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Form Factor Ratio Measurement in $\Lambda_c^+ \to \Lambda e^+ \nu_e$

G. Crawford,[1] C. M. Daubenmier,[1] R. Fulton,[1] D. Fujino,[1] K.K. Gan,[1] K. Honscheid,[1] H. Kagan,[1] R. Kass,[1] J. Lee,[1] M. Sung,[1] C. White,[1] A. Wolf,[1] M.M. Zoeller,[1] F. Butler,[2] X. Fu,[2] B. Nemati,[2] W.R. Ross,[2] P. Skubic,[2] M. Wood,[2] M. Bishai,[3] J. Fast,[3] E. Gerndt,[3] J.W. Hinson,[3] R.L. McIlwain,[3] T. Miao,[3] D.H. Miller,[3] M. Modesitt,[3] D. Payne,[3] E.I. Shibata,[3] I.P.J. Shipsey,[3] P.N. Wang,[3] M. Battle,[4] J. Ernst,[4] L. Gibbons,[4] Y. Kwon,[4] S. Roberts,[4] E.H. Thorndike,[4] C.H. Wang,[4] J. Dominick,[5] M. Lambrecht,[5] S. Sanghera,[5] V. Shelkov,[5] T. Skwarnicki,[5] R. Stroynowski,[5] I. Volobouev,[5] G. Wei,[5] P. Zadorozhny,[5] M. Artuso,[6] M. Gao,[6] M. Goldberg,[6] D. He,[6] N. Horwitz,[6] G.C. Moneti,[6] R. Mountain,[6] F. Muheim,[6] Y. Mukhin,[6] S. Playfer,[6] Y. Rozen,[6] S. Stone,[6] X. Xing,[6] G. Zhu,[6] J. Bartelt,[7] S.E. Csorna,[7] Z. Egyed,[7] V. Jain,[7] D. Gibaut,[8] K. Kinoshita,[8] P. Pomianowski,[8] B. Barish,[9] M. Chadha,[9] S. Chan,[9] D.F. Cowen,[9] G. Eigen,[9] J.S. Miller,[9] C. O'Grady,[9] J. Urheim,[9] A.J. Weinstein,[9] M. Athanas,[10] W. Brower,[10] G. Masek,[10] H.P. Paar,[10] J. Gronberg,[11] C.M. Korte,[11] R. Kutschke,[11] S. Menary,[11] R.J. Morrison,[11] S. Nakanishi,[11] H.N. Nelson,[11] T.K. Nelson,[11] C. Qiao,[11] J.D. Richman,[11] A. Ryd,[11] D. Sperka,[11] H. Tajima,[11] M.S. Witherell,[11] M. Procario,[12] R. Balest,[13] K. Cho,[13] W.T. Ford,[13] D.R. Johnson,[13] K. Lingel,[13] M. Lohner,[13] P. Rankin,[13] J.G. Smith,[13] J.P. Alexander,[14] C. Bebek,[14] K. Berkelman,[14] K. Bloom,[14] T.E. Browder,[14*] D.G. Cassel,[14] H.A. Cho,[14] D.M. Coffman,[14] D.S. Crowcroft,[14] P.S. Drell,[14] D.J. Dumas,[14] R. Ehrlich,[14] P. Gaidarev,[14] M. Garcia-Sciveres,[14] B. Geiser,[14] B. Gittelman,[14] S.W. Gray,[14] D.L. Hartill,[14] B.K. Heltsley,[14] S. Henderson,[14] C.D. Jones,[14] S.L. Jones,[14] J. Kandaswamy,[14] N. Katayama,[14] P.C. Kim,[14] D.L. Kreinick,[14] G.S. Ludwig,[14] J. Masui,[14] J. Mevissen,[14] N.B. Mistry,[14] C.R. Ng,[14] E. Nordberg,[14] J.R. Patterson,[14] D. Peterson,[14] D. Riley,[14] S. Salman,[14] M. Sapper,[14] F. Würthwein,[14] P. Avery,[15] A. Freyberger,[15] J. Rodriguez,[15] S. Yang,[15] J. Yelton,[15] D. Cinabro,[16] T. Liu,[16] M. Saulnier,[16] R. Wilson,[16] H. Yamamoto,[16] T. Bergfeld,[17] B.I. Eisenstein,[17] G. Gollin,[17] B. Ong,[17] M. Palmer,[17] M. Selen,[17] J. J. Thaler,[17] K.W. Edwards,[18] M. Ogg,[18] A. Bellerive,[19] D.I. Britton,[19] E.R.F. Hyatt,[19] D.B. MacFarlane,[19] P.M. Patel,[19] B. Spaan,[19] A.J. Sadoff,[20] R. Ammar,[21] P. Baringer,[21] A. Bean,[21] D. Besson,[21] D. Coppage,[21] N. Copty,[21] R. Davis,[21] N. Hancock,[21] M. Kelly,[21] S. Kotov,[21] I. Kravchenko,[21] N. Kwak,[21] H. Lam,[21] Y. Kubota,[22] M. Lattery,[22] M. Momayezi,[22] J.K. Nelson,[22] S. Patton,[22] R. Poling,[22] V. Savinov,[22] S. Schrenk,[22] R. Wang,[22] M.S. Alam,[23] I.J. Kim,[23] Z. Ling,[23] A.H. Mahmood,[23] J.J. O'Neill,[23] H. Severini,[23] C.R. Sun,[23] and F. Wappler[23]

(CLEO Collaboration)

[1] *Ohio State University, Columbus, Ohio, 43210*
[2] *University of Oklahoma, Norman, Oklahoma 73019*
[3] *Purdue University, West Lafayette, Indiana 47907*
[4] *University of Rochester, Rochester, New York 14627*
[5] *Southern Methodist University, Dallas, Texas 75275*
[6] *Syracuse University, Syracuse, New York 13244*
[7] *Vanderbilt University, Nashville, Tennessee 37235*
[8] *Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061*
[9] *California Institute of Technology, Pasadena, California 91125*
[10] *University of California, San Diego, La Jolla, California 92093*
[11] *University of California, Santa Barbara, California 93106*
[12] *Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*
[13] *University of Colorado, Boulder, Colorado 80309-0390*
[14] *Cornell University, Ithaca, New York 14853*
[15] *University of Florida, Gainesville, Florida 32611*
[16] *Harvard University, Cambridge, Massachusetts 02138*
[17] *University of Illinois, Champaign-Urbana, Illinois, 61801*
[18] *Carleton University, Ottawa, Ontario K1S 5B6 and the Institute of Particle Physics, Canada*
[19] *McGill University, Montréal, Québec H3A 2T8 and the Institute of Particle Physics, Canada*
[20] *Ithaca College, Ithaca, New York 14850*
[21] *University of Kansas, Lawrence, Kansas 66045*
[22] *University of Minnesota, Minneapolis, Minnesota 55455*
[23] *State University of New York at Albany, Albany, New York 12222*

Abstract

The angular distributions of the decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$ have been studied using the CLEO II detector. By performing a 3-dimensional maximum likelihood fit, the form factor ratio, $R = f_2/f_1$, is determined to be $-0.25 \pm 0.14 \pm 0.08$. The decay asymmetry parameter of the Λ_c averaged over q^2 is calculated to be $\alpha_{\Lambda_c} = -0.82^{+0.09}_{-0.06}{}^{+0.06}_{-0.03}$.

*Permanent address: University of Hawaii at Manoa

Charm semileptonic decays allow a determination of the magnitude of the form factors which parameterize the hadronic current because the Cabibbo-Kobayashi-Maskawa (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 and isospin 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 decays since HQET relates the form factors in Λ_c decay to those governing Λ_b 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]:

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

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]:

$$\begin{aligned}
\Gamma_S = \frac{d\Gamma}{dq^2 d\cos\Theta_W d\cos\Theta_\Lambda} &= B(\Lambda \to p\pi) \frac{1}{2} \frac{G_F^2}{(2\pi)^4} |V_{cs}|^2 \frac{q^2 P}{24 M_{\Lambda_c}^2} \\
\times \{ \frac{3}{8} (1 - \cos\Theta_W)^2 |H_{\frac{1}{2}1}|^2 (1 + \alpha_\Lambda \cos\Theta_\Lambda) &+ \frac{3}{8} (1 + \cos\Theta_W)^2 |H_{-\frac{1}{2}-1}|^2 (1 - \alpha_\Lambda \cos\Theta_\Lambda) \\
+ \frac{3}{4} \sin^2\Theta_W [|H_{\frac{1}{2}0}|^2 (1 + \alpha_\Lambda \cos\Theta_\Lambda) &+ |H_{-\frac{1}{2}0}|^2 (1 - \alpha_\Lambda \cos\Theta_\Lambda)] \}
\end{aligned} \tag{2}$$

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, and α_Λ is the $\Lambda \to p\pi$ decay asymmetry parameter measured to be 0.64 ± 0.01 [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 paper we follow reference [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 relationship 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_S an assumption must be made about the q^2 dependence of the form factors. We follow the model of Körner and Krämer (KK) [4] who use the dipole form, $f(q^2) = f(q^2_{max})(1 - q^2_{max}/m^2_{ff})^2/(1 - q^2/m^2_{ff})^2$, where the pole mass is chosen to be $m_{ff} = 2.11\mathrm{GeV/c}^2$. With the current statistical power, the angular distributions are not sensitive to the q^2 dependence of the form factors.

The data sample used in this study was collected with the CLEO II detector [5] at the Cornell Electron Storage Ring (CESR). The integrated luminosity consists of 3.0 fb^{-1} taken at and just below the $\Upsilon(4S)$ resonance, corresponding to approximately 4 million $e^+e^- \to c\bar{c}$ events. 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 the range $m_\Lambda < m_{\Lambda e^+} < m_{\Lambda_c}$ [6]. The minimum allowed momentum for positron candidates is 0.7 GeV/c. The Λ is reconstructed through its decay to $p\pi$. The dE/dx measurement of the proton candidate is required to be consistent with the expected value. We require the momentum of the $p\pi$ pair to be greater than 0.8 GeV/c in order to reduce combinatorial background. These Λ candidates are then combined with positrons, and the sum of Λ and e^+ momentum, $p_{\Lambda e^+}$, is required to be greater than 1.4 GeV/c. This cut reduces our dependence on the shape of the Λ_c fragmentation function at low momentum, which is poorly known.

The number of events passing these requirements is 1076, of which 137 ± 12 are consistent with fake Λ background, 120 ± 36 are consistent with fake positron background and 106 ± 21 with $\Xi_c \to \Xi e^+ \nu_e$, $\Xi \to \Lambda(\pi)$ feedthrough. Details of the background estimates can be found in a previous paper [7]. The sidebands of the $p\pi$ invariant mass distribution are used to estimate the fake Λ background in this study [8]. The fake positron background is estimated using events containing a Λ candidate, by multiplying the number of tracks satisfying our kinematic criteria which are not positively identified as a positron with the probability for a hadron to be identified as positron. The background from $\Xi_c \to \Xi e^+ \nu_e$ decays is estimated using the result of a previous analysis [9]. With the selection criteria described above, we find no evidence for $\Lambda e^+ \nu_e$ final states in which there are additional Λ_c^+ decay products [7]. In Fig. 1, we show the $m_{\Lambda e^+}$ distribution after Λ sideband subtraction and comparisons between the data and Monte Carlo (MC) distributions.

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 by the thrust axis of the event. The magnitude of the Λ_c momentum is then obtained by solving the equation $\vec{P}^2_{\Lambda_c} = (\vec{P}_\Lambda + \vec{P}_e + \vec{P}_{\nu_e})^2$. We determine the best solution by MC simulation following the procedure described in detail in [7]. After the Λ_c momentum is estimated, the three kinematic variables are obtained by working in the Λ_c center-of-mass frame. The resolutions on q^2/q^2_{max}, $\cos\Theta_\Lambda$ and $\cos\Theta_W$ determined by MC are 0.25, 0.25 and 0.2 respectively.

Using q^2/q^2_{max}, $\cos\Theta_\Lambda$ and $\cos\Theta_W$, we perform a 3-dimensional unbinned maximum likelihood fit in a manner similar to reference [10]. This technique enables a multi-dimensional 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 MC events in the three dimensional kinematic space. This is accomplished by generating one high statistics sample of MC events with a known value of the form factor ratio R and corresponding known values of the three kinematic variables q^2/q^2_{max}, $\cos\Theta_\Lambda$, and $\cos\Theta_W$ for each event. The generated events are then processed through the full detector simulation, offline analysis programs and selection criteria. Using the generated kinematic variables, the accepted MC events are weighted by the ratio of the decay distribution for the trial values of R to that of the generated distribution. The accepted MC events are now, therefore, distributed according to the probability density corresponding to the trial values of R. By such weighting, a likelihood may be evaluated for each data event for different values of the form factor ratio, and a fit performed. 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 MC events is not prohibitively high.

The $\Lambda_c^+ \to \Lambda e^+ \nu_e$ sample has signal to background in the approximate ratio 2:1. Background is incorporated into the fitting technique by constructing the log-likelihood function $ln\mathcal{L} = \sum_{i=1}^{N} ln(P_S\Gamma_S + P_B\Gamma_B)$, where N is the number of events in the signal region, P_S and P_B are the probabilities that events in this region are signal and background respectively, Γ_S is the signal shape modeled from signal MC and Γ_B is the background shape modeled by the background samples. Fake positron background is modeled by the fake positron data sample. Feedthrough background from $\Xi_c \to \Xi e^+ \nu_e$ is modeled by the MC sample which is generated according to the HQET consistent KK model. Fake Λ background is modeled using data events in the sidebands of the $p\pi$ invariant mass distribution.

Using the above method we find $R = -0.25 \pm 0.14$ where the error is statistical. The confidence level of the fit is determined to be 15% using the method of nearest neighbors [11]. Fig. 2 and Fig. 3 show the projections of the q^2/q^2_{max}, $\cos\Theta_\Lambda$ and $\cos\Theta_W$ distributions for the data and for the fit. Correlations between kinematic variables for the data and fit are shown in Fig. 4.

We have considered the following sources of systematic error and give our estimate of their magnitude in parentheses. The statistical error in the MC sample is estimated by dividing the MC into three equal parts and repeating the fit (0.02). The error due to the search volume size is determined by varying the size of the search volume (0.04). The error due to background normalization and shape are determined by varying the estimated number of the background events in the signal region by one standard deviation and by using different background samples (0.03). The error associated with the ratio of form factors for the decay of $\Xi_c \to \Xi e^+ \nu_e$ is determined by varying this ratio and repeating the fit (0.04). As this measurement is insensitive to the production polarization, $\mathcal{P}$, of the Λ_c no systematic error has been included from this source [12]. The sensitivity to the q^2 dependence is also investigated by using functional forms other than the dipole form and by using a modified dipole form which gives mildly different q^2 dependences for f_1 and f_2. The variation of the value of R derived from these different fits is found to be small and no systematic error has been included. The error associated with the uncertainty in the Λ_c fragmentation function is estimated by varying this function (0.01). The error associated with MC modeling of slow pions from Λ decay is obtained by varying this efficiency according to our understanding of the CLEO II detector (0.01). To estimate the error associated with the technique of incorporating background into the fit, two other methods of computing the log-likelihood ratio are used: direct background subtraction and a hybrid of the method outlined earlier and direct subtraction. The difference between the central values found by these three methods (0.03) is taken as the systematic error. Adding all sources of systematic error in quadrature we find $R = -0.25 \pm 0.14 \pm 0.08$.

Using the value of R obtained here and the HQET consistent KK model, the mean value of the decay asymmetry parameter of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ is calculated to be $\alpha_{\Lambda_c} = -0.82^{+0.09}_{-0.06}{}^{+0.06}_{-0.03}$. The average value of q^2 in the KK model ($R = -0.25$) is 0.7 $(\mathrm{GeV}/c^2)^2$. This is consistent with our previous measurement of α_{Λ_c} determined from the $\cos\Theta_\Lambda$ distribution [7] but has a smaller error since it is obtained using more experimental information and additional data.

In conclusion, using a 3-dimensional maximum likelihood fit the angular distributions of $\Lambda_c^+ \to \Lambda e^+ \nu_e$ have been studied and the form factor ratio, $R = f_2/f_1$, is found to be $-0.25 \pm 0.14 \pm 0.08$. At the current level of experimental sensitivity the hadronic matrix element in the semileptonic decay of the Λ_c baryon is adequately described by two form factors as predicted by HQET.

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FIGURES

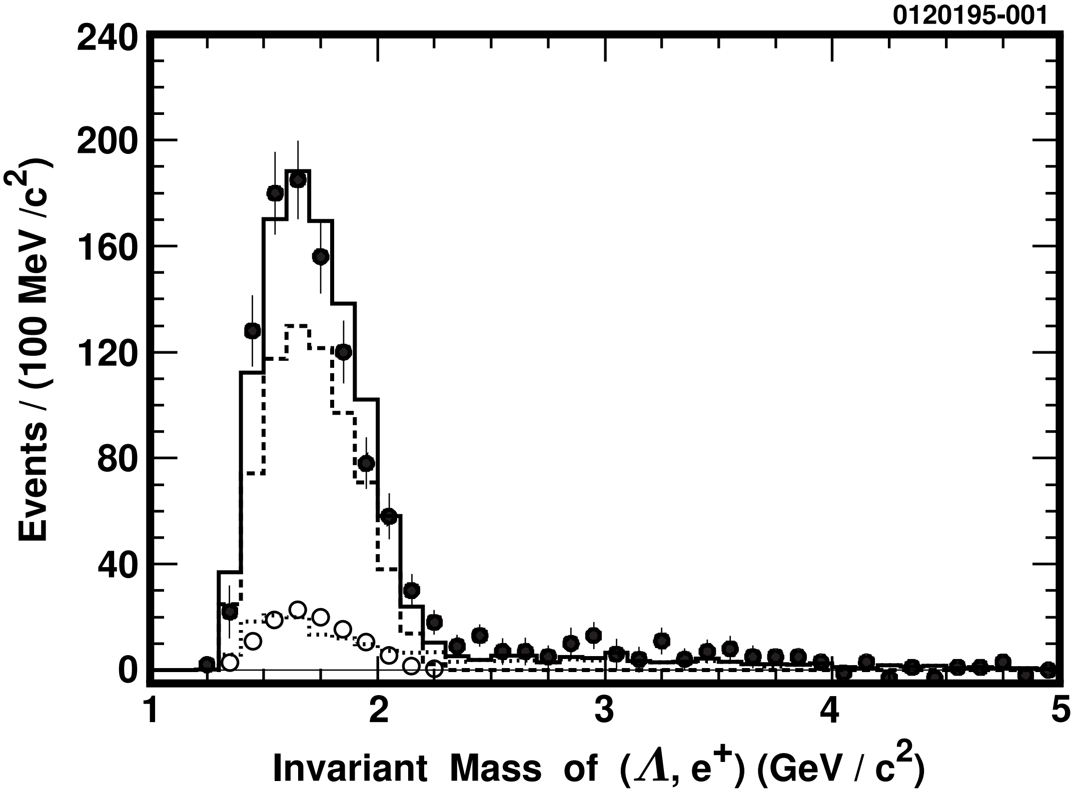

FIG. 1. Invariant Λe^+ mass for right sign combinations. The points with error bars are data after subtraction of the contribution of fake lambdas estimated using the $p\pi$ invariant mass sidebands. The dotted line and the open circles show the fake positron and the feedthrough backgrounds respectively. The dashed line shows the MC prediction for $\Lambda_c^+ \to \Lambda e^+ \nu_e$ normalized to the data after subtraction of the backgrounds. The solid line shows the sum of the MC prediction and the backgrounds.

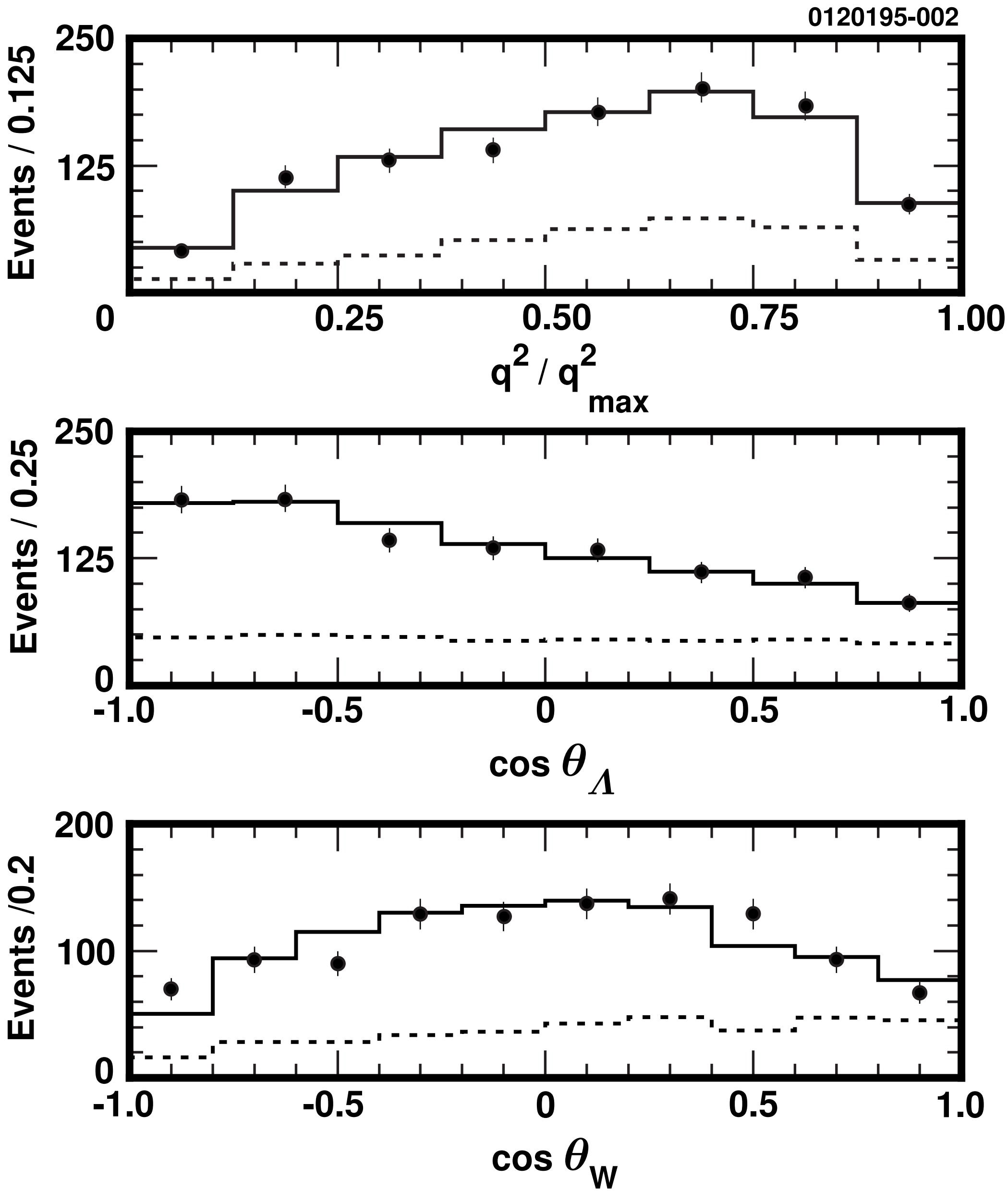

FIG. 2. Projections of the data (points with error bars) and the fit (solid histogram) for q^2/q^2_{max}, $\cos\Theta_\Lambda$ and $\cos\Theta_W$. The dashed lines show the background distributions.

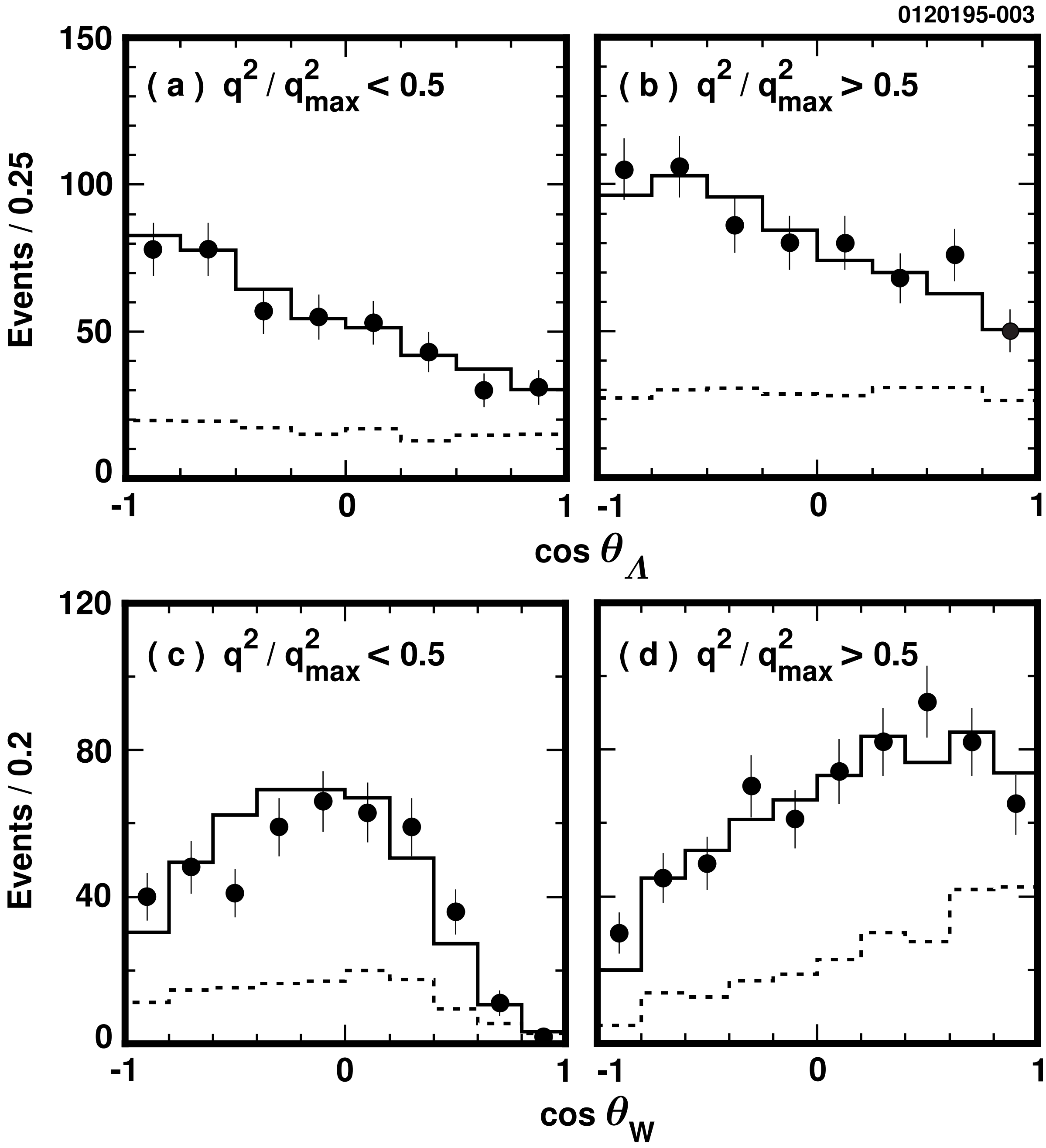

FIG. 3. Projections of the data (points with error bars) and the fit (solid histogram) onto $\cos\Theta_\Lambda$ and $\cos\Theta_W$ for different q^2/q^2_{max} regions. The dashed lines show the background distributions.

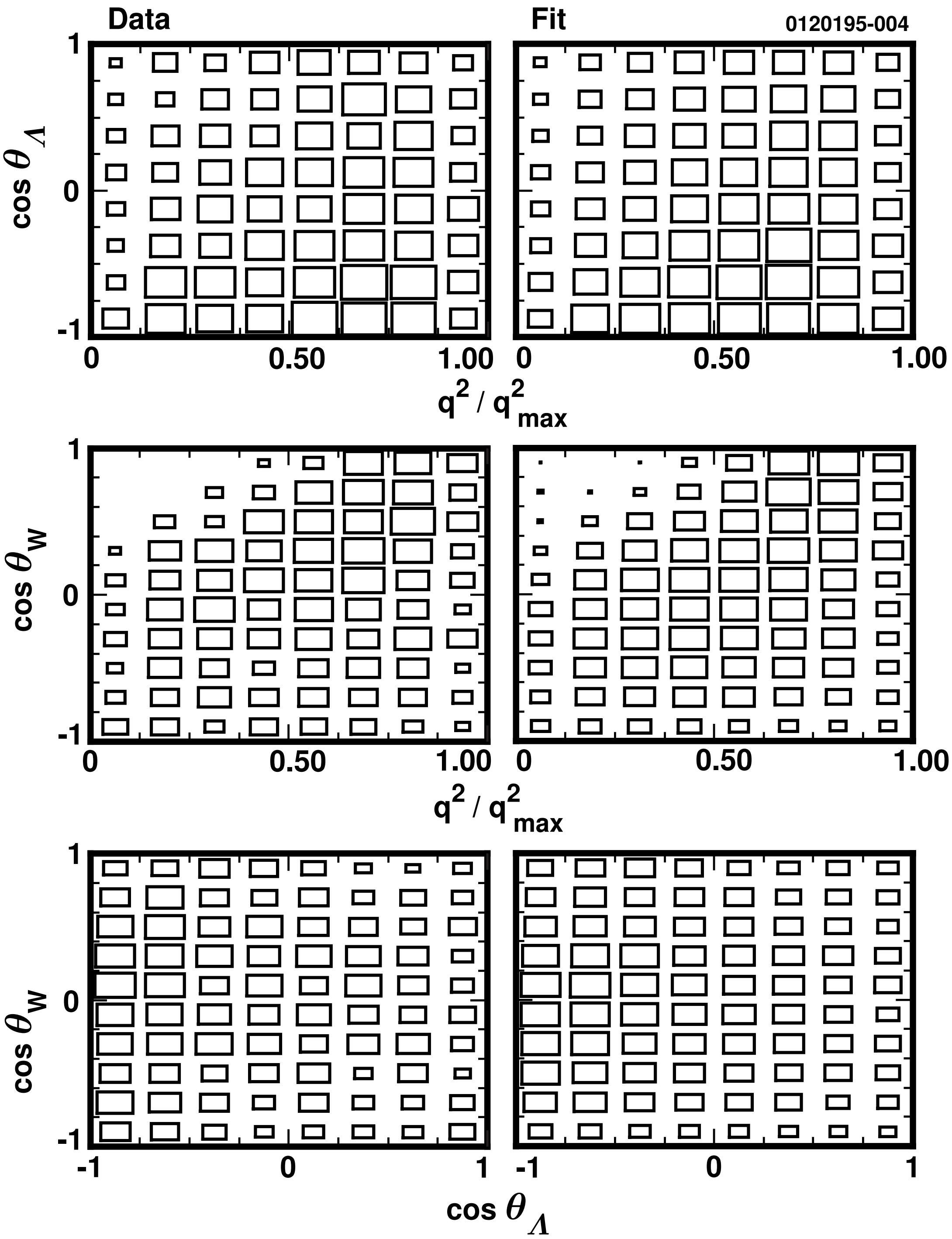

FIG. 4. Correlations between q^2/q^2_{max}, $\cos\Theta_\Lambda$ and $\cos\Theta_W$ for data (left) and the fit (right). The size of the box in the plots is proportional to the number of events.