The Production and Decay Dynamics of the Charmed Baryon Λ_c^+ in e^+e^- Annihilations near Threshold

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abstract

The study of charmed baryons is crucial for investigating the strong and weak interactions in the Standard Model and for gaining insights into the internal structure of baryons. In e^+e^- experiments, the lightest charmed baryon, Λ_c^+, can be produced in pairs through single photon annihilation. This process can be described by two complex electromagnetic form factors, whose non-zero relative phase gives rise to a transverse polarization of the charmed baryon. We present the first observation of the transverse polarization of Λ_c^+ in the reaction $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$, based on 6.4 fb^{-1} of e^+e^- annihilation data collected at center-of-mass energies between 4600 MeV and 4951 MeV with the BESIII detector. The decay asymmetry parameters and strong phase shifts in the decays $\Lambda_c^+ \to pK_S^0$, $\Lambda\pi^+$, $\Sigma^0\pi^+$, $\Sigma^+\pi^0$ are simultaneously extracted from joint angular distributions. These results are vital for understanding CP violation and its role in the matter-antimatter asymmetry of the Universe.

Introduction

Although baryons constitute the most abundant form of matter, our understanding of them lags behind that of mesons. The addition of one constituent quark in baryons compared to quark-antiquark mesons introduces numerous challenges in theoretical calculations, making high-order and diquark correlation contributions difficult to predict accurately. One effective approach to study baryon structure is through measuring their electromagnetic form factors (EMFFs). In e^+e^- annihilation processes, time-like form factors are accessible, providing insights into the electromagnetic structure of baryons.

For a spin-1/2 baryon like Λ_c^+, the process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ is dominated by single photon exchange. The cross-section can be described by the complex electric form factor G_E and magnetic form factor G_M, which are functions of the four-momentum squared q^2 of the photon. The angular distribution of the produced baryon is characterized by two parameters: the angular parameter α_0 and the phase difference between the EMFFs $\Delta\Phi = \arg(G_M) - \arg(G_E)$.

Physics Objectives

Transverse Polarization Measurement

The transverse polarization of the baryon can be parameterized as:

$$P_y(\cos\theta_0) = \frac{3}{2(3+\alpha_0)}\sqrt{1-\alpha_0^2}\sin\theta_0\cos\theta_0\sin\Delta\Phi \quad (1)$$

where θ_0 is the polar angle of the Λ_c^+ in the CM frame. A non-vanishing $\Delta\Phi$ gives rise to the transverse polarization effect, which depends on the momentum direction of the baryon. This polarization effect has been observed in hyperons by BESIII, leading to the highest precision measurements of decay parameters. However, this effect has never been observed in charmed baryons until now. Figure 1 shows the definitions of helicity frames and angles used in the angular analysis.

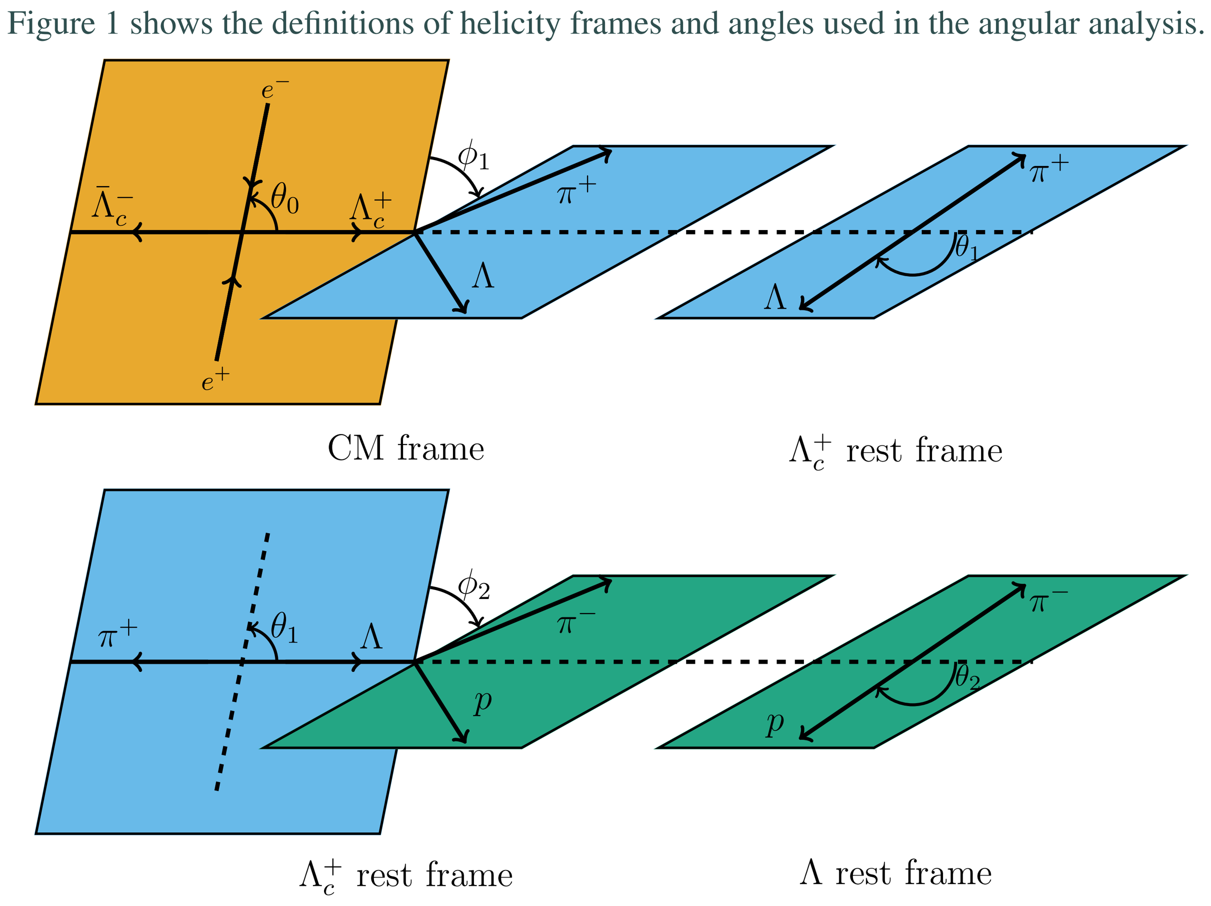

Figure 1: Definitions of helicity frames and angles for the decay chain $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$, $\Lambda_c^+ \to \Lambda\pi^+$, $\Lambda \to p\pi^-$

Decay Asymmetry Parameters

For weak decays of $\Lambda_c^+ \to BP$ (where B is a spin-1/2 baryon and P is a pseudoscalar meson), the angular distribution is described by three decay asymmetry parameters. The parameter α represents the parity-violating decay asymmetry arising from interference between S- and P-wave amplitudes. The parameters β and γ describe the polarization transfer components, related through: $\beta = \sqrt{1-\alpha^2}\sin\Delta_{BP}$, $\gamma = \sqrt{1-\alpha^2}\cos\Delta_{BP}$ where Δ_{BP} is the phase shift between helicity amplitudes [1]. These parameters satisfy the constraint $\alpha^2+\beta^2+\gamma^2 = 1$. In the Standard Model, the amplitude can be written as $\mathcal{M} = i\bar{u}_f(A - B\gamma_5)u_i$, where A and B are the S- and P-wave amplitudes reflecting the weak decay dynamics. With polarization and decay parameters defined, conjoint angular distribution can be constructed [2].

Method

Data Sample and Detector

The analysis is performed using 6.4 fb^{-1} of e^+e^- annihilation data collected with the BESIII detector at thirteen center-of-mass energies between 4600 and 4951 MeV. The BESIII detector is a cylindrical magnetic spectrometer covering 93% of the full solid angle, consisting of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), a CsI(Tl) electromagnetic calorimeter (EMC), and a superconducting solenoid providing a 1.0 T magnetic field.

Signal Reconstruction and Angular Analysis

A single tag approach is employed, reconstructing only one Λ_c^+ or $\bar{\Lambda}_c^-$ baryon per event. Five decay channels are studied: four two-body hadronic decays ($\Lambda_c^+ \to pK_S^0$, $\Lambda\pi^+$, $\Sigma^0\pi^+$, $\Sigma^+\pi^0$) and one three-body decay ($\Lambda_c^+ \to pK^-\pi^+$) which is used only to constrain polarization with polarimeter method from LHCb collaboration [3]. The beam-constrained mass $M_{BC} = \sqrt{E_{beam}^2/c^4 - |\vec{p}_{\Lambda_c^+}|^2/c^2}$ is used to identify signal candidates. The joint angular distribution is analyzed using a multidimensional unbinned maximum likelihood fit, with free parameters including α_0, $\Delta\Phi$, and the decay asymmetry parameters.

Results

Observation of Transverse Polarization

The transverse polarization of Λ_c^+ baryons is discovered for the first time with an overall significance exceeding 10.0σ. The phase difference $\Delta\Phi$ between electromagnetic form factors is measured at thirteen energy points, demonstrating significant non-zero values with the highest significance of 14.1σ at $\sqrt{s} = 4682$ MeV. Figure 2 displays the moment distribution that directly demonstrates the transverse polarization effect through the oscillation pattern as a function of $\cos\theta_0$.

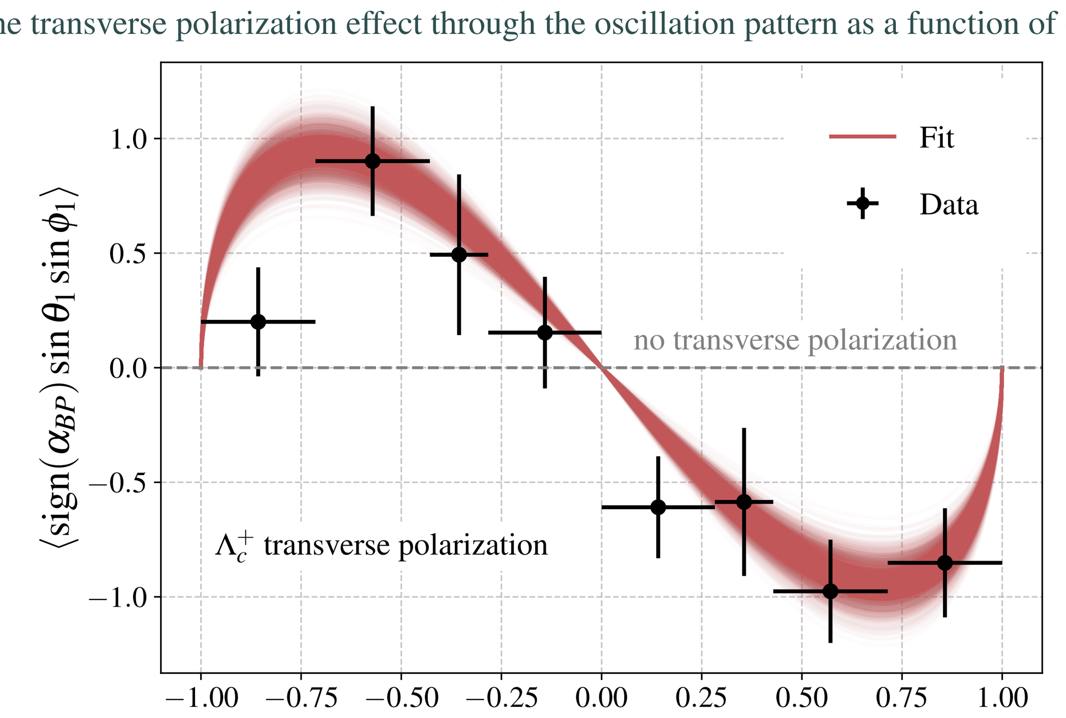

Figure 2: The moment $\langle \mathrm{sign}(\alpha_{BP})\sin\theta_1\sin\phi_1\rangle$ distribution showing the transverse polarization effect for $\Lambda_c^+ \to pK_S^0$, $\Lambda\pi^+$, and $pK^-\pi^+$ channels

The comparison between experimental measurements and theoretical predictions is shown in Figure 3. The measured $|G_E/G_M|$ ratios and $\sin\Delta\Phi$ values reveal significant deviations from theoretical predictions based on vector meson dominance models, indicating that the production mechanism of Λ_c^+ in e^+e^- collisions requires further theoretical investigation.

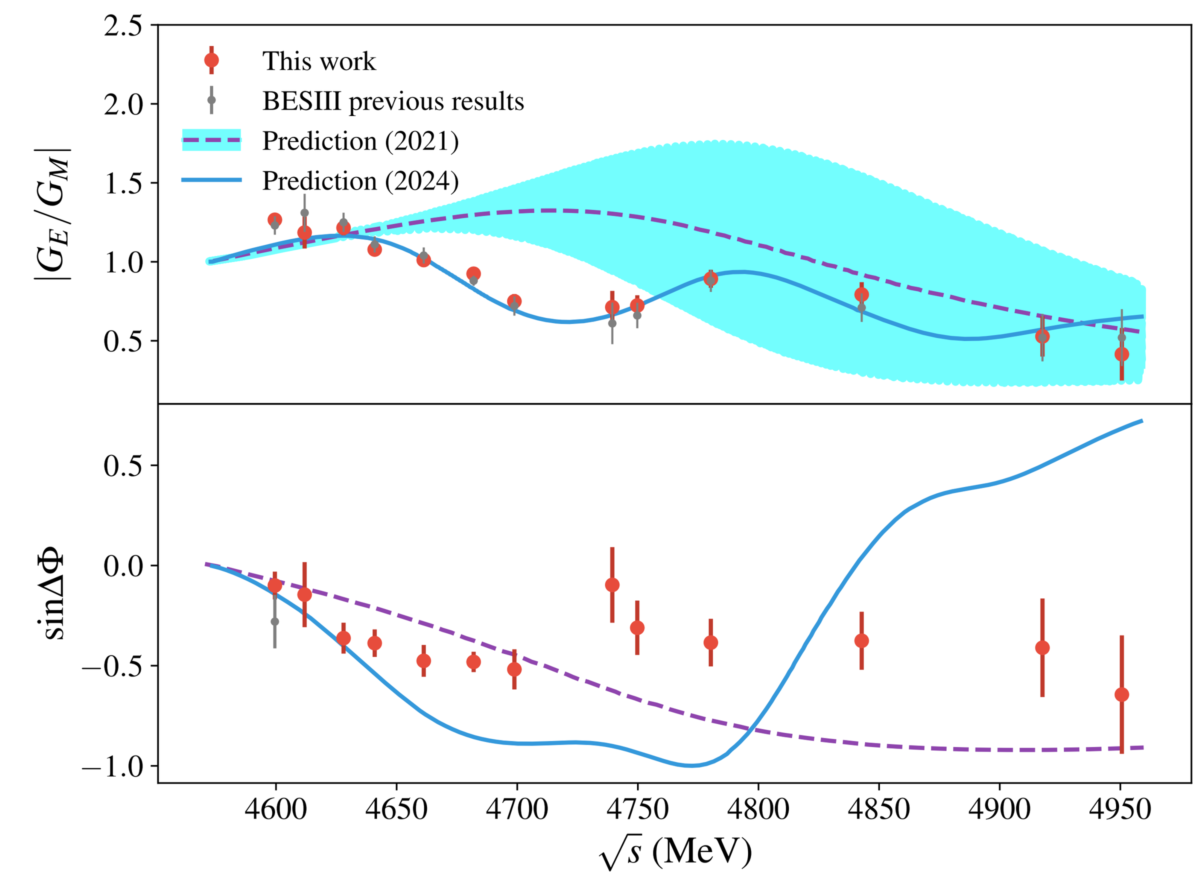

Figure 3: Comparison of $|G_E/G_M|$ (top) and $\sin\Delta\Phi$ (bottom) between this work (red points) and theoretical predictions from 2021 (dashed line) and 2024 (solid line)

Decay Asymmetry Parameters and Phase Shifts

The decay asymmetry parameters are precisely measured for all channels with significantly improved precision. and CP violation is tested with these parameters. Notably, $\alpha_{pK_S^0} = -0.918^{+0.133}_{-0.082} \pm 0.031$ changes sign compared to previous BESIII results, now consistent with theoretical calculations and recent LHCb measurements.Figure 4 shows the comprehensive comparison of decay asymmetry parameters with theoretical predictions spanning three decades and experimental measurements. The results from this work (shown in red with yellow bands) resolve the long-standing discrepancy in the sign of $\alpha_{pK_S^0}$ and provide the most precise measurements to date.

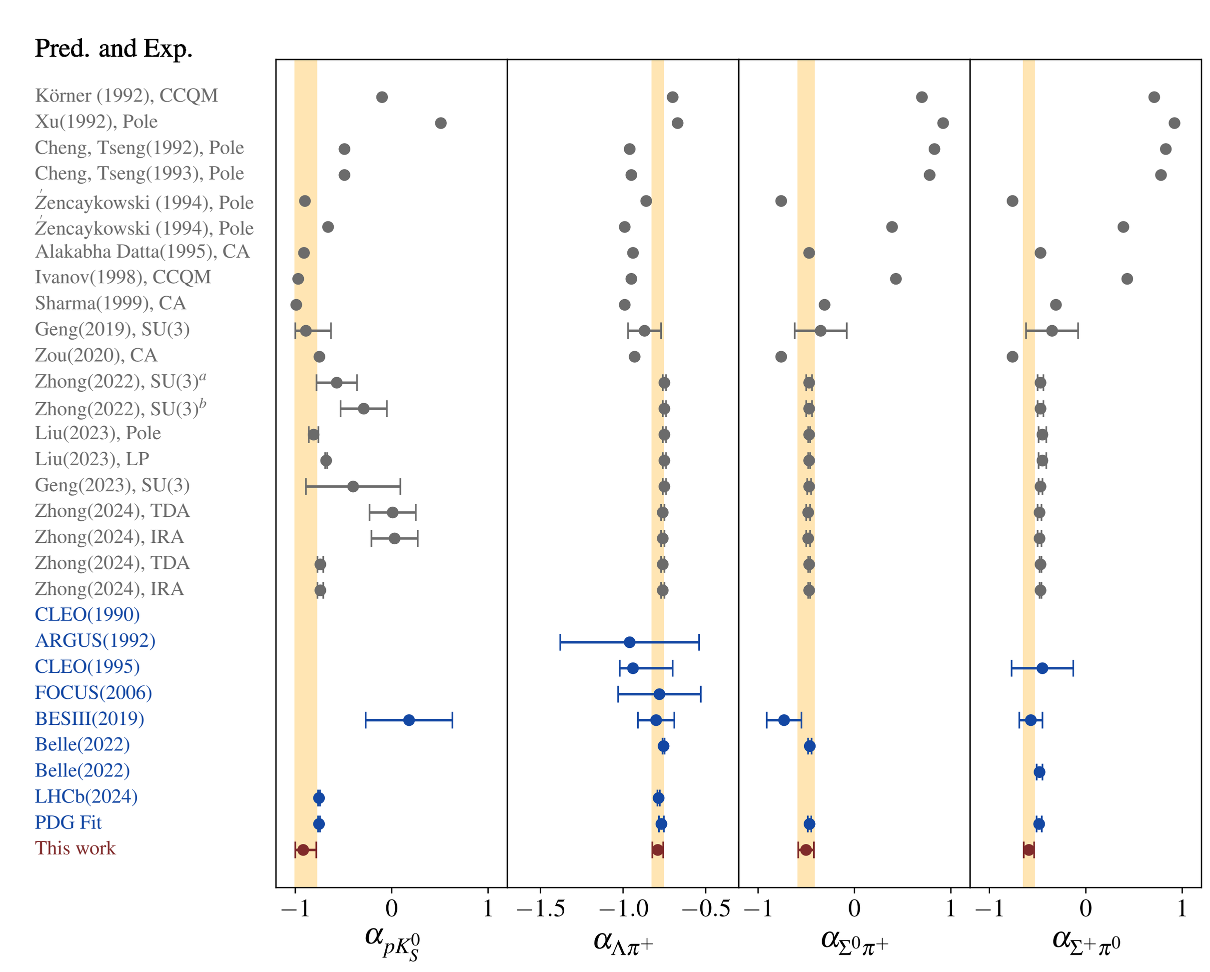

Figure 4: Comparison of decay asymmetry parameters with theoretical predictions (gray points) and experimental measurements (blue points). This work is shown in red with yellow uncertainty bands.

Weak Decay Amplitudes

The weak decay amplitudes $|A|$ and $|B|$ are extracted from the measured decay asymmetry parameters [4]. Figure 5 presents the two-dimensional density distributions of these amplitudes for different decay channels, compared with various theoretical models. The contours correspond to 68.2%, 95.4%, and 99.7% confidence levels. The evolution from early theoretical predictions to recent calculations incorporating strong phase shifts is clearly visible, demonstrating improved agreement with experimental data.

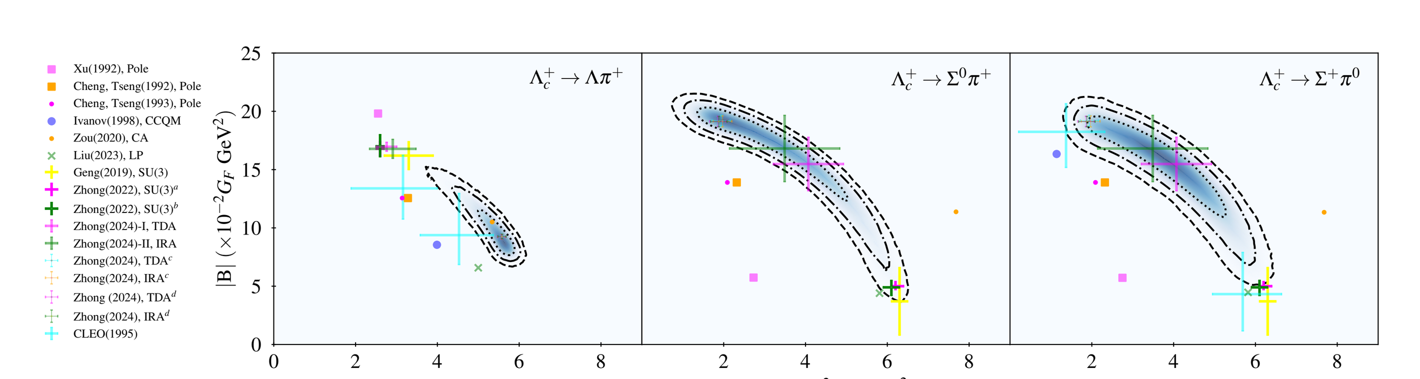

Figure 5: Two-dimensional density distributions of weak amplitudes $|A|$ and $|B|$ for $\Lambda_c^+ \to \Lambda\pi^+$, $\Sigma^0\pi^+$, and $\Sigma^+\pi^0$ channels

Conclusions

The observation of transverse polarization in Λ_c^+ baryons represents a complete description of charmed baryon production in e^+e^- annihilations. Our precise measurements of decay asymmetry parameters resolve previous discrepancies and reveal significant strong phase shifts between S- and P-waves, providing crucial constraints on theoretical models. The extraction of weak decay amplitudes offers direct tests of QCD calculations and helps refine our understanding of non-perturbative effects. These findings establish a robust framework for future experimental programs at Belle II, LHCb, and the proposed Super Tau-Charm Facility, setting the stage for deeper insights into hadronic dynamics and potential new physics beyond the Standard Model.

Acknowledgements

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