PRECISE MEASUREMENT OF CHARM MESON LIFETIMES USING THE NEW CLEOII SILICON VERTEX DETECTOR

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We present preliminary results of the measurement of charm meson lifetimes. This is the first measurement using the new CLEOII silicon vertex detector and it serves as a calibration measurement to explore the detector's capabilities in charged particle tracking. We obtain the following lifetimes which are in good agreement with the current PDG averages.

$$\tau_{\mathrm{D}^0} = 0.403 \pm 0.009 \text{ (stat.) } {}^{+0.007}_{-0.011} \text{ (syst.) ps}$$

$$\tau_{\mathrm{D}^+} = 1.034 \pm 0.033 \text{ (stat.) } {}^{+0.033}_{-0.038} \text{ (syst.) ps}$$

$$\tau_{\mathrm{D}_s^+} = 0.475 \pm 0.024 \text{ (stat.) } {}^{+0.025}_{-0.025} \text{ (syst.) ps}$$

1 Introduction

In the coming years, silicon vertex detectors will play a crucial role in heavy flavor physics analyses at the $\Upsilon(4S)$ resonance. The high resolution three-dimensional coordinates provided by these detectors will allow unprecedented track trajectory precision. As a result of this precision, an efficient charm-tag (or veto) using a decay length based topology will be possible, even in the multiple scattering limited $\Upsilon(4S)$ environment.

At the end of 1995 the CLEOII detector[1] was upgraded with a Silicon Vertex Detector[2] (SVX) becoming CLEOII.V. The SVX is the first multi-layer silicon vertex detector operated at the $\Upsilon(4S)$ and is regarded as the prototype for similar detectors currently under construction for CLEOIII[3], BaBar[4] and Belle[5].

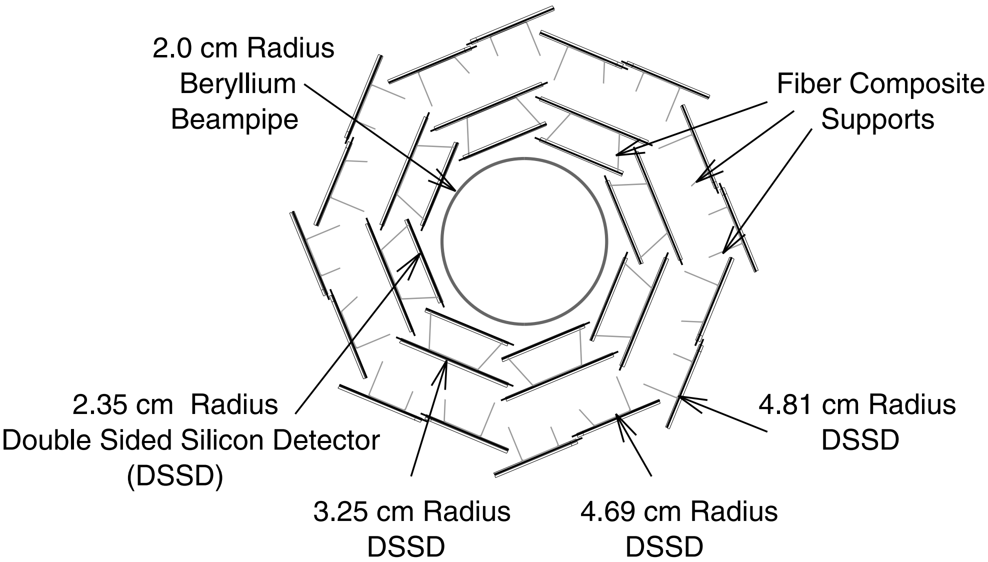

Figure 1: View of the CLEOII.V silicon vertex detector in the $r\phi$ plane.

The SVX (see Fig. 1) consists of three concentric layers of 300 μm, double-sided silicon strip detectors to measure $r\phi$ and z track coordinates. The three layers are at radii of 2.35, 3.25 and 4.7 cm. Together with a beryllium beam pipe at 2.0 cm radius the SVX represents 1.8 % of a radiation length. The average signal to noise ratio is about 10:1 and the efficiency for having at least two silicon hits in both coordinates is 95 % per track. The measured impact parameter resolutions as function of momentum p are

$$\sigma_{r\phi} = 24 \oplus \frac{42}{p\ [\mathrm{GeV}] \sin^{3/2}\theta}\ \mu\mathrm{m} \quad \text{and} \quad \sigma_z = 54 \oplus \frac{48}{p\ [\mathrm{GeV}]}\ \mu\mathrm{m}\ (\theta = 90^\circ) \tag{1}$$

The good impact parameter resolution leads to typical vertex uncertainties for D mesons along their flight direction of 60–110 μm. The SVX also improves the momentum measurement giving a $D^{*+} - D^0$ mass difference resolution of less than 250 KeV[a]. These improvements will allow background suppression in B decays using charm-tagging (in $B \to D^{*+} l\nu$) or charm-vetoing (in $b \to u$) methods. Other interesting analyses which will profit greatly from these improvements are the search for $D^0 - \bar{D}^0$ mixing and the measurement of the τ lepton and charm baryon lifetimes.

The measurement of the charm meson lifetimes serves as a calibration measurement to explore the capabilities of the SVX in charged particle tracking. The charm meson lifetimes have been measured precisely by fixed target experiments[6]. The different experimental environment and analysis technique complements the fixed target results.

[a] This is achieved by fitting the soft pion π_s^+ through the reconstructed three-dimensional interaction point.

2 Data Sample and Event Selection

The measurements presented in this paper were performed with the CLEOII.V detector[1,2] at the Cornell Electron Storage Ring. The data sample used here was collected at center of mass energies around $\sqrt{s} = 10.6$ GeV. The integrated luminosity is ≈ 1.6 fb^{-1}, with about 1.9 million $c\bar{c}$ pairs produced. This corresponds to roughly 1/3 of the data already taken with the SVX.

From our sample of hadronic events we have reconstructed D mesons via the following decay channels[b]: (1) $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$, (2) $D^{*+} \to D^+\pi_s^0$, $D^+ \to K^-\pi^+\pi^+$ and (3) $D_s^+ \to \phi\pi^+$, $\phi \to K^-K^+$.

To ensure good impact parameter resolution, the D daughter tracks were required to have at least 2 hits in the SVX in each coordinate[c]. A minimal momentum requirement $p > 0.2$ GeV limits the effect of multiple scattering. Energy loss information dE/dx was required to be within 2.5 $\sigma_{dE/dx}$ of the expected energy loss.

Table 1: Summary of D meson selection criteria. Momenta are in units of GeV/c, masses in GeV/c^2. $\delta m_{0,+}$ refer to the $D^{*+} - D^{0,+}$ mass differences. $\cos\theta_{\pi D_s}^{D_s}$ is the angle between the π and the D_s^+ boost direction in the D_s^+ rest frame. $\cos\theta_{K\pi}^{\phi}$ is the helicity angle between the K^- and the π^+ in the ϕ rest frame.

D^0 ($D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$)	D^+ ($D^{*+} \to D^+\pi_s^0$, $D^+ \to K^-\pi^+\pi^+$)	D_s^+ ($D_s^+ \to \phi\pi^+$, $\phi \to K^-K^+$)
$\lvert m_{K\pi\pi} - m_{K\pi} - \delta m_0\rvert < 0.8$	$\lvert m_{K\pi\pi\pi^0} - m_{K\pi\pi} - \delta m_+\rvert < 1.4$	$\lvert m_{KK\pi} - m_{D_s}\rvert < 48$
$\lvert m_{K\pi} - m_{D^0}\rvert < 48$	$\lvert m_{K\pi\pi} - m_{D^+}\rvert < 48$	$\lvert m_{KK} - m_\phi\rvert < 6$
$p_{K\pi\pi} > 2.5$	$p_{K\pi\pi\pi^0} > 2.5$	$p_{\phi\pi} > 2.5$
		$\lvert\cos\theta_{\pi D_s}^{D_s}\rvert > -0.85$
		$\lvert\cos\theta_{K\pi}^{\phi}\rvert > 0.4$

The kinematic selection criteria are given in Table 1. In addition to these cuts, the decay vertex χ^2 must not be greater than 100/DOF for the D^+ and the D_s^+ candidates. To ensure a good vertex measurement, we require the decay length uncertainty $\sigma_{l_{\rm dec}} < 200$ μm.

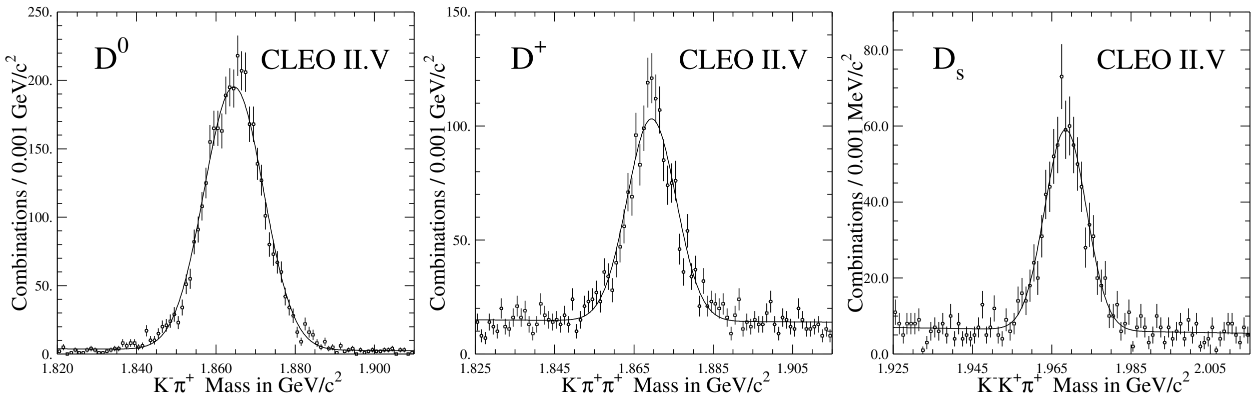

Figure 2: $K\pi$ mass distribution (left), $K\pi\pi$ mass distribution (center) and $KK\pi$ mass distribution (right).

The mass difference requirements are very efficient in background suppression. The width of the $D^{*+} - D^0$ mass difference is 440 KeV, by fitting the soft pion π_s^+ through the reconstructed two-dimensional interaction point. Due to the good energy resolution of the CsI calorimeter the $D^{*+} - D^+$ mass difference resolution is 1.01 MeV. After all cuts we have 3610 $\pm$ 64 D^0 candidates, 1370 $\pm$ 49 D^+ candidates and 697 $\pm$ 32 D_s^+ candidates with background levels around $\pm$ 2 σ_{m_D} of the D mass peaks of 2.8 %, 21.4 % and 16.8 %, respectively. The mass distributions of the D candidates are shown in Fig. 2.

[b] Charge conjugate modes are implied throughout this paper.

[c] Although SVX z information is available, in this analysis vertex reconstruction is done in two dimensions ($r\phi$).

3 Measurement Technique

We reconstruct the momentum vector $\vec{p}_D$ and the decay vertex $\vec{r}_{\rm dec}$ of each D candidate in two dimensions. The decay vertex resolution along the D flight direction is $\sim$ 100 μm. This compares to the average decay length of 200 μm, 480 μm and 250 μm for the D^0, the D^+ and the D_s^+. To reconstruct the interaction point $\vec{r}_{\rm IP}$ (IP), we extrapolate the D pseudo-track[d] back into the beam spot. The dimensions of the beam spot ellipse at CLEOII.V are σ_x = 350 μm, σ_y = 7 μm and σ_z = 1.1 cm. The decay length resolution is dominated by the D decay vertex resolution except for D mesons traveling parallel to the x-axis. We improve the IP resolution by using fragmentation tracks. To minimize a decay length bias from tracks from the other charmed hadron, we use only tracks compatible with the pseudo-track/beam spot vertex (χ^2/DOF < 5). We correct for a small remaining decay length bias. We calculate the two-dimensional projected decay length $l_{\rm dec}$ from the two vertices and the D momentum vector $\vec{p}_D$. For the calculation of the proper time t, we use the PDG D masses [6] m_D.

$$l_{\rm dec} = (\vec{r}_{\rm dec} - \vec{r}_{\rm IP}) \cdot \frac{\vec{p}_D}{p_D} \quad \text{and} \quad t = \frac{m_D}{c} \frac{(\vec{r}_{\rm dec} - \vec{r}_{\rm IP}) \cdot \vec{p}_D}{p_D^2} \tag{2}$$

The proper time distributions for the D mesons are shown in Fig. 3. The average proper time uncertainty $< \sigma_t >$ for the selected candidates is about 0.2 ps.

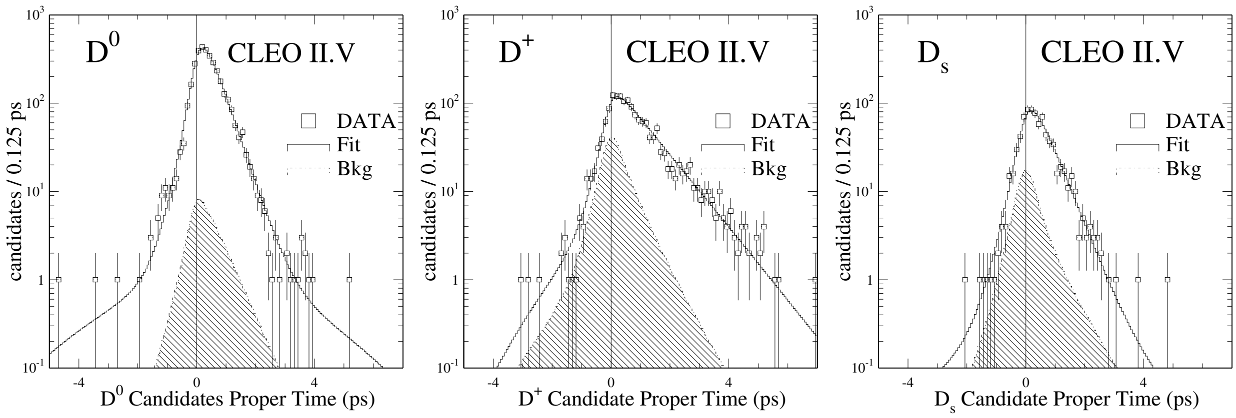

Figure 3: Proper time distribution for D^0 candidates (left), D^+ candidates (center) and D_s^+ candidates (right) around $\pm$ 2 σ_{m_D} of the D mass peaks. The points are the binned proper time distributions and the solid line is the scaled fitting function. The estimated background fraction is indicated by the shaded area.

4 Unbinned Likelihood Lifetime Fit

We extract the D meson lifetimes from the proper time distributions with an unbinned log-likelihood fit. The likelihood function is given in (3) where the product is over all candidates which pass the selection criteria.

$$L(\tau_{\rm Sig}, S, \sigma_{\rm mis}, f_{\rm mis}, \tau_{\rm BG}, f_{\tau_{BG}}) = \prod_i \int_0^\infty \Bigg[\underbrace{p_{\rm Sig,i} E(t'|\tau_{\rm Sig})}_{\text{signal fraction}} + \underbrace{(1 - p_{\rm Sig,i}) \left(f_{\tau_{\rm BG}} E(t'|\tau_{\rm BG}) + (1 - f_{\tau_{BG}}) \delta(t') \right)}_{\text{background fraction}} \Bigg] \tag{3}$$

[d]The D pseudo-track is the D momentum vector fixed at the reconstructed D decay vertex.

$$\times \left[\underbrace{(1-f_{\text{mis}})G(t_i - t'|S\sigma_{t,i})}_{\text{proper time resolution}} + \underbrace{f_{\text{mis}}G(t_i - t'|\sigma_{\text{mis}})}_{\text{mis-measured frac.}} \right] dt'$$

$G(t|\sigma) \equiv 1/(\sqrt{2\pi}\sigma)\exp(-t^2/2\sigma^2)$ is a normalized Gaussian centered around zero and $E(t|\tau) \equiv 1/\tau \exp(-t/\tau)$ is a normalized exponential. To each D candidate we assign a signal probability p_{Sig} based on the candidate's mass. The six fit parameters are τ_{Sig}, $f_{\tau_{\text{BG}}}$, τ_{BG}, S, f_{mis} and σ_{mis}. The most important fit parameter is the signal lifetime τ_{Sig}. The background is modeled by a fraction $f_{\tau_{\text{BG}}}$ with a *background lifetime* τ_{BG} and a fraction with zero lifetime. To estimate the background properties, we fit candidates in a wide region of ± 48 MeV around the D mass peaks. Each candidate is weighted in the fit according to its proper time uncertainty $\sigma_{t,i}$. The fit allows for a global scale factor S to the calculated proper time uncertainty. For a small fraction of mis-measured candidates f_{mis} the fitted uncertainty $S\sigma_{t,i}$ underestimates the actual uncertainty. This is a result of track reconstruction errors e.g. if a silicon noise hit is used in a track fit. We fit for the fraction of mis-measured candidates f_{mis} and associate a proper time uncertainty σ_{mis} to them. We do not use a Monte Carlo simulation to model the proper time distributions. The fit results for the D meson lifetimes are listed in Table 2 and in Fig. 3 the proper time distributions are overlaid with the scaled resulting fitting function.

Table 2: Results from the unbinned log-likelihood fit to the charm meson proper time distributions. The uncertainties are statistical only.

Parameter	D^0	D^+	D_s^+
τ_{Sig}	0.403 ± 0.009 ps	1.034 ± 0.033 ps	0.475 ± 0.024 ps
τ_{BG}	0.530 ± 0.081 ps	0.529 ± 0.064 ps	0.704 ± 0.116 ps
$f_{\tau_{\text{BG}}}$	0.67 ± 0.10	0.38 ± 0.04	0.22 ± 0.05
S	1.54 ± 0.04	1.47 ± 0.05	1.57 ± 0.06
f_{mis}	0.014 ± 0.003	0.052 ± 0.014	0.009 ± 0.006
σ_{mis}	2.8 ps ± 0.4 ps	1.66 ± 0.20 ps	2.7 ± 0.82 ps
χ^2/DOF	84/95	79/95	60/95

5 Systematic Uncertainties and Consistency Checks

A list of systematic uncertainties is given in Table 3. It contains the sizes of the contributing systematic uncertainties and the methods used to estimate them. Note, since we calculate all systematic uncertainties from data, with additional decay channels and more integrated luminosity not only the statistical but also the systematic uncertainty will decrease.

Table 3: Systematic uncertainties for the charm meson lifetimes. The uncertainties marked with a star will decrease with more data and additional decay channels. The uncertainty *consistency* is due to the preliminary status of the results (see text).

Uncertainty	D^0	D^+	D_s^+	Method
decay vertex*	± 3.3 fs	± 9.4 fs	± 9.6 fs	$\gamma\gamma \to 4\pi$ events
decay length corr.*	$^{+3.9}_{-3.8}$ fs	$^{+3.4}_{-3.2}$ fs	$^{+3.4}_{-3.3}$ fs	varied ± 1 σ
y beam position*	$^{+0.4}_{-1.4}$ fs	$^{+0.0}_{-2.1}$ fs	$^{+0.0}_{-8.3}$ fs	varied ± 5 μm
y beam size*	$^{+0.5}_{-0.4}$ fs	$^{+0.0}_{-0.8}$ fs	$^{+1.0}_{-0.6}$ fs	varied ± 30 %
background*	$^{+2.2}_{-0.1}$ fs	$^{+14.3}_{-2.0}$ fs	$^{+0.0}_{-10.1}$ fs	fit region varied
D mass	±0.1 fs	±0.3 fs	±0.1 fs	PDG D mass
D momentum	±0.1 fs	±0.3 fs	±0.1 fs	PDG D mass
consistency	$^{+4.2}_{-9.1}$ fs	$^{+27.7}_{-36.2}$ fs	$^{+23.3}_{-21.5}$ fs	cut variations
Total	$^{+6.9}_{-10.5}$ fs	$^{+32.8}_{-37.7}$ fs	$^{+25.4}_{-25.3}$ fs	

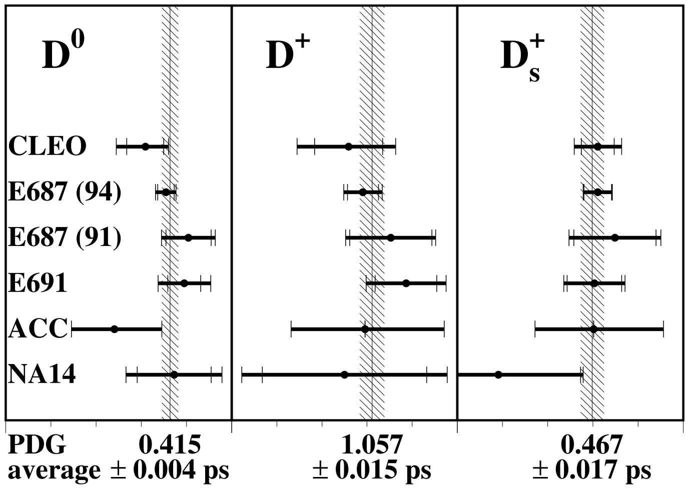

Figure 4: CLEOII.V charm meson lifetime measurements compared to the PDG averages[6] and to high precision fixed target results[6].

We checked for consistency by splitting our data sample in subsamples according to various parameters such as the D polar angle, the D azimuthal angle and dataset. We also tightened and loosened cuts on the decay length uncertainty and the decay vertex χ^2. We do not observe a significant dependence in any of these variables, but due to the preliminary status of the results, we add very conservatively deviations in the fitted lifetime in quadrature to obtain the row called *consistency.* This row will most likely become very small or may even disappear.

6 Summary and Outlook

We measured the charm meson lifetimes with 1.6 fb^{-1} of integrated luminosity taken at $\sqrt{s} \approx$ 10.6 GeV with the CLEOII.V detector using one decay mode for each charm meson. The measured lifetimes are in agreement with the PDG averages[6] (see Fig. 4).

We plan to use the entire CLEOII.V dataset taken with SVX information and add more decay modes such as $D^0 \to K^-\pi^+\pi^0$ and $D_s^+ \to \bar{K}^{*0}K^+$. We will also do the analysis in 3 dimensions to exploit the excellent z resolution of the SVX. It is expected that the increase in data and the better resolution will make CLEOII.V's charm lifetime measurement precision competitive with the current world's best charm lifetime measurements.

The CLEOII.V silicon vertex detector performance in the measurement of charm meson lifetimes gives an idea what improvements can be expected in (rare) B decays and other analyses.

References

1. Y. Kubota *et al.*,(CLEO Collaboration), *Nucl. Instrum. Methods* A **320**, 66 (1992).
2. T. Hill, Talk presented 6th International Workshop on Vertex Detectors, VERTEX 97, Rio de Janeiro, Brazil.
3. See `http://www.lns.cornell.edu/public/CLEO/CLEO3/CLEO3.html` for a summary of the CLEOIII upgrade plans.
4. D. Boutigny *et al.*,(BaBar Collaboration), BaBar Technical Design Report, SLAC Internal Report SLAC-R-0457, (1995).
5. M.T. Cheng *et al.*,(Belle Collaboration), Technical Design Report, Belle Internal Report BELLE-TDR-3-95, (1995).
6. R.M. Barnett *et al.*,(Particle Data Group), *Phys. Rev.* D **54**, 1 (1996).