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# Observation of polarization effects in $\Lambda_c^+$ semileptonic decay

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**Abstract**

Polarization of the $\Lambda$ daughter baryon from $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decay has been measured for the first time using the ARGUS detector at the DORIS II $e^+e^-$ storage ring. Expressed in terms of the $\Lambda_c^+$ semileptonic asymmetry parameter the result is $\alpha_{\Lambda_c} = -0.91 \pm 0.49$ for events in the mass region $1.85 < M(\Lambda l^+) < 2.20$ GeV/$c^2$.

The semileptonic decays of charmed baryons, and in particular the $\Lambda_c^+$ baryon, have recently received the attention of the experimentalist [1–3], and theorist [4–10]. The $\Lambda_c^+$ is of interest since it is the most experimentally accessible charmed baryon. This makes it ideal as a laboratory to further complement previous semileptonic charmed meson measurements and to test theoretical models developed to understand the $c \to s$ weak transitions in these decays. Of particular interest are the ideas of heavy quark effective theory (HQET) [11] and the issue of whether the decaying charmed baryon is heavy enough to be considered within this framework. To this end, a brief discussion of the theory of $\Lambda_c^+$ semileptonic decays and the application of HQET is useful. The most general Lorentz invariant structure that describes the $\Lambda_c^+ \to \Lambda l^+ \nu_l$ hadronic current in the zero lepton mass approximations is [4]

$$\langle \Lambda | \gamma_\mu (1-\gamma_5) | \Lambda_c^+ \rangle = \bar{u}_s [\gamma_\mu (F_1^V + F_1^A \gamma_5) + i\sigma_{\mu\nu} q^\nu (F_2^V + F_2^A \gamma_5)] u_c . \quad (1)$$

Here $q_\mu = (p_{\Lambda_c} - p_\Lambda)_\mu$ is the four-momentum transfer and $F_i^V(q^2)$ and $F_i^A(q^2)$ $(i=1, 2)$ are the vector and axial-vector standard hadronic form factors. These are functions of $q^2$ with phase space boundaries at $q^2_{\min} = m_l^2 \approx 0$ and $q^2_{\max} = (M_{\Lambda_c} - M_\Lambda)^2 = 1.368$ (GeV/$c^2$)$^2$. If we consider a heavy quark to light quark transition then the most general leading order HQET form factor structure allowing for a light quark spin interaction is [4–6]

$$\langle \Lambda | \gamma_\mu (1-\gamma_5) | \Lambda_c^+ \rangle = \bar{u}_s [f_1(q^2) \gamma_\mu (1-\gamma_5) + f_2(q^2) \not{v}_c \gamma_\mu (1-\gamma_5)] u_c , \quad (2)$$

where $v_c$ is the charmed quark four-velocity, and $f_1(q^2)$ and $f_2(q^2)$ are heavy quark form factors which have no normalization condition at $q^2_{\max}$. Comparison of Eq. (1) with Eq. (2) allows the standard form factors to be expressed in terms of the heavy quark ones as

$$F_1^V(q^2) = -F_1^A(q^2) = f_1(q^2) + \frac{M_\Lambda}{M_{\Lambda_c}} f_2(q^2) ,$$

$$F_2^V(q^2) = -F_2^A(q^2) = \frac{1}{M_{\Lambda_c}} f_2(q^2) . \quad (3)$$

Thus, the problem has been simplified from finding four form factors to only two. Furthermore, HQET tells us that the $\Lambda_c^+$ vector and axial-vector form factors are

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equal and opposite to each other, which implies that the charmed quark decay is maximally left-handed. Thus, a demonstration of this effect would be of interest.

This paper sets out to measure the $\Lambda_c^+$ asymmetry parameter in $\Lambda_c^+ \to \Lambda l^+ \nu_l$ [#1] decay where $l^+$ is either a $e^+$ or $\mu^+$. This is accomplished by using the parity violating weak decay $\Lambda \to p\pi^-$ as a polarization analyzer. This has a decay angular distribution of the form

$$W(\theta_{\Lambda_c}) = 1 + \alpha_{\Lambda_c}\alpha_\Lambda \cos\theta_{\Lambda_c}, \tag{4}$$

where $\theta_{\Lambda_c}$ is defined to be the angle between the proton momentum vector and the negative $\Lambda_c^+$ momentum vector, both in the $\Lambda$ rest frame (see Fig. 1a). The $\Lambda$ asymmetry parameter is experimentally well measured and is found to be $\alpha_\Lambda = +0.642 \pm 0.013$ [12]. The $\Lambda_c^+$ asymmetry parameter $\alpha_{\Lambda_c}$ is a measure of the polarization passed to the $\Lambda$ daughter baryon in the semileptonic decay process, and is related to the form factor structure of the weak decay. Following the prescription of [4], the $\Lambda_c^+$ asymmetry parameter is defined in terms of the helicity form factors

$$\alpha_{\Lambda_c}(q^2) = \frac{(|H_{1/21}|^2 + |H_{1/20}|^2) - (|H_{-1/2-1}|^2 + |H_{-1/20}|^2)}{(|H_{1/21}|^2 + |H_{1/20}|^2) + (|H_{-1/2-1}|^2 + |H_{-1/20}|^2)}, \tag{5}$$

which ranges between $+1$ and $-1$. The helicity form factors correspond to $H_{\lambda_s \lambda_W}$, where $\lambda_s = \pm\frac{1}{2}$ is the daughter baryon helicity and $\lambda_W = 0, \pm 1$ (longitudinal and transverse, respectively) is the $W$ helicity. These are just functions fo $q^2$ and the standard from factors defined above [4]. Fig. 2 shows a plot of the asymmetry parameter as a function of $q^2$ for various ratios of the heavy quark form factors $R = f_2(q^2)/f_1(q^2)$. This ratio uniquely determines $\alpha_{\Lambda_c}$ and is a constant since $f_1$ and $f_2$ are assumed to have the same $q^2$ dependence [4]. The $q^2$ behavior of $\alpha_{\Lambda_c}$ varies drastically for different values of $R$. However, the one outstanding feature is that $\alpha_{\Lambda_c} \to -1$ in the $q^2 \to 0$ limit, independent of $R$. This results from the $\lambda_W = 0$ helicity form factors dominating as $q^2 \to 0$, and the HQET prediction $H_{-1/20} \gg H_{1/20}$ that results from $F_1^V = -F_1^A$. This is in fact model independent and only depends on the assumption that the decaying charmed quark is heavy. This prediction would not even be spoiled by including $1/m_c$ corrections [4,5]. It is the purpose of the following analysis to observe this unique effect. It should be noted that there are three other asymmetry parameters related to $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decay [4], but these cannot be measured because of the missing neutrino.

The data presented here was collected using the ARGUS detector at the $e^+e^-$ storage ring DORIS II at DESY. The ARGUS detector is a $4\pi$ solenoidal magnetic spectrometer detector described in detail elsewhere [13]. The data sample comprises an integrated luminosity of 511.4 $pb^{-1}$ on the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(4S)$ resonances and the nearby continuum with an average center of mass energy of 10.4 GeV. The reconstruction of the $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decay channel by ARGUS, where $\Lambda l^+$ refers to both $\Lambda e^+$ and $\Lambda \mu^+$ right-sign combinations, has been described in detail in [1] and recently updated in [3]. In this paper we use the same right-sign $\Lambda l^+$ data samples as above but with the requirement that the scaled momentum cut be relaxed from $x_p > 0.5$ to $x_p > 0.4$. This is necessary to increase statistics and does not worsen the signal to background ratio. The dominant source of background to the right-sign signal comes from fake $\Lambda$ and fake lepton candidates. A measure of this background comes from wrong-sign $\Lambda l^-$ combinations [1,3,14]. Finally, $\Lambda$ baryons that are consistent with originating from $\Xi_c^0 \to \Xi^- l^+ \nu_l$ decay, where $\Xi^- \to \Lambda\pi^-$, are removed from subsequent analysis [2].

The reconstruction of the daughter baryon polar angle $\theta_{\Lambda_c}$ is not trivial. In fact, knowledge of this angle is very poor since the neutrino momentum cannot be reconstructed reliably. We approximate the $\Lambda_c^+$ momentum vector with that of the measured $\Lambda l^+$ momentum vector

$$\boldsymbol{P}_{\Lambda_c} \approx \boldsymbol{P}_{\Lambda l} = \boldsymbol{P}_\Lambda + \boldsymbol{P}_l, \tag{6}$$

where $\boldsymbol{P}_{\Lambda l}$ is the measured $\Lambda l^+$ momentum boosted into the $\Lambda$ rest frame. The angle between $\boldsymbol{P}_p$ and $-\boldsymbol{P}_{\Lambda l}$ is called $\theta_{\Lambda l}$ and is shown in Fig. 1b. This angle is not necessarily equal to $\theta_{\Lambda_c}$ and a Monte Carlo analysis is required to determine how much angular smearing is introduced by this approximation. Monte Carlo data are generated using the LUND model [15] with $\Lambda_c^+ \to \Lambda l^+ \nu_l$ events weighted by the full differential distribution given in [4]. The $\Lambda_c^+$ form factors are taken from [3]. However, the following analysis is

[#1] In this paper, all references to a specific charge state imply the charge conjugate state also, unless otherwise stated.

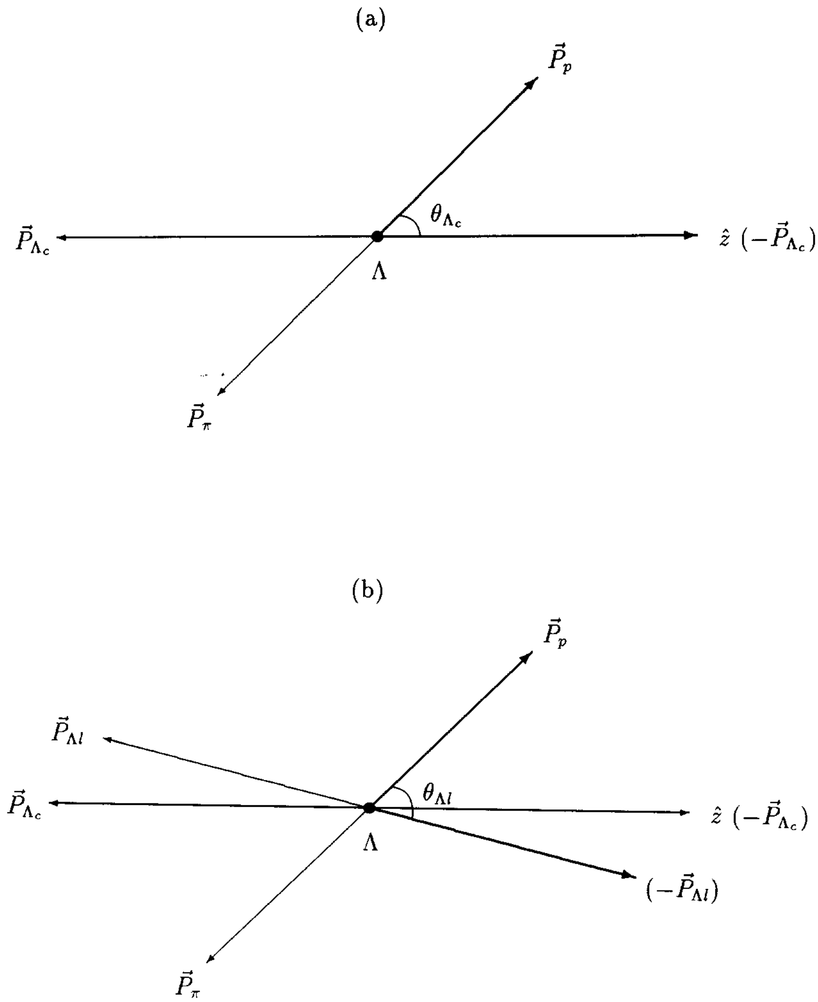


Fig. 1. Definition of the angles (a) $\theta_{\Lambda_c}$ and (b) $\theta_{\Lambda l}$. All vectors are in the $\Lambda$ rest frame.

insensitive to the actual form factor structure. The $\Lambda_c^+$ momentum spectrum parameterization is specified in [1]. Further references to Monte Carlo analysis in this paper imply the above simulation, unless otherwise stated.

The result of the Monte Carlo analysis is shown in Fig. 3 where the mass of the $\Lambda l^+$ system, $M(\Lambda l^+)$, is plotted against $\boldsymbol{P}_{\Lambda_c} \cdot \boldsymbol{P}_{\Lambda l} / (|\boldsymbol{P}_{\Lambda_c}|\,|\boldsymbol{P}_\Lambda|)$. The latter quantity is the cosine of the angle between $\boldsymbol{P}_{\Lambda_c}$ and $\boldsymbol{P}_{\Lambda l}$ in the $\Lambda$ rest frame and is a measure of the angular resolution of this technique. Only for $M(\Lambda l^+)$ approaching $M_{\Lambda_c}$ does the angular resolution become acceptable. This result is intuitive since the neutrino momentum becomes smaller as the mass of the $\Lambda l^+$ system approaches $M_{\Lambda_c}$. Thus, the amount of smearing due to the missing neutrino becomes less significant. Since the differential decay rate decreases with higher mass a compromise between optimal angular resolution and sufficient statistics must be found. A mass selection of 1.85 GeV/$c^2 < M(\Lambda l^+) < M_{\Lambda c}$ was found to be a reasonable solution. Fig. 4 shows a Monte Carlo plot of $\cos\theta_{\Lambda_c}$ versus $\cos\theta_{\Lambda l}$ for the entire kinematically allowed mass region $M_\Lambda < M(\Lambda l^+) < M_{\Lambda_c}$ and for the region defined above. An exact correlation between the

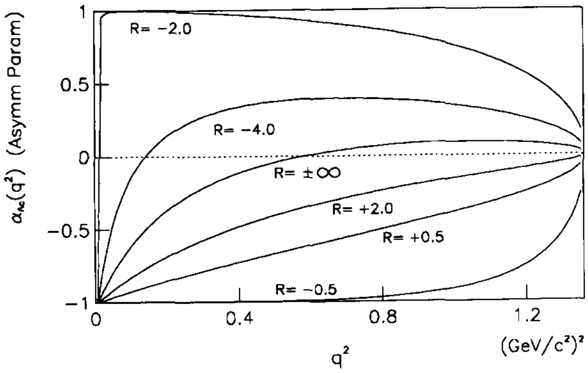


Fig. 2. The semileptonic $\Lambda_c^+$ asymmetry parameter as a function of $q^2$ for various $R=f_2/f_1$ values.

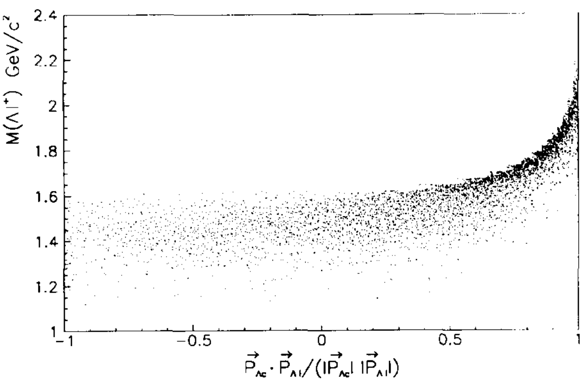


Fig. 3. The Monte Carlo generated $\Lambda l^+$ mass versus the cosine of the angle between $P_{\Lambda_c}$ and $P_{\Lambda l}$ in the $\Lambda$ rest frame.

two would be represented by a diagonal line through the middle of the plot, corresponding to $\cos\theta_{\Lambda_c}=\cos\theta_{\Lambda l}$. As can be seen, the mass cut removes events with poorly correlated $\theta_{\Lambda_c}$ and $\theta_{\Lambda l}$ angles.

The $\Lambda e^+$ and $\Lambda\mu^+$ data samples are combined for maximum statistics and the masses of these combinations are required to lie in the range $1.85<M(\Lambda l^+)<2.20\ \mathrm{GeV}/c^2$. The upper mass requirement is necessary to cut down on fakes and random background events which dominate in the region between this limit and the $\Lambda_c^+$ mass. This mass selection results in 101 right-sign and 35 wrong-sign events. The polar angle is reconstructed as in Fig. 1b and the resulting $\cos\theta_{\Lambda l}$ distributions are shown in Fig. 5 for the right-sign and wrong-sign data for entries in the selected mass region. Also shown is the right-sign $\cos\theta_{\Lambda l}$ distribution for events from the mass region $M(\Lambda l^+)>2.47\ \mathrm{GeV}/c^2$, which is above the mass of the $\Xi_c^+$ baryon and any contamination from possible semileptonic decays. A clear polarization signal, as demonstrated by the negatively sloping distribution, is observed in the right-sign data. The two background distributions are flat within errors, indicating no polarization, as expected for these processes. A maximum likelihood fit [16] is performed on the right-sign signal distribution of the form

$$W(\theta_{\Lambda l})=N_{sg}(1+\alpha_{\Lambda_c}\alpha_\Lambda\cos\theta_{\Lambda l})=N_{bg}\,, \tag{7}$$

where $N_{sg}=N_{\Lambda l^+}-N_{bg}$ is the number of signal events and $N_{bg}$ is the number of background events in the right-sign distribution. As discussed in [1], wrong-sign combinations provide a good description of the background to the right-sign data. Thus, the magnitude of $N_{bg}$ is fixed to the number of wrong-sign events in the selected mass region and it is assumed to have a flat angular distribution (i.e. $\alpha_{\Lambda_c}=0$). The fit to the right-sign distribution yields for the $\Lambda_c^+$ asymmetry parameter $\alpha_{\Lambda_c}=-0.91\pm0.42$. The $\chi^2$ of the fit is 1.4 while the fit for a flat hypothesis yields a $\chi^2$ of 7.0, both for four degrees of freedom. The fit to the wrong-sign data gives an asymmetry parameter of $-0.05\pm0.23$, while for the right-sign data in the mass region above $M_{\Xi_c^+}$ one obtains $+0.19\pm0.29$ (both fits are with $N_{bg}=0$). These two background results are compatible with flat angular distributions and have been scaled by $N_{bg}/N_{sg}$ so as to be directly comparable to the right-sign signal asymmetry parameter. The fits clearly demonstrate that polarization effects exist for $\Lambda_c^+\to\Lambda l^+\nu_l$ events and that this hypothesis is statistically more likely than a null result. The mass cut was varied to ensure that the above results are stable and not due to some random fluctuation.

The systematic errors involved in the measurement of $\alpha_{\Lambda_c}$ have to be considered. The first error arises from the angular smearing introduced by the approximation $\cos\theta_{\Lambda_c}\approx\cos\theta_{\Lambda l}$. Monte Carlo studies indicate that this produces a systematic shift to larger asymmetries by $-0.09$ for the selected mass region.

The second source of systematic error comes from the assumption that $\alpha_{\Lambda_c}=0$ for the background $\cos\theta_{\Lambda l}$ distribution. The background contribution to the right-sign data is expected to be flat and is represented by the constant term in Eq. (7). The wrong-sign distribution, which represents this background, is found to be consistent with a flat hypothesis. This is also

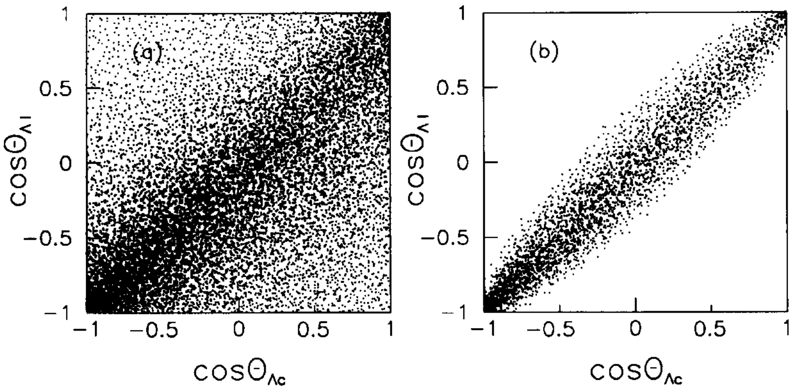


Fig. 4. The Monte Carlo generated $\cos\theta_{\Lambda l}$ versus $\cos\theta_{\Lambda_c}$ scatter plot for the mass regions (a) $M_\Lambda < M(\Lambda l^+) < M_{\Lambda_c}$ and (b) 1.85 GeV/$c^2 <$ $M(\Lambda l^+) < M_{\Lambda_c}$.

verified by Monte Carlo studies of polarized $\Lambda$ baryons from $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decays combined with a random pion misidentified as a lepton (i.e. pions that satisfy the lepton identification criteria). However, because of low statistics the wrong-sign data may fluctuate from a flat distribution. The magnitude of this error is assumed to be the scaled statistical error of the fit to the wrong-sign data which is $\pm 0.23$. This number is also consistent with the Monte Carlo predictions.

A third systematic error comes from contamination of the $\cos\theta_{\Lambda l}$ distribution originating from other charmed baryon semileptonic decays which also have decay asymmetry. The decay $\Lambda_c^+ \to \Lambda^* l^+ \nu_l$, followed by $\Lambda^* \to (\Sigma\pi)^0$, does not contribute since its $\Lambda l^+$ combinations only populate the mass region below 1.75 GeV/$c^2$ [14]. The decay $\Xi_c^0 \to \Xi^- l^+ \nu_l$ also does not significantly contribute since all $\Lambda$ candidates that are consistent with $\Xi^-$ decays are removed from the analysis. The only mode that cannot be removed is from $\Xi_c^+ \to \Xi^0 l^+ \nu_l$ decays. In order to determine its effects a Monte Carlo simulation was performed with the added complication of the double weak hyperon decay chain $\Xi^0 \to \Lambda\pi^0$, followed by $\Lambda \to p\pi^-$. The angular distribution of the second decay has been worked out in detail [17] and was included in the simulation. With the assumption that the $\Lambda_c^+$ and $\Xi_c^+$ baryons have the same internal form factor structure [3,14] the Monte Carlo study indicates that the asymmetry in the $\cos\theta_{\Lambda l}$ distribution from this decay sequence is smaller than that from $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decay and corresponds to a systematic shift to lower asymmetries of $+0.10$. This result includes a scaling by the expected number of $\Xi_c^+$ semileptonic events [14].

Combining all the systematic errors from the above considerations yields the final result $\alpha_{\Lambda_c} = -0.91 \pm 0.42 \pm 0.25$ for the mass region $1.85 < M(\Lambda l^+) < 2.20$ GeV/$c^2$. A careful interpretation fo this measured asymmetry parameter is in order since it is averaged over some $q^2$ region of the $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decay. A knowledge of the experimentally accessible $q^2$ region, or at least the $q^2$ efficiency for various selection criteria is required for this interpretation. There is insufficient information in the events for reconstruction of $q^2$. Thus, we resort to Monte Carlo studies which indicate that there is little $q^2$ efficiency dependence on the individual momentum of the reconstructed $\Lambda$ and lepton and on the $x_p$ cut. However, there is a correlation between $q^2$ and $M(\Lambda l^+)$ which is shown in Fig. 6. It is evident that a cut in $M(\Lambda l^+)$ removes a portion of the available $q^2$. A cut at higher mass restricts $q^2$ to smaller values and in the limit $M(\Lambda l^+) \to M_{\Lambda_c}$ one has $q^2 \to 0$. The effect of this cut is demonstrated in Fig. 7 which shows the predicted asymmetry parameter as a function of the $M(\Lambda l^+)$ mass cut. The solid lines correspond to various values of the heavy quark form factor ratio $R = f_2/f_1$. It can be seen that in the limit $M(\Lambda l^+) \to M_{\Lambda_c}$ all the $R$ models tend towards $\alpha_{\Lambda_c} \to -1$. This is just the HQET $q^2 \to 0$ limit prediction. The data does not discriminate very well between the various $R$ values because of the large errors. However, it does demonstrate that it is consistent with the HQET prediction. Also shown are the asymmetry parameters for two other mass selections at 1.75 and 1.95 GeV/$c^2$, which indi-

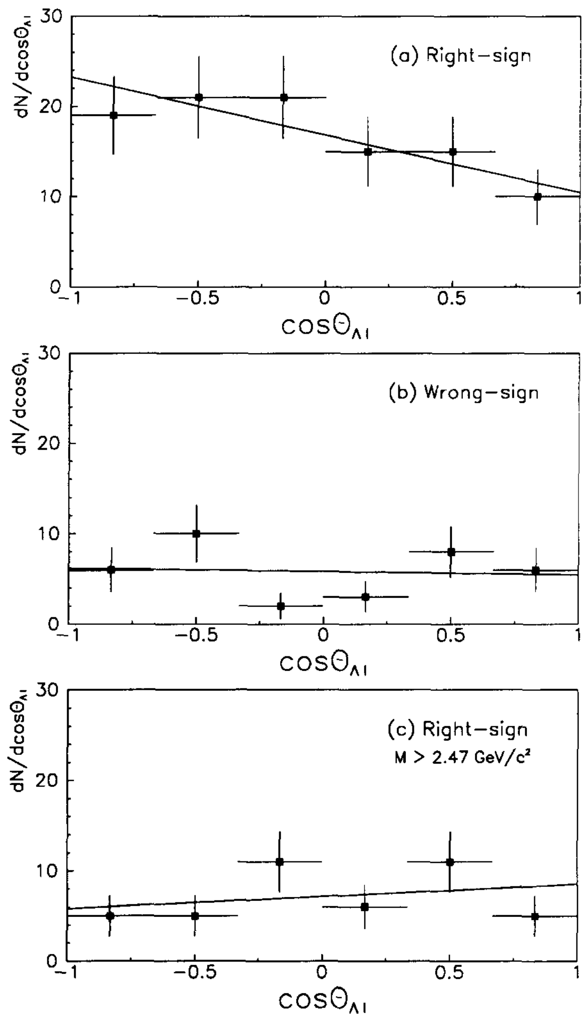


Fig. 5. The $\cos\theta_{\Lambda l}$ distributions for events in the mass region $1.85 < M(\Lambda l^+) < 2.20$ GeV/$c^2$ for (a) the right-sign and (b) wrong-sign data. The right-sign background from the mass region $M(\Lambda l^+) > 2.47$ GeV/$c^2$ is shown in (c). The overlaid lines are the results of the fits described in the text.

cate that the result is stable. It should be noted that these three measurements are not independent since each high mass data point is a subset of the lower mass points. Thus, the errors shown are correlated.

There have not been any other measurements to date of the semileptonic $\Lambda_c^+$ asymmetry parameter. However, there have been two measurements of the hadronic $\Lambda_c^+$ asymmetry parameter in the decay $\Lambda_c^+ \to \Lambda\pi^+$. The ARGUS Collaboration has measured $\alpha^{\rm H}_{\Lambda_c} = -0.96 \pm 0.42$ [18] and CLEO similarly found $\alpha^{\rm H}_{\Lambda_c} = -1.1 \pm 0.4$ [19]. The $\Lambda$ angular distribution resulting from $\Lambda_c^+ \to \Lambda\pi^+$ decay is similar to that of Eq. (4) except now there is no dependence of $\alpha^{\rm H}_{\Lambda_c}$ on $q^2$ since this is just the mass of the mass of the $\pi^+$ produced by the off-shell $W^+$. The hadronic asymmetry parameter is given by

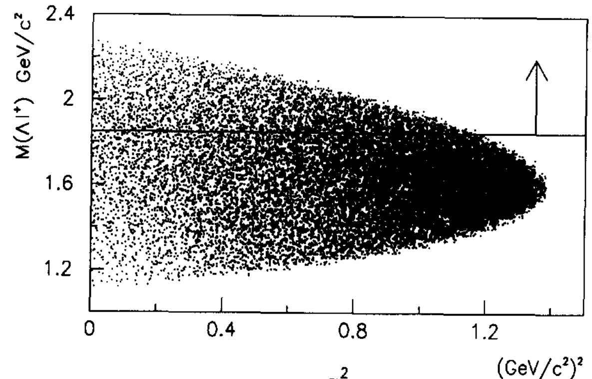


Fig. 6. The Monte Carlo generated $\Lambda l^+$ mass versus $q^2$ scatter plot. The solid line shows the $M(\Lambda l^+) > 1.85$ GeV/$c^2$ mass selection.

$$\alpha^{\rm H}_{\Lambda_c} = \frac{(|H_{1/2 0}|^2) - (|H_{-1/2 0}|^2)}{(|H_{1/2 0}|^2) + |H_{-1/2 0}|^2)}. \tag{8}$$

This is the same as the semileptonic asymmetry parameter in Eq. (5) except that the $\lambda_W = \pm 1$ helicity form factors are dropped since the $\pi^+$ is spin zero. Also, HQET predicts that $\alpha^{\rm H}_{\Lambda_c} = -1$ in analogy to semileptonic decays [5,6].

The semileptonic asymmetry parameter in Eq. (5) is directly comparable to the above hadronic one in the $q^2 \to 0$ limit because the spin structure of $\Lambda_c^+ \to \Lambda l^+ \nu_l$ decay becomes similar to that of $\Lambda_c^+(\frac{1}{2}^+) \to \Lambda(\frac{1}{2}^+)\pi^+(0^-)$ decay. In this $q^2 \to 0$ limit the charged lepton and neutrino momentum vectors become parallel and since they have opposite helicities the $l^+\nu_l$ system then becomes a spin 0 object, which is similar to the pion (this is in contrast to the $q^2 \to q^2_{\rm max}$ limit where the $l^+\nu_l$ system becomes a spin 1 object). Thus, the $\lambda_W = \pm 1$ helicity form factors become zero and the semileptonic asymmetry parameter in Eq. (5) equals the hadronic one in Eq. (8). This implies that the measurement made here of $\alpha_{\Lambda_c}$ in the high mass limit can

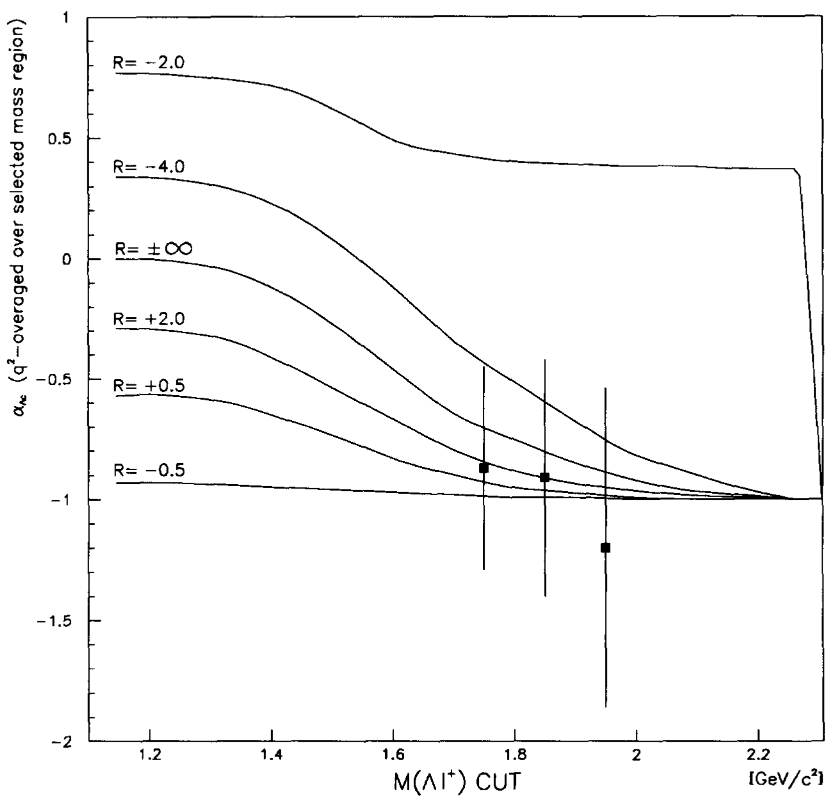


Fig. 7. The $q^2$-averaged semileptonic $\Lambda_c^+$ asymmetry parameter as a function of the selected $\Lambda l^+$ mass region (from $M(\Lambda l^+)$ to $M_{\Lambda_c}$) for various $R=f_2/f_1$ values (line). Also shown are the measured values of $\alpha_{\Lambda_c}$ for various mass regions (solid squares). The error bars displayed are the combined statistical and systematic errors.

be compared to the above ARGUS and CLEO hadronic results (this is only approximately true because we are not exactly at $q^2=0$) motivating us to average all three asymmetry parameters giving $\alpha_{\Lambda_c}=-1.00\pm0.25$. The picture that emerges from the agreement between this average and the prediction of leading order HQET is that the charmed quark inside the $\Lambda_c^+$ baryon can be considered heavy.

In conclusion, the asymmetry parameter in $\Lambda_c^+\to\Lambda l^+\nu_l$ decay has been measured by observing polarization in the $\Lambda\to p\pi^-$ decay angular distribution. The result is $\alpha_{\Lambda_c}=-0.91\pm0.49$ for events in the mass region $1.85<M(\Lambda l^+)<2.20$ GeV$/c^2$. This measurement is consistent with observations of the hadronic asymmetry parameter in $\Lambda_c^+\to\Lambda\pi^+$ decay and with the HQET prediction of $\alpha_{\Lambda_c}\to-1$ in the $q^2\to0$ limit.

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