose statistics forbids DCSD when the D^0 mesons are in an relative l=1 state. When the D^0 are in an l=0 state, then mixing and DCSD interfere, allowing a measurement of both.

The quantity $\hat{\rho}$ is defined by Bigi's convention: $\hat{\rho} = \frac{1}{\tan^2\theta_c}\frac{\Gamma(D^0\to K^+\pi^-)}{\Gamma(D^0\to K^-\pi^+)}$. The doubly Cabibbo suppressed amplitudes can be measured in parallel with tagged events (see below).

At a Tau-Charm Factory our preliminary analysis suggests that we can reconstruct at the $\psi(3770)$, in ex-

Table VI. Establishing Mixing and DCSD

$e^+e^- \to$	No Mixing Signature No New Physics	Mixing Signature
	$\frac{K^\mp\pi^\pm K^\mp\pi^\pm}{K^-\pi^+K^+\pi^-}$	
$D^0\bar{D}^0$	0	r_D
$D^0\bar{D}^0\ \gamma$	$4tan^4\theta_c \mid \bar{\rho} \mid^2$	$3r_D + 8(\frac{\Delta\Gamma}{2\Gamma})tan^2\theta_c\hat{\rho}$ $+4tan^4\theta_c \mid \hat{\rho} \mid^2$
$D^0\bar{D}^0\ \pi^0$	0	r_D
	$\frac{K^\mp l^\pm K^\mp l^\pm}{K^\mp l^\pm K^\pm l^\mp}$	
$D^0\bar{D}^0$	0	r_D
$D^0\bar{D}^0\ \gamma$	0	$3r_D$
$D^0\bar{D}^0\ \pi^0$	0	r_D

cess of 1.80×10^5 events in the two categories of Table VI.[22] Backgrounds appear to be reducible by a combination of detector particle identification and kinematic constraints. At any of the higher energies suggested (4.03 or 4.14 GeV/c^2), similar numbers of events should be reconstructible. One study has been done to verify this conclusion.[23] Similar studies using $D^{*+} \to \pi^+ D^0$ have also been done.[24] This implies that $D^0\bar{D}^0$ mixing should be *measurable* at the level of $r_D \approx 10^{-4}$, and unambiguously *observable* at the level of $r_D \approx 10^{-5}$ by several independent techniques.

A clear understanding of doubly Cabibbo suppressed decays can be reached by measuring D^+ decays, where the signature is not confused by a mixing component present in D^0 decays. D^+ doubly Cabibbo suppressed decays have an added attraction, because unlike allowed D^+ decays, they do not suffer from interference effects, and hence may be significantly enhanced. This was first noted in ref. 18. At the present time, no experiment has yet reported clear evidence for D^0 or D^+ DCSD. One of the severe experimental problems is the kinematic reflection from non-suppressed decays. Table VII. gives estimates for our sensitivity (see ref. 20).

4. CONCLUSIONS

The Tau-Charm Factory combines a high luminosity collider and dedicated injector to optimize $L_{avg}=L_{peak}$. Experience from previous generations of detectors at SPEAR, suggests that a new detector that marries highly efficient, fine-grained electromagnetic calorimeter to a precision low mass tracker would provide a significant

Table VII. Double Cabibbo Suppressed D^+

Channel $D^+ \to$	$\tan^4\theta_c$ coeff.	Events Detected
$K^+\pi^0$	0.02	142
$K^+\omega$	0.01	56
$K^+\rho^0$	0.07	498
$K^{*0}\pi^+$	0.06	232
$K^{*0}\rho^+$	0.01	42
$K^{*+}\pi^0$	0.05	106
$K^+\pi^-\pi^+$	0.07	512

improvement in the efficiency for tagging charm and tau events over earlier detectors. Coupled with a redundant particle identification systems and a unique hermetic hadron (K_L^0) veto system, the facility should probe the region of physics of charm and tau decays with unprecedented precision and control of systematics, lying ~ 3 orders of magnitude below our present level

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