Search for CP Violation in Ξ and Λ Hyperon Decays: Status of the *HyperCP* Experiment

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HyperCP (E871), a Fermilab experiment searching for CP violation in Ξ and Λ hyperon decays, finished its first data taking run at the end of 1997, and accumulated over one billion Ξ^- and $\overline{\Xi}^+$ decays. A sensitivity of approximately 2×10^{-4} in $A_{\Xi\Lambda} = (\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}})/(\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}})$ is expected. A non-zero value of $A_{\Xi\Lambda}$ would be unambiguous evidence for direct CP violation. A brief review of CP violation in hyperon decays is given, the *HyperCP* spectrometer is described, and the status of the analysis and future prospects are discussed.

1. Introduction

In the 35 years since the discovery of CP violation our understanding of the phenomenon has improved little despite a long series of beautiful experiments. Experimentally it remains a small peculiarity unique to a few decays of the K_L. In the standard model CP violation lies with the complex phase in the Cabbibo–Kobayashi–Maskawa (CKM) matrix. The origin of this phase, if it exists, remains a mystery. If our theoretical prejudices are correct, CP violation should appear outside of the decay of the K_L, and should express itself directly in the weak decays of hadrons, and not only indirectly through the mixing between particle and anti-particle. It is vital to confirm these theoretical expectations and determine experimentally whether CP violation is a universal property of the weak interaction, and whether direct CP violation exists.

Large experimental efforts have been underway for some twenty years to search for direct CP violation in kaon decays, and the search for CP violation in B decays will commence in earnest with the next generation of electron-positron and hadron colliders. There is, however, another promising arena in which to look for direct CP violation, and CP violation outside of the neutral kaon system: in the nonleptonic decays of strange baryons, or hyperons. This is the goal of *HyperCP*, the first *dedicated* hyperon CP violation experiment, which will probe hyperon CP violation through the decays $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$, $\overline{\Lambda} \to \overline{p}\pi^+$.

2. Signatures for Hyperon CP Violation

The phenomenology of CP violation in hyperon decays has been discussed in several excellent references (see Ref. [1] for example). We briefly review it here. Conservation of angular momentum allows both *S*- and *P*-wave final states in hyperon two-body decays. Since the parity of the final state is $(-1)^{L+1}$, only the *P*-wave final state would be allowed if parity were conserved. It is not and the decay can go into admixtures of both *S*- and *P*-wave final states:

$$\begin{aligned} S &= +\sum_i S_i e^{i(\delta_i^S+\phi_i^S)}, \\ P &= +\sum_i P_i e^{i(\delta_i^P+\phi_i^P)}, \\ \overline{S} &= -\sum_i S_i e^{i(\delta_i^S-\phi_i^S)}, \\ \overline{P} &= +\sum_i P_i e^{i(\delta_i^P-\phi_i^P)}, \end{aligned} \quad (1)$$

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where δ_i are the strong final-state interaction phases, ϕ_i are the weak-interaction phases, and i runs over all possible amplitudes for final isospin states and changes in isospin ΔI. The overlined quantities refer to the anti-hyperon.

In terms of the S- and P-wave amplitudes, the hyperon non–leptonic decays are conventionally described by the Lee–Yang variables α, β, and γ:

$$\alpha = \frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2\mathrm{Im}(S^* P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}, \tag{2}$$

where $\alpha^2 + \beta^2 + \gamma^2 = 1$. The decay distribution of the daughter spin 1/2 baryon in the rest frame of the parent hyperon (the Λ in the decay $\Xi^- \to \Lambda\pi^-$, for example) is not isotropic, because of parity violation, but is given by:

$$\frac{dP}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_p \vec{P}_p \cdot \hat{p}_d), \tag{3}$$

where $\vec{P}_p$ is the parent hyperon polarization and $\hat{p}_d$ is the daughter baryon momentum direction in the rest frame of the parent. The daughter itself is polarized with a polarization given by:

$$\vec{P}_d = \frac{(\alpha_p + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta_p(\vec{P}_p \times \hat{p}_d) + \gamma_p(\hat{p}_d \times (\vec{P}_p \times \hat{p}_d))}{(1 + \alpha_p \vec{P}_p \cdot \hat{p}_d)}.$$

Note that when the parent is unpolarized the daughter is emitted in a helicity state with a polarization given by the parent alpha parameter, α_p.

If CP is conserved then the Lee-Yang parameters and the partial decay rate ($\Gamma \propto |S|^2 + |P|^2$) transform under CP according to

$$\alpha = -\overline{\alpha}, \quad \beta = -\overline{\beta}, \quad \gamma = \overline{\gamma}, \quad \Gamma = \overline{\Gamma}. \tag{4}$$

If T invariance holds, β would be zero in the absence of final state interactions. Observables that are sensitive to CP asymmetries include:

$$\Delta = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}, \quad A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}, \quad B = \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}}. \tag{5}$$

Determining α requires measuring the decay distribution of the daughter from a hyperon parent of precisely known polarization. Determining β requires measurement of the daughter polarization from a hyperon parent of precisely known polarization.

3. Theoretical Expectations

Model independent expressions for the observables given in Eqs. 5 have been explicitly calculated for various hyperon decays [1]. To leading order they are, for $\Lambda \to p\pi^-$ decay:

$$\begin{aligned} \Delta_\Lambda &\cong \sqrt{2}\frac{S_{33}}{S_{11}} \sin(\delta_3^S - \delta_1^S)\sin(\phi_3^S - \phi_1^S), \\ A_\Lambda &\cong -\tan(\delta_1^P - \delta_1^S)\sin(\phi_1^P - \phi_1^S), \\ B_\Lambda &\cong \cot(\delta_1^P - \delta_1^S)\sin(\phi_1^P - \phi_1^S), \end{aligned} \tag{6}$$

and for $\Xi^- \to \Lambda\pi^-$ decay:

$$\begin{aligned} \Delta_\Xi &= 0, \\ A_\Xi &\cong -\tan(\delta_2^P - \delta_2^S)\sin(\phi_1^P - \phi_1^S), \\ B_\Xi &\cong \cot(\delta_2^P - \delta_2^S)\sin(\phi_1^P - \phi_1^S), \end{aligned} \tag{7}$$

where S_{ij} corresponds to $S_{2\Delta I,2I}$, ΔI is the change in isospin, and I is the isospin of the final state. The CP asymmetry Δ results from the interference between the $|\Delta I| = 1/2$ and $|\Delta I| = 3/2$ amplitudes whereas the other asymmetries are expressed through the interference of S- and P-wave amplitudes. The parameter Δ_Ξ vanishes because in Ξ^- decays there is only one final-state isospin. Note that CPT invariance only guarantees the total decay width or lifetime be the same for particle and anti-particle.

A difference in the S- and P-wave final-state interaction phases is needed for A or B to be nonzero. The $p\pi^-$ hadronic phase shifts have been measured to be [2]:

$$\delta_1^S = 6.0°, \quad \delta_3^S = -3.8°, \quad \delta_1^P = -1.1°, \quad \delta_3^P = -0.7°, \tag{8}$$

where the errors are approximately $\pm 1.5°$. There are no measurements of the $\Lambda\pi$ final-state phase shifts and theoretical predictions span a large range. In calculations done over 30 years ago Nath and Kumar [3] obtained: $\delta_2^S = -18.7°$ and

Table 1
Some predictions for A_Ξ and A_Λ.

Model	A_Ξ $[10^{-4}]$	A_Λ $[10^{-4}]$	Reference
CKM Model	$-(0.1-1)$	$-(0.1-0.5)$	[8]
Weinberg	≈ -3.2	≈ -0.25	[1]
Multi-Higgs (FCNE)	≈ 0	≈ 0	[8]
LR (isoconjugate)	≈ 0.5	≈ -0.11	[1]
LR (with mixing)	< 1	< 7	[9]

Table 2
Experimental limits on A_Λ.

Mode	Limit	Experiment	Reference
$pp \to \Lambda X$, $\overline{p}p \to \overline{\Lambda}X$	-0.02 ± 0.14	R608	[10]
$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	0.01 ± 0.10	DM2	[11]
$p\overline{p} \to \Lambda\overline{\Lambda}$	0.013 ± 0.022	PS185	[12]

$\delta_2^P = -2.7°$, and Martin [4] obtained $\delta_2^P = -1.2°$. Recent calculations using chiral perturbation theory give smaller values with Lu *et al.* [5] obtaining $\delta_2^S = 0°$ and $\delta_2^P = -1.7°$ and Datta and Pakvasa [6] obtaining $\delta_2^S = 0.3°$. If these recent calculations hold up, then finding CP violation through A_Ξ will be extremely difficult.

Calculations of the CP asymmetries in hyperon decays are difficult and results are not thought to be reliable to better than an order of magnitude, with the largest uncertainty due to the inability to determine the hadronic matrix elements. The hierarchy of the observables given above has been estimated by Donoghue *et al.* who find very roughly that $\Delta \approx A/10 \approx B/100$ [1]. A is suppressed relative to B by the small value of the final state phase shifts, whereas Δ is further suppressed by the $|\Delta I| = 1/2$ rule. The large value of B is somewhat misleading because the denominator, $\beta - \overline{\beta}$, is small. Also the advantage of the larger B is offset by the extreme experimental difficulty in precisely measuring the polarization of both parent and daughter.

The magnitudes of the predicted CP asymmetries are model dependent. In the standard model CP violation effects are due solely to the complex phase in the CKM matrix and hence hyperon CP asymmetries can only arise from matrix elements which involve transitions to the third quark generation. These are thought to be dominated by the gluon penguin diagram for both kaon and hyperon decays. Theories with no $|\Delta S| = 1$ CP-odd effects, such as superweak models and models with a very heavy neutral Higgs, predict no CP asymmetries. Models in which $|\Delta S| = 1$ CP nonconservation is dominant, such as the Weinberg model [7], predict asymmetries which are on the order of those calculated in the standard model. In Table 1 are shown recent predictions for the CP asymmetries A_Ξ and A_Λ.

4. Present Experimental Limits

The only tests of CP invariance in hyperon decays come from the comparison of the alpha parameters in $\Lambda \to p\pi^-$ and $\overline{\Lambda} \to \overline{p}\pi^+$ decays. The three published results are given in Table 2. Each of the three experiments used a different technique, and all were limited by statistical, not systematic errors.

The first result in Table 2 is from an ISR experiment (R608) which produced Λ and $\overline{\Lambda}$ in the beam fragmentation region in $pp \to \Lambda X$ and $\overline{p}p \to \overline{\Lambda}X$ reactions. They quote $\alpha P(\overline{\Lambda})/\alpha P(\Lambda) = -1.04 \pm 0.29$ from 17 028 Λ and 9553 $\overline{\Lambda}$ decays. Assuming that the Λ and $\overline{\Lambda}$ polarizations are identical — which is rigorously true under C invariance only if the Λ and $\overline{\Lambda}$ polarizations are identical in $p\overline{p} \to \Lambda X$ and $pp \to \Lambda X$ reactions —

their result can be converted to a measurement of $A_\Lambda = -0.02 \pm 0.14$.

The second result of Table 2 is from $J/\psi \rightarrow \Lambda\overline{\Lambda}$ decays measured by the DM2 detector at the Orsay DCI e^+e^- colliding ring. Measurement of the correlation between the proton and anti-proton momenta allows the product $\alpha_\Lambda \alpha_{\overline{\Lambda}}$ to be extracted through the differential cross section. Fixing α_Λ to its standard value (0.642) they obtain from 1077 $\Lambda\overline{\Lambda} \rightarrow p\pi^-$ decays $\alpha_{\overline{\Lambda}} = -0.63 \pm 0.13$ corresponding to $A_\Lambda = 0.01 \pm 0.10$.

The third result is from a LEAR experiment (PS185) producing Λ hyperons in the exclusive reaction $\overline{p}p \rightarrow \Lambda\overline{\Lambda}$. The Λ and $\overline{\Lambda}$ are found to have a large predominately negative polarization. The two polarizations are rigorously equal by C-parity conservation in strong interactions. A total of 95 832 $\Lambda\overline{\Lambda}$ pairs taken at several different beam momenta were used to obtain $A_\Lambda = 0.013 \pm 0.022$.

5. The HyperCP Experiment

A new Fermilab experiment — the ***HyperCP*** experiment (E871) [13] — intends to measure both A_Λ and A_Ξ to a sensitivity of approximately 10^{-4}, two orders of magnitude better than the present limit. ***HyperCP*** finished a first data taking run late in 1997 and is preparing for a second run in 1999.

5.1. Experimental Technique

In ***HyperCP*** the hyperon and anti-hyperon are not produced simultaneously, and hence they are no longer required by symmetry arguments to have the same polarization, as is the case with threshold $p\overline{p} \rightarrow \Lambda\overline{\Lambda}$ production at LEAR. The ***HyperCP*** experiment, however, takes advantage of the fact that Ξ^- and $\overline{\Xi}^+$ hyperons with *zero* polarization can be made by requiring that they be produced at zero degrees, where parity conservation in the strong interaction requires that the polarization be identically zero. A Λ from the weak decay of an unpolarized Ξ ($\rightarrow \Lambda\pi$) is found in a pure helicity state with a polarization magnitude given by the parent Ξ alpha parameter: $P_\Lambda = \alpha_\Xi$. Hence, if CP is a good symmetry in Ξ and $\overline{\Xi}$ decays, then Λ and $\overline{\Lambda}$ have equal and opposite polarizations. The decay distributions of the

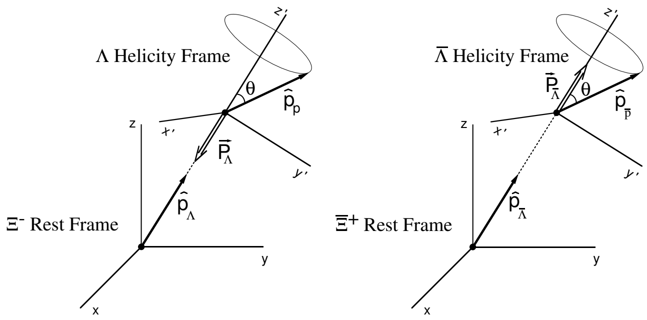

Figure 1. The Λ and $\overline{\Lambda}$ helicity frames.

proton and anti-proton in the frame in which the Λ direction in the Ξ rest frame defines the polar axis — the Λ helicity frame (see Fig. 1) — are given by:

$$\begin{aligned} \frac{dN}{d(\cos\theta)} &= \frac{N_0}{2}(1 + \alpha P \cos\theta), \\ &= \frac{N_0}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta), \\ &= \frac{N_0}{2}(1 + \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}} \cos\theta). \end{aligned} \tag{9}$$

If CP symmetry is good in ***both*** Ξ and Λ decays then $\alpha_{\overline{\Xi}} = -\alpha_\Xi$ and $\alpha_{\overline{\Lambda}} = -\alpha_\Lambda$ and the decay distributions of the proton and anti-proton are identical, as is every other kinematic parameter in the Ξ^- and $\overline{\Xi}^+$ decays. Hence exactly reversing the polarity of the spectrometer magnet results in a CP symmetric apparatus.

It is evident from Eq. 9 that differences between the slopes of the Ξ^- and $\overline{\Xi}^+$ $\cos\theta$ distributions can be due to CP violation in either the Ξ or Λ decays — the experiment is by necessity sensitive to CP violation in both:

$$A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}}}{\alpha_\Xi \alpha_\Lambda + \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}}} \cong A_\Xi + A_\Lambda. \tag{10}$$

Most theoretical calculations predict that A_Ξ and A_Λ should have the same sign, and as mentioned above, current theoretical prejudice favors a large value of A_Λ. If a nonzero asymmetry is mea-

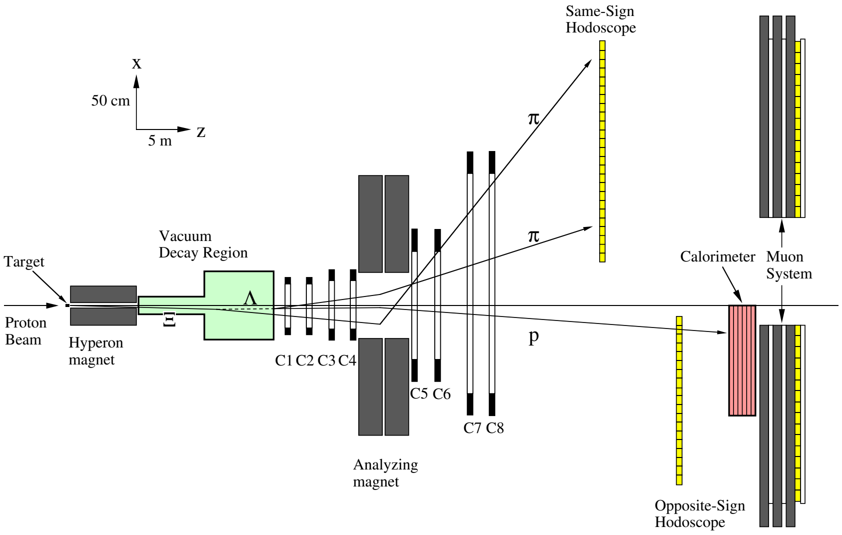

Figure 2. Plan view of the *HyperCP* apparatus.

sured the experiment cannot distinguish which hyperon, if not both, is the source.

5.2. The HyperCP Spectrometer

A plan view of the *HyperCP* spectrometer is shown in Fig. 2. The apparatus consists of a target immediately followed by a curved collimator — with a 4.88 μsr solid angle acceptance — embedded in a 6 m long dipole magnet. Charged particles are bent up at a mean angle of 19.5 mrad. Following a vacuum decay region is a conventional magnetic spectrometer employing high-rate, narrow-pitch wire chambers. At the rear of the spectrometer is a muon system used to allow the study of rare and forbidden hyperon decays. The spectrometer analyzing magnet has sufficient strength to insure that the proton from the Λ decay is always bent to one side of the spectrometer and that the two pions from the Ξ and Λ decays are always bent to the opposite side, and that both are well separated from the intense charged beam exiting the collimator. A simple, yet selective trigger is formed by requiring the coincidence at the rear of the spectrometer of charged particles on either side of the spectrometer. Scintillator hodoscopes on the pion and proton sides and a hadronic calorimeter (on the proton side) are used to detect the charged particles. The calorimeter makes the trigger "blind" to muons produced in the beam dump, and suppresses triggers from secondary interactions in the spectrometer material. The main trigger background is from interactions of the charged particle beam exiting the collimator with material in the spectrometer.

With 800 GeV protons incident on a 2×2 mm^2 Cu target, the mean momentum acceptance of the magnetic channel is about 170 GeV/c, at which the Ξ to charged particle ratio is approximately maximal. To switch between Ξ^- and $\overline{\Xi}^+$ running the polarities of both the hyperon and spectrometer magnets are reversed. A typical primary beam intensity of 7.5×10^9 protons per second gives a secondary beam rate of 14 MHz at the exit of the collimator.

The data are recorded with an extremely high-rate data acquisition system [14] — probably the fastest in the world. Approximately 65,000 events per spill second were logged onto magnetic tape during normal running.

5.3. Status of the Analysis

A total of 75 billion events on 11,266 data tapes were accumulated during about four months of running in 1997. We expect to reconstruct 1.6 billion $\Xi \to \Lambda\pi$ decays and 280 million $K^{\pm} \to 3\pi$ decays, as well as a large number of $\Omega \to \Lambda K$, and $K_s \to \pi^+\pi^-$ decays. This translates to a sensitivity of $\delta A_{\Xi\Lambda} \simeq 2 \times 10^{-4}$.

Analysis of the data set — the largest ever taken by a particle physics experiment — is an enormous undertaking. Preliminary analyses indicate that the spectrometer performed well and that the data is good. To give an idea of the quality of the data, and the differences between positive and negative running, Fig. 3 shows the $p\pi^-\pi^-$ and $\overline{p}\pi^+\pi^+$ invariant masses from about 20 million reconstructed Ξ events. The mass resolution is about 1.6 MeV/c^2. Note the simularity between the Ξ^- and $\overline{\Xi}^+$ distributions, and the excellent signal to noise ratio.

The successful measurement of the CP asymmetry $A_{\Xi\Lambda}$ to 10^{-4} requires careful control of potential biases. Sources of systematic error include: acceptance differences, differences in the Ξ^- and $\overline{\Xi}^+$ polarizations, differences in the p and $\overline{p}$ as well as the π^+ and π^- interaction cross sections with material in the spectrometer, and different backgrounds under the Λ and $\overline{\Lambda}$ and the Ξ^- and $\overline{\Xi}^+$ mass peaks.

It is important to emphasize that the measurement of the product of the Λ and Ξ alpha parameters is done by the measurement of the slope of the proton distribution in the Λ helicity frame. Since the polar axis of the Λ helicity frame — defined by the Λ direction in the Ξ rest frame — changes from event to event, acceptance differences localized to a particular part of the apparatus do ***not*** map to a particular part of the proton $\cos\theta$ distribution, and the proton $\cos\theta$ acceptance in the Λ helicity frame is quite uniform. Indeed, in the limit of uniform Λ acceptance, any correlation vanishes.

To illustrate the power of the helicity frame analysis in reducing biases, we have plotted the proton $\cos\theta$ distributions from two Ξ^- data sets taken at different production angles: ± 2.5 mrad in the horizontal xz plane. The acceptances of the two data sets are quite different and the two data sets not only have Ξ^-'s of non-zero polarization, but opposite polarizations (in the $\pm y$ directions). These differences are obvious in Fig. 4, showing the proton $\cos\theta$ distributions along an axis parallel to the laboratory y-axis in the Λ rest frame. The situation in the Λ helicity frame is entirely different. The two $\cos\theta$ distributions are essentially identical as can be seen in Fig. 5.

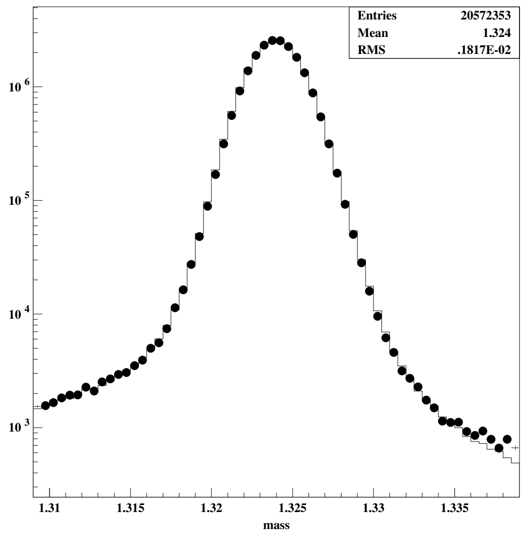

Figure 3. The $\Lambda\pi$ invariant mass for positive and negative Ξ trigger events.

Studies have shown that without corrections most biases should produce false asymmetries in $A_{\Xi\Lambda}$ of less than several times 10^{-4}.

6. Future Prospects

The *HyperCP* collaboration is preparing for a second run in 1999, where modest upgrades to the apparatus should enable a four-fold increase in statistics resulting in a sensitivity in $A_{\Xi\Lambda}$ of better than 1×10^{-4}. With luck we should see an effect and throw some light on this mysterious phenomenon called CP violation.

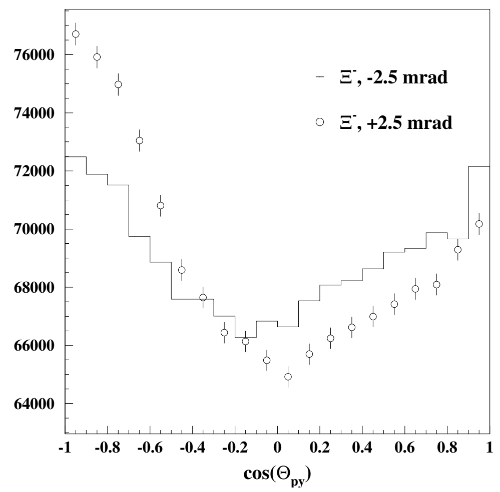

Figure 4. The proton $\cos\theta$ distributions along the y-axis in the Λ rest frame for Ξ^- events from ± 2.5 mrad production angles.

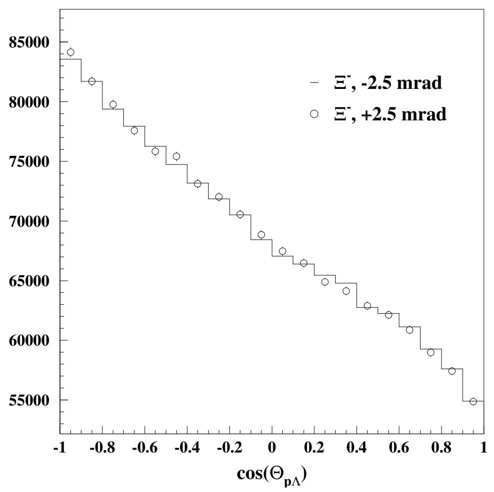

Figure 5. The proton $\cos\theta$ distributions in the Λ helicity frame for Ξ^- events from ± 2.5 mrad production angles.

7. Acknowledgements

I thank the conference organizers for their splendid work, my collaborators on *HyperCP*, and the Fermilab staff for their help and support. Finally, let me thank my colleagues at Lawrence Berkeley National Lab for their kind hospitality while writing this paper. This work was supported in part by the U.S. Department of Energy.

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