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Improved Measurement of the Form Factors and First Search for CP Violation in the Decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$ *

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Abstract

Using the CLEO detector at the Cornell Electron Storage Ring we have studied the angular distributions in the decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$. By performing a four-dimensional maximum likelihood fit, we extract the form factor ratio, $R = f_2/f_1$, and the pole mass, which determines the shape of the form factors, M_{pole}. They are found to be $-0.31 \pm 0.05_{stat} \pm 0.04_{sys}$ and $(2.13 \pm 0.07_{stat} \pm 0.10_{sys})$ GeV/c^2 respectively. These results correspond to the following value of the decay asymmetry parameter $\alpha_{\Lambda_c} = -0.85 \pm 0.03_{stat} \pm 0.02_{sys}$, for $\langle q^2 \rangle = 0.67$ (GeV/c^2)^2. We search for CP violation in the angular distributions of the decay and find no evidence for CP violation: $\mathcal{A}_{\Lambda_c} = \frac{(\alpha_{\Lambda_c} + \alpha_{\overline{\Lambda}_c})}{(\alpha_{\Lambda_c} - \alpha_{\overline{\Lambda}_c})} = 0.01 \pm 0.03_{stat} \pm 0.01_{sys} \pm 0.02_{\mathcal{A}_\Lambda}$, where the third error is from the uncertainty in the world average of the CP violating parameter, $\mathcal{A}_\Lambda$, for $\Lambda \to p\pi^-$. All results presented in this paper are preliminary.

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Charm semileptonic decays allow a measurement of the form factors which parameterize the hadronic current because the Cabbibo-Kobayashi-Masawa (CKM) matrix element $|V_{cs}|$ is known from unitarity [1]. Within heavy quark effective theory (HQET) [2], Λ-type baryons are more straightforward to treat than mesons as they consist of a heavy quark and a spin zero light diquark. This simplicity allows for more reliable predictions concerning heavy quark to light quark transitions [3, 4] than is the case for mesons. A measurement of the form factors in $\Lambda_c^+ \to \Lambda e^+ \nu_e$ will help the future determination of the matrix element $|V_{ub}|$ using Λ_b^0 decays since HQET relates the form factors in Λ_c^+ decay to those governing Λ_b^0 semileptonic decays.

In the limit of negligible lepton mass, the semileptonic decay of a charmed baryon $(1/2^+ \to 1/2^+)$ is usually parameterized in terms of four form factors: two axial form factors F_1^A and F_2^A and two vector form factors F_1^V and F_2^V. These form factors are functions of q^2, the invariant mass squared of the virtual W^+. In the zero lepton mass approximation, the decay may be described in terms of helicity amplitudes $H_{\lambda_\Lambda \lambda_W} = H^V_{\lambda_\Lambda \lambda_W} + H^A_{\lambda_\Lambda \lambda_W}$, where λ_Λ and λ_W are the helicities of the Λ and W^+. The helicity amplitudes are related to the form factors by [4]

$$\begin{aligned}
\sqrt{q^2} H^V_{\frac{1}{2}0} &= \sqrt{Q_-}\,[(M_{\Lambda_c} + M_\Lambda) F_1^V - q^2 F_2^V], \\
H^V_{\frac{1}{2}1} &= \sqrt{2Q_-}\,[-F_1^V + (M_{\Lambda_c} + M_\Lambda) F_2^V], \\
\sqrt{q^2} H^A_{\frac{1}{2}0} &= \sqrt{Q_+}\,[(M_{\Lambda_c} - M_\Lambda) F_1^A + q^2 F_2^A], \\
H^A_{\frac{1}{2}1} &= \sqrt{2Q_+}\,[-F_1^A - (M_{\Lambda_c} - M_\Lambda) F_2^V],
\end{aligned} \tag{1}$$

where $Q_\pm = (M_{\Lambda_c} \pm M_\Lambda)^2 - q^2$. The remaining helicity amplitudes can be obtained using the parity relations $H^{V(A)}_{-\lambda_\Lambda - \lambda_W} = +(-) H^{V(A)}_{\lambda_\Lambda \lambda_W}$. In terms of the helicity amplitudes, the decay angular distribution can be written as [4] [5]

$$\begin{aligned}
\Gamma &= \frac{d\Gamma}{dq^2 d\cos\theta_\Lambda d\cos\theta_W d\chi} = \mathcal{B}(\Lambda \to p\pi^-) \frac{1}{2} \frac{G_F^2}{(2\pi)^4} |V_{cs}|^2 \frac{q^2 P}{24 M_{\Lambda_c}^2} \times \\
&\{\frac{3}{8}(1-\cos\theta_W)^2 |H_{\frac{1}{2}1}|^2 (1+\alpha_\Lambda \cos\theta_\Lambda) + \frac{3}{8}(1+\cos\theta_W)^2 |H_{-\frac{1}{2}-1}|^2 (1-\alpha_\Lambda \cos\theta_\Lambda) \\
&+\frac{3}{4}\sin^2\theta_W [|H_{\frac{1}{2}0}|^2 (1+\alpha_\Lambda\cos\theta_\Lambda) + |H_{-\frac{1}{2}0}|^2 (1-\alpha_\Lambda \cos\theta_\Lambda)] \\
&+\frac{3}{2\sqrt{2}} \alpha_\Lambda \cos\chi \sin\theta_W \sin\theta_\Lambda [(1-\cos\theta_W) Re(H_{-\frac{1}{2}0} H^*_{\frac{1}{2}1}) + (1+\cos\theta_W) Re(H_{\frac{1}{2}0} H^*_{-\frac{1}{2}-1})]\},
\end{aligned} \tag{2}$$

where G_F is the Fermi coupling constant, V_{cs} is the CKM matrix element, P is the Λ momentum in the Λ_c^+ rest frame, θ_Λ is the angle between the momentum vector of the proton in the Λ rest frame and the Λ momentum in the Λ_c^+ rest frame, θ_W is the angle between the momentum vector of the positron in the W^+ rest frame and the Λ momentum in the Λ_c^+ rest frame, χ is the angle between the decay planes of the Λ and W^+, and α_Λ is the $\Lambda \to p\pi^-$ decay asymmetry parameter measured to be 0.642 ± 0.013 [1].

Within the framework of HQET the heavy flavor and spin symmetries imply relations among the form factors which reduce their number to one when the decay involves only heavy quarks. In this Letter we follow Ref. [4] where it is argued that the HQET formalism may also work for $\Lambda_c^+ \to \Lambda e^+ \nu_e$. Treating the c quark as a heavy quark, two independent form factors f_1 and f_2 are required to describe the hadronic current. The relationships between these form factors and the standard form factors are $F_1^V(q^2) = -F_1^A(q^2) = f_1(q^2) + \frac{M_\Lambda}{M_{\Lambda_c}} f_2(q^2)$ and $F_2^V(q^2) = -F_2^A(q^2) = \frac{1}{M_{\Lambda_c}} f_2(q^2)$. In general f_2 is expected to be negative and smaller in magnitude than f_1. If the strange quark is treated as heavy, f_2 is zero.

In order to extract the form factor ratio $R = f_2/f_1$ from a fit to Γ an assumption must be made about the q^2 dependence of the form factors. We follow the model of Korner and Kramer (KK) [4] who use the dipole form $f(q^2) = \frac{f(q^2_{max})}{(1-q^2/m^2_{pole})^2}(1 - \frac{q^2_{max}}{m^2_{pole}})^2$, where the pole mass is chosen to be $m_{D_s^*(1^-)} = 2.11$ GeV/c^2. We will perform a simultaneous fit for the form factor ratio and the pole mass.

The data sample used in this study was collected with the CLEO II [6] and the upgraded CLEO II.V [7] detector operating at the Cornell Electron Storage Ring (CESR). The integrated luminosity consists of 13.7 fb^{-1} taken at and just below the $\Upsilon(4S)$ resonance, corresponding to approximately 18×10^6 $e^+e^- \to c\bar{c}$ events. Throughout this paper charge conjugate states are implicitely included, unless otherwise is indicated, and we use the symbol e to denote an electron or positron.

The analysis technique is an extension of previous work [8][9]. We search for the decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$ in $e^+e^- \to c\bar{c}$ events by detecting a Λe^+ pair with invariant mass in range $m_{\Lambda e^+} < m_{\Lambda_c}$ [8]. All tracks are required to come from the region of the event vertex. To reduce the background from B decays, we require $R_2 = H_2/H_0 > 0.2$, where H_i are Fox-Wolfram event shape variables [10]. Positrons are identified using a likelihood function which incorporates information from the calorimeter and dE/dx systems. The minimum allowed momentum for positron candidates is 0.7 GeV/c, as the positron fake rates are much higher in the lower momentum range. Positrons are required to have been detected in the region $|\cos\theta| < 0.7$, where θ is the angle between the positron momentum and the beam line.

The Λ is reconstructed through its decay to $p\pi^-$. We require the point of intersection of the two charged tracks, measured in the $r-\phi$ plane, to be greater than 5 mm away from the primary vertex. In addition, we require the sum of the p and π^- momentum vectors to extrapolate back to the beam line. The dE/dx measurement of the proton is required to be consistent with the expected value. We reject combinations which satisfy interpretation as a K_s^0. Finally, we require the momentum of the $p\pi^-$ pair to be greater than 0.8 GeV/c in order to reduce combinatoric background. These Λ candidates are then combined with Right Sign (RS) tracks consistent with positrons, and the sum of the Λ and e^+ momenta is required to be greater than 1.4 GeV/c, in order to reduce the background from B decays.

The number of events passing these requirements is 4060, of which 123 ± 12 are consistent with fake Λ background, 338 ± 67 with $\Xi_c \to \Xi e^+ \nu$ feedthrough and 398 ± 58 are consistent with the e fake background. The sidebands of the $p\pi^-$ invariant mass distribution are used to estimate the fake Λ. The background from $\Xi_c \to \Xi e^+ \nu$ decays is estimated using the result of a previous CLEO analysis [11]. The e fake background is estimated using the Wrong Sign (WS) $h^+\overline{\Lambda}$ (no charge conjugation is implied here) data sample, where $h^+\overline{\Lambda}$ are WS combinations passing the analysis selection criteria. The h^+ tracks in this sample are mostly fakes as there are few processes contributing $e^+\overline{\Lambda}$ pairs after the selection criteria are applied. We expect that the estimate of the normalization and the momentum spectrum of the e fake background from the $h^+\overline{\Lambda}$ sample is accurate for the following reasons. The probability to form a $h^+\Lambda$ or $h^-\Lambda$ pair is approximately equal because the net charge of the event is zero. The baryon number and the (sud) quark content of the Λ imply (1) that, due to baryon conservation, a Λ is more likely to be produced with an antiproton in WS rather than RS combinations and (2) that if a Λ is produced as a result of a $s\bar{s}$ quark pair creation, such events have a higher fraction of kaons in RS rather than WS combinations. In addition antiprotons and kaons have higher e fake rates. By using only one charge conjugate state ($h^+\overline{\Lambda}$) and by excluding the momentum region where the e fake rate from kaons is high by requiring $|\vec{p_e}| > 0.7$ GeV/c^2, differences between the momentum spectra and particle species of hadronic tracks between $h^+\overline{\Lambda}$ and $h^+\Lambda$ are minimised. Differences that remain are second order and are accounted for as a systematic uncertainty on the final result.

Calculating kinematic variables requires knowledge of the Λ_c^+ momentum which is unknown due to the undetected neutrino. The direction of the Λ_c^+ is approximated based on the information provided by the thrust axis of the event and the kinematic constraints of the decay. The magnitude of the Λ_c^+ momentum is obtained as a weighted average of the roots of the quadratic equation $\vec{p}_{\Lambda_c}^{\,2} = (\vec{p}_\Lambda + \vec{p}_e + \vec{p}_\nu)^2$. The weights are assigned based on the fragmentation function of Λ_c^+. After the Λ_c^+ momentum is estimated, the four kinematic variables are obtained by working in the Λ_c^+ center-of-mass frame.

Using $t = q^2/q^2_{max}$, $\cos\theta_\Lambda$, $\cos\theta_W$, and χ, we perform a four-dimensional maximum likelihood fit in a manner similar to Ref. [12]. The technique enables a multidimensional likelihood fit to be performed to variables modified by experimental acceptance and resolution and is necessary for this analysis due to the substantial smearing of the kinematic variables. The essence of the method is to determine the probability density function by using the population of appropriately weighted Monte Carlo events in the four-dimensional kinematic space. This is accomplished by generating one high statistics sample of Monte Carlo events with known values of the form factor ratio R, the pole mass M_{pole} and corresponding known values of the four kinematic variables t, $\cos\theta_\Lambda$, $\cos\theta_W$, and χ for each event. The generated events are then processed through the full detector simulation, off-line analysis programs, and selection criteria. Using the generated kinematic variables, the accepted Monte Carlo events are weighted by the ratio of the decay distribution for the trial values of R and M_{pole} to that of the generated distribution. The accepted Monte Carlo events are now, therefore, distributed according to the probability density corresponding to the trial values of R and M_{pole}. By such weighting, a likelihood may be evaluated for each data event for different values of the form factor ratio and the pole mass, and a fit performed.

The fit is unbinned in $\cos\theta_\Lambda, \cos\theta_W$ and χ and takes into account the correlations among these variables. The probability for each event is determined by sampling this distribution using a search volume around each data point. The volume size is chosen so that the systematic effect from finite search volumes is small and the required number of Monte Carlo events is not prohibitively high. We bin the fit in t for the following reason. In the course of this analysis we observed an inconsistency between datasets for one subsample of data for $0.8 < t < 1.0$ (a total of 237 evnets). The projections in the other three variables for this subsample are consistent with the remainder of the data. To avoid bias we wish to include these events in the fit for three variables, but not for t. This is not possible if the fit is unbinned in 4 dimensions. Instead we include the events in the 3 dimensional fit but, by virtue of perfoming a binned fit in t, we exclude their contribution to the calculation of the likelihood in t. A systematic uncertainty is assigned by varying the excluded region.

The $\Lambda_c^+ \to \Lambda e^+\nu$ sample has signal to background in the approximate ratio 4:1. Background is incorporated into the fitting technique by constructing the log-likelihood function

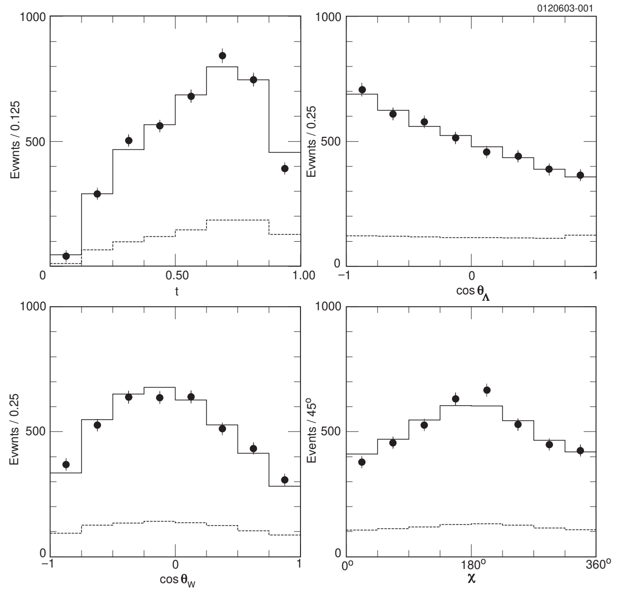

FIG. 1: Projections of the data (points with error bars) and the fit (solid histogram) onto t, $\cos\theta_\Lambda$, $\cos\theta_W$ and χ. The dashed lines show the sum of the background distributions.

$$\mathcal{L} = \{ \sum_{i=1}^{N_{events}} 2\ln\left(P_S^i \Gamma_S^i + \sum_j P_{j\ B}^i \Gamma_{j\ B}^i\right)\} - \{ \sum_{i=1}^{N_{bins}} (n^i_{observed} - n^i_{estimated})^2 / \sigma^2_{n^i_{observed}} \}. \quad (3)$$

The first term is the sum over the number of events, where N_{events} is the number of events in the signal region, P_S^i and $P_{j\ B}^i$ are the probabilities for the ith event to be signal and belong to the jth background component, respectively, Γ_S^i is the signal shape modeled from signal Monte Carlo, and $\Gamma_{j\ B}^i$ is the background shape modeled by a sample of events for the jth background component. The second term is the sum over bins of t, where $n^i_{observed}$ is the number of events in the ith bin, $n^i_{estimated}$ is our prediction of that number, which is dependent on the trial values for R and M_{pole} and is estimated similarly to Γ_S and $\Gamma_{j\ B}^i$.

The e fake background is modeled by the fake positron data sample. Feedthrough background from $\Xi_c \to \Xi e^+ \nu$ is modeled by the Monte Carlo sample which is generated according to the HQET-consistent KK model. Fake Λ background is modeled using the data events in the sidebands of the $p\pi^-$ invariant mass distribution.

Using the above method we perform a simultaneous fit for the form factor ratio and the pole mass and find $R = -0.31 \pm 0.05$ and $M_{pole} = (2.13 \pm 0.07)$ GeV/c^2, where the uncertainties are statistical. This is our main result. Figures 1 and 2 show the t, $\cos\theta_\Lambda$, $\cos\theta_W$ and χ projections for the data and for the fit.

We have considered the following sources of systematic uncertainty and give our estimate of their magnitude in parentheses for R and M_{pole}. The uncertainty associated with the size of the search volume is measured from a statistical experiment in which a set of mock data samples, including signal and all background components, was fit in the same way as the data (0.006, 0.048). The uncertainty due to the limited size of the Monte Carlo sample is estimated by dividing the Monte Carlo sample into four independent equal samples and repeating the fit (0.007, 0.012). The uncertainty due to background normalizations is de-

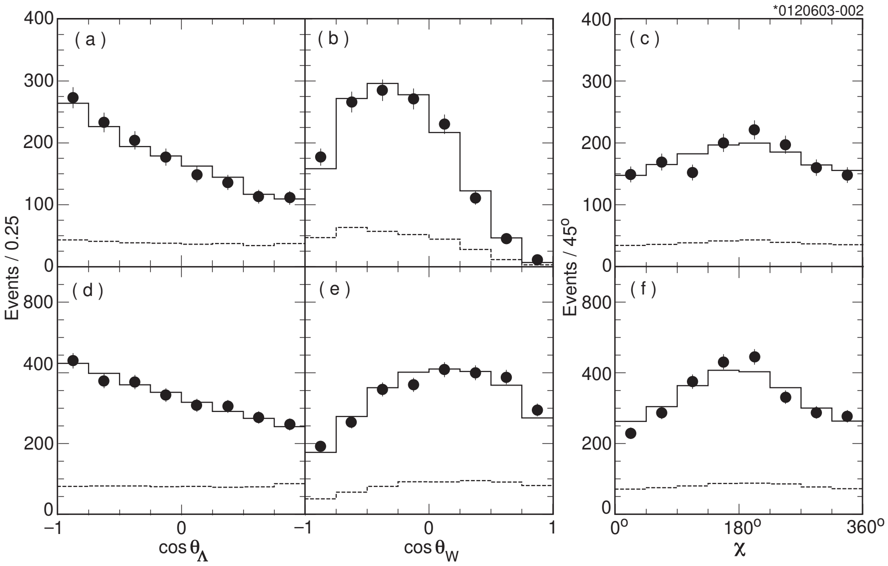

FIG. 2: Projections of the data (points with error bars) and the fit (solid histogram) onto $\cos\theta_\Lambda$, $\cos\theta_W$ and χ for two t regions. The plots labeled (a), (b) and (c) are for $t < 0.5$; (d), (e) and (f) are for $t > 0.5$. The dashed lines show the sum of the background distributions.

termined by varying estimated number of the background events in the signal region by one standard deviation for each type of background separately (0.023, 0.024). The uncertainty associated with the modeling of the background shapes, including uncertainties originating from the unknown form factor ratio and pole mass for the decay $\Xi_c \to \Xi e^+\nu$, are estimated by varying these shapes and by using different background samples (0.024, 0.049). The uncertainty from random $e^+\Lambda$ pairs from in $q\overline{q}$ and $\Upsilon(4S) \to B\overline{B}$ events is estimated by repeating the fit with and without correcting for this background contributions (0.013, 0.038). The modes $\Lambda_c^+ \to \Lambda X e^+\nu$, where X represents unobserved decay products, have never been observed. The current upper limit is $\mathcal{B}(\Lambda_c^+ \to \Lambda X e^+\nu)/\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu) < 0.15$, where $X \neq 0$, at 90% confidence level [9]. The uncertainty due to the possible presence of these modes is estimated from a series of fits, each with an additional background component representing possible $\Lambda_c^+ \to \Lambda X e^+\nu$ modes. The normalizations of the additional components are allowed to float in the fits. By performing fits with a variety of $\Lambda_c^+ \to \Lambda X e^+\nu$ modes, and combining the results, we obtain an estimate of the uncertainty in the final result due to the possible presence of $\Lambda_c^+ \to \Lambda X e^+\nu$ (0.020, 0.060). The uncertainty associated with the Λ_c^+ fragmentation function is estimated by varying this function (0.003, 0.002). The uncertainty associated with Monte Carlo modeling of slow pions from Λ decay is obtained by varying this efficiency according to our understanding of the CLEO detector (0.004, 0.003). Finally, we account for the effect of excluding $0.8 < t < 1.0$ by varying the size of the excluded region (0.000; 0.014). Adding all sources of systematic uncertainty in quadrature, our final result is $R = -0.31 \pm 0.05_{stat} \pm 0.04_{sys}$ and $M_{pole} = (2.13 \pm 0.07_{stat} \pm 0.10_{sys})$ GeV/c^2. We also find $R = -0.32 \pm 0.04_{stat} \pm 0.03_{sys}$ for a fit for the form factor ratio with $M_{pole} = 2.11$ GeV/c^2 fixed.

Using the value of R and M_{pole} obtained in the simultaneous fit and the HQET-consistent KK model, the mean value of the decay asymmetry parameter of $\Lambda_c^+ \to \Lambda e^+\nu_e$ averaged over the charge conjugate states is calculated to be $\alpha_{\Lambda_c} = -0.85 \pm 0.03_{stat} \pm 0.02_{sys}$, for $\langle q^2 \rangle = 0.67$ $(\mathrm{GeV}/c^2)^2$.

In the Standard Model CP violation is expected to be very small for semileptonic decays. In the KK model, the shape of the decay rate distribution in the 4D space of t, $\cos\theta_\Lambda$, $\cos\theta_W$ and χ is governed by R and M_{pole} only. We determine $\alpha_{\Lambda_c}\alpha_\Lambda$ and $\alpha_{\overline{\Lambda}_c}\alpha_{\overline{\Lambda}}$ by repeating the simultaneous fit to R and M_{pole} for each charge conjugate state separately. We find $\alpha_{\Lambda_c}\alpha_\Lambda = -0.561 \pm 0.026_{stat}$ and $\alpha_{\overline{\Lambda}_c}\alpha_{\overline{\Lambda}} = -0.535 \pm 0.024_{stat}$. Following [13] and by extension we define the CP violating asymmetry of the Λ_c^+ as $\mathcal{A}_{\Lambda_c} = \frac{(\alpha_{\Lambda_c} + \alpha_{\overline{\Lambda}_c})}{(\alpha_{\Lambda_c} - \alpha_{\overline{\Lambda}_c})}$. From the measurement of the CP asymmetry in the product of $\alpha_{\Lambda_c}\alpha_\Lambda$, and using the relation

$$\frac{\alpha_{\Lambda_c}\alpha_\Lambda - \alpha_{\overline{\Lambda}_c}\alpha_{\overline{\Lambda}}}{\alpha_{\Lambda_c}\alpha_\Lambda + \alpha_{\overline{\Lambda}_c}\alpha_{\overline{\Lambda}}} = \mathcal{A}_{\Lambda_c} + \mathcal{A}_\Lambda + \mathcal{O}(\mathcal{A}^2_{\Lambda_c}, \mathcal{A}^2_\Lambda), \tag{4}$$

we obtain $\mathcal{A}_{\Lambda_c} = 0.01 \pm 0.03_{stat} \pm 0.01_{sys} \pm 0.02_{\mathcal{A}_\Lambda}$, where in the systematic uncertainty we have taken into account the correlations among the systematic uncertainties for the charge conjugate states and the third error is from the uncertainty in the world average of the CP violating parameter, $\mathcal{A}_\Lambda$, for $\Lambda \to p\pi^-$ [1].

In conclusion, using a four-dimensional maximum likelihood fit the angular distributions of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ have been studied and the form factor ratio $R = f_2/f_1$ and M_{pole} are found to be $-0.31 \pm 0.05_{stat} \pm 0.04_{sys}$ and $(2.13 \pm 0.07_{stat} \pm 0.10_{sys})$ GeV/c^2 respectively. These results correspond to the following value of the decay asymmetry parameter $\alpha_{\Lambda_c} = -0.85 \pm 0.03_{stat} \pm 0.02_{sys}$, for $\langle q^2 \rangle = 0.67$ $(\mathrm{GeV}/c^2)^2$. We have searched for CP violation in the angular distributions of the decay and find no evidence for CP violation: $\mathcal{A}_{\Lambda_c} = 0.01 \pm 0.03_{stat} \pm 0.01_{sys} \pm 0.02_{\mathcal{A}_\Lambda}$, where the third error is from the uncertainty in the world average of the CP violating parameter, $\mathcal{A}_\Lambda$, for $\Lambda \to p\pi^-$. All results presented in this paper are preliminary.

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[5] The interference term (the term containing $\cos\chi$) in expression (2) contributes with a positive sign to the decay angular distribution. In the data, the sign of the term is opposite (Figure 1). In our derivation we reproduced the expressions for the helicity amplitudes in terms of the traditional form factors and the expressions relating the traditional form factors to the two HQET consistent form factors, which are given in [4]. We used the helicity formalism to derive

the four fold decay rate and to reproduce all the terms and their signs; the only exception was the sign of the interference term. In the rest of the analysis it is assumed that the correct sign of the interference term is minus.

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