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HyperCP (E871) Experiment at Fermilab : search for direct CP violation in hyperon decays

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The Fermilab *HyperCP* experiment has accumulated the world's largest sample of Ξ^- and $\overline{\Xi}^+$ hyperon decays within two running periods in 1997 and 1999. The primary goal of the experiment is to search for direct CP violation in the decay sequences $\Xi^- \to \Lambda\,\pi^- \to p\,\pi^-\,\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\,\pi^+ \to \bar{p}\,\pi^+\,\pi^+$. A violation of CP would manifest itself as a difference between the angular distribution of the proton and the antiproton in the Λ and $\overline{\Lambda}$ helicity frame. The amount of data is enough to reach a statistical sensitivity of 1.4×10^{-4} in the CP violating asymmetry $\mathcal{A}_{\Xi\Lambda} = (\alpha_\Xi\,\alpha_\Lambda - \alpha_{\overline{\Xi}}\,\alpha_{\overline{\Lambda}})/(\alpha_\Xi\,\alpha_\Lambda + \alpha_{\overline{\Xi}}\,\alpha_{\overline{\Lambda}})$. We present an analysis method used to take into account the slight differences in the production of the Ξ^- and $\overline{\Xi}^+$ samples. A preliminary result on $\mathcal{A}_{\Xi\Lambda}$ at the level of a few 10^{-3} and based on a few percent of the 1997 data will be presented.

1. INTRODUCTION

A few years after the discovery of CP violation in the neutral-kaon decay[1] in 1964, Sakharov suggested that this CP asymmetry was one of the three conditions necessary for explaining the domination of matter over anti-matter in the Universe[2]. Despite a long history, CP violation is still not very well understood. To date it has been observed only in K_L^0 decays. This CP asymmetry is related to $K^0 - \overline{K^0}$ mixing and is called indirect CP violation. Direct CP violation has been a controversial matter for a long time with two incompatible published results[3,4]. Only recently, new measurements have settled the issue and demonstrated the existence of direct CP violation[5,6]. Several efforts are underway to establish CP violation in B-meson decays. First measurements of CP asymmetry in $B \to J/\psi + K_s^0$ decays have been obtained at LEP, Tevatron and B-factories. In the baryon sector, Pais stressed a long time ago that if CP symmetry is exact, the slope parameter, α, of the Λ decay should be equal in magnitude but opposite in sign to $\overline{\alpha}$

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of the $\overline{\Lambda}$ decay[7]. Some limits have been published for Λ decay [8–10]. HyperCP is the first dedicated experiment designed to search for hyperon CP violation. Observation of an asymmetry would provide a complementary insight into direct CP violation.

2. PHENOMENOLOGY OF HYPERON DECAY

Hyperons, strange baryons, with spin-1/2 decay into a spin-1/2 baryon and a pion, reducing strangeness by one unit. Angular momentum conservation allows S- and P-wave final states, which are mixed since parity is not conserved in these weak decays. Hyperon nonleptonic decays are conventionally described by the Lee-Yang variables[11], defined in terms of these S- and P-wave amplitudes (1).

$$\begin{aligned} \alpha &= \frac{2\Re e(S*P)}{|S|^2+|P|^2}, \\ \beta &= \frac{2\Im m(S*P)}{|S|^2+|P|^2}, \\ \gamma &= \frac{|S|^2-|P|^2}{|S|^2+|P|^2}, \end{aligned} \tag{1}$$

where $\alpha^2+\beta^2+\gamma^2=1$. The parameter α characterizes the forward-backward asymmetry in the distribution of the daughters associated with parity violation. The polarization of the daughter baryon, $\vec{\mathcal{P}}_d$, is given by:

$$\begin{aligned} \vec{\mathcal{P}}_d &= \frac{(\alpha+\vec{\mathcal{P}}_p\cdot\hat{p}_d)\,\hat{p}_d+\beta\,(\vec{\mathcal{P}}_p\times\hat{p}_d)}{(1+\alpha\,\vec{\mathcal{P}}_p\cdot\hat{p}_d)} \\ &\quad+\frac{\gamma\,(\hat{p}_d\times(\vec{\mathcal{P}}_p\times\hat{p}_d))}{(1+\alpha\,\vec{\mathcal{P}}_p\cdot\hat{p}_d)}, \end{aligned} \tag{2}$$

where $\hat{p}_d$ is the unit vector of the daughter baryon in the parent rest frame and $\vec{\mathcal{P}}_p$ is the polarization of the parent hyperon.

If the parent is unpolarized this simplifies to

$$\vec{\mathcal{P}}_d = \alpha\hat{p}_d\,. \tag{3}$$

In a fixed target experiment using protons, Ξ produced in the forward direction with $p_t = 0$ are unpolarized due to parity conservation in the strong interactions. The Ξ decays to $\Lambda+\pi$ and the Λ polarization along its momentum is

$$\vec{\mathcal{P}}_\Lambda = \alpha_\Xi\hat{p}_\Lambda\,. \tag{4}$$

The Λ decays in turn to a proton and a π, with a proton distribution given by

$$\frac{dN}{d(cos\theta)} = \frac{1}{2}\,(1+\alpha_\Lambda\,\alpha_\Xi\,cos\theta_p)\,, \tag{5}$$

where θ_p is the angle between the proton momentum and the Λ polarization vectors in the Λ helicity frame, which varies event-by-event relative to the Ξ frame. The decay parameter product $\alpha_\Xi\alpha_\Lambda$ can be extracted by measuring the slope of the decay $cos\theta_p$ distribution. A CP observable $\mathcal{A}$ is defined as

$$\mathcal{A} = \frac{\alpha_\Xi\,\alpha_\Lambda-\alpha_{\overline{\Xi}}\,\alpha_{\overline{\Lambda}}}{\alpha_\Xi\,\alpha_\Lambda+\alpha_{\overline{\Xi}}\,\alpha_{\overline{\Lambda}}} \simeq \mathcal{A}_\Lambda+\mathcal{A}_\Xi\,. \tag{6}$$

$\mathcal{A}$ is determined by measuring the difference in slope $\Delta\alpha = \alpha_{\overline{\Xi}}\,\alpha_{\overline{\Lambda}}-\alpha_\Xi\,\alpha_\Lambda$. Using this method, one cannot distinguish whether an observed asymmetry originates in the decay of the Ξ or the Λ, since α_Ξ and α_Λ are not measured separately.

3. DESCRIPTION OF THE EXPERIMENT

The HyperCP spectrometer is shown schematically in Figure 1. Hyperons are produced by an intense 800 GeV/c proton beam incident on a copper target. Charged particles of a given sign, produced at 0^o and with a momentum around 170 GeV/c, are selected by a thick curved collimator located inside of a 6 meter long dipole magnet. At the exit of the selection magnet the unpolarized surviving hyperons can decay within a 13 meter long vacuum region. A magnetic spectrometer allows reconstruction of the sequential decay $\Xi^-\to\pi^-+\Lambda$ and $\Lambda\to\pi^-+p$. The spectrometer consists of a second dipole magnet and 8 fast multiwire proportional chambers (32 planes). The dipole field is high enough to separate the decay particles from the intense 170 GeV/c transmitted beam. The trigger of the experiment is made downstream of the spectrometer magnet with two hodoscopes of plastic scintillators, one

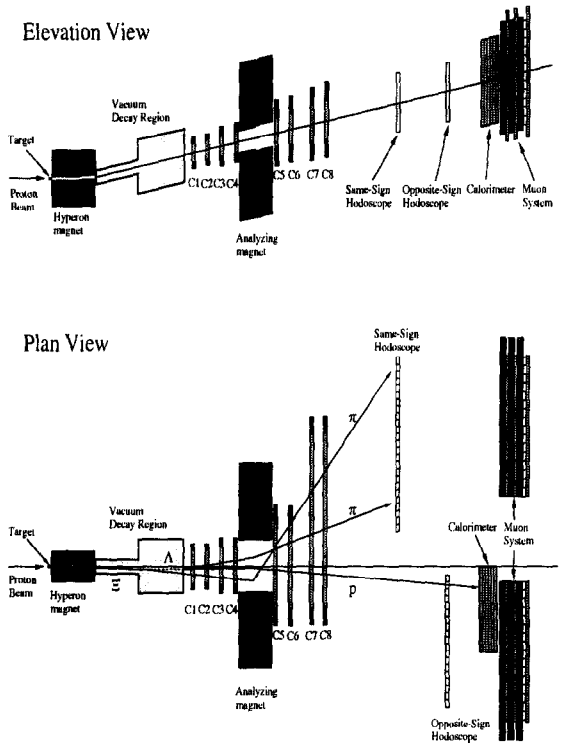

Figure 1. *The HyperCP Spectrometer*

on either side of the secondary beam, followed by a hadron calorimeter. The trigger requirement is a coincidence of particle in each hodoscope and a minimum energy deposition in the calorimeter. Two muon stations are used for rare decay studies. By reversing the polarities of both the selection and analysis magnets, Ξ^- and $\overline{\Xi}^+$ decays are collected with the same trigger. Up to small differences in the production, decay particle densities in the spectrometer are identical for both polarities. Systematics are therefore reduced to a minimum.

HyperCP collected data during the 1996-1997 fixed target run at FNAL and during a second run in 1999. The amount of data accumulated is summarized in table 1 which also gives the projected number of reconstructed events.

Table 1
Number of reconstructed events

	1997 Runs	1999 Runs
Number of tapes	9376	18838
Data volume	38 TB	71 TB
	particle	antiparticle
Ξ	2×10^9	0.5×10^9
K	0.32×10^9	0.13×10^9
Ω	14×10^6	5.3×10^6

4. DATA ANALYSIS

The first step of the CP violation analysis is to select events corresponding to this specific trigger and to try to reconstruct a Ξ. The information stored on raw tapes includes the list of hit wires in the spectrometer, the list of fired trigger scintillators and energy detected in the calorimeter. The average event size is 550 bytes. Only events with at least three tracks, at least two of which have the same charge as the transmitted beam and one with opposite charge, are considered for further analysis. Λ candidates are searched by evaluation of the invariant mass of either pair of particles of opposite charge. If found, the Λ momentum is determined and the $\Lambda - \pi$ invariant mass of this Λ and the third particle is computed. If close to the known Ξ mass, the event is saved. The sample of Ξ is then purified by application of further cuts.

A very valuable check of the experiment is to compare same-sign data. In this case no asymmetry at all is expected and any observed difference is an indication of a potential bias in the data or the analysis.

5. SYSTEMATICS

A precise measurement of the asymmetry can only be successful if systematic effects can be controlled and understood. To minimize corrections, magnetic field, detector components and reconstruction efficiency should remain stable

between positive ($\overline{\Xi}^+$ data) and negative (Ξ^- data) running. Magnetic fields were monitored to high precision (10^{-4}) with Hall probes, and, the data were corrected accordingly during reconstruction. The secondary beam flux was maintained approximatively constant for the two beam polarities, by using production targets of different lengths. The mass calibration constant of the spectrometer, based on the reconstructed Ξ mass, drifted continuously by 2.5×10^{-3} over the whole 1997 running period. This slight change of the spectrometer appears to be related to the measurement of angles, but its origin is not yet fully understood. The effect of this shift on the asymmetry measurement has been investigated by comparison of negative runs recorded at different times. No run to run difference in slope has been observed at a few 10^{-5} level. Since the running polarity was changed frequently (about every ten hours) the effect can be neglected (at most 0.5×10^{-4} on the asymmetry for our four data sets) when data recorded over a short (few runs) period of time are compared, and this effect will decrease as $1/\sqrt{N}$ with N being the number of data sets.

The effect of differences in the particle-antiparticle interaction rates within the whole spectrometer has been evaluated. Starting with 60×10^6 reconstructed Ξ decays, losses were evaluated for both polarities with compiled momentum-dependant total cross sections for p, $\overline{p}$, π^+ and π^- with nucleons. An observed slope difference of $\Delta\alpha = (-0.17 \pm 0.53) \times 10^{-4}$ between $\overline{\Xi}^+$ decays and Ξ^- decays allows setting an upper limit contribution to the asymmetry of 0.9×10^{-4}.

Assuming CP symmetry and stability for both the spectrometer and the magnetic field, no acceptance or trigger efficiency effects are expected if $\overline{\Xi}^+$ and Ξ^- are produced in exactly the same conditions. Unfortunately, because of differences in the production cross section for particles and antiparticles, the momentum and angular distributions of Ξ^- and $\overline{\Xi}^+$ hyperons accepted by the selection magnet are slightly different. The momentum distributions for Ξ^- and $\overline{\Xi}^+$, normalized to their respective number of events, are shown in figure 2. For Ξ^-, the $cos\theta_p$ distributions of the proton in the rest frame of the Λ, in two momentum bands of 1 GeV/c width centered around 160 and 200 GeV/c, are shown in figure 3. The change in acceptance with momentum is seen to have a substantial effect on the shape of the distribution.

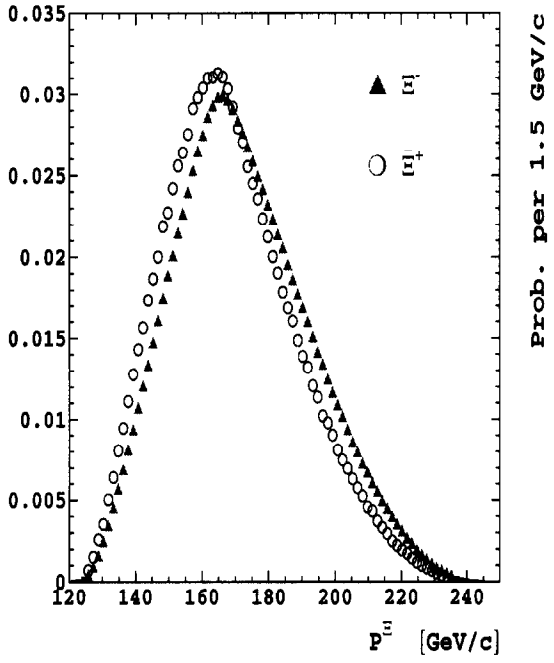

Figure 2. *The momentum distributions for Ξ^- and $\overline{\Xi}^+$, normalized to their respective number of events.*

Furthermore the incident 800 GeV/c proton beam may move a little bit on the target despite the fact that its position was adjusted at the beginning of each run.

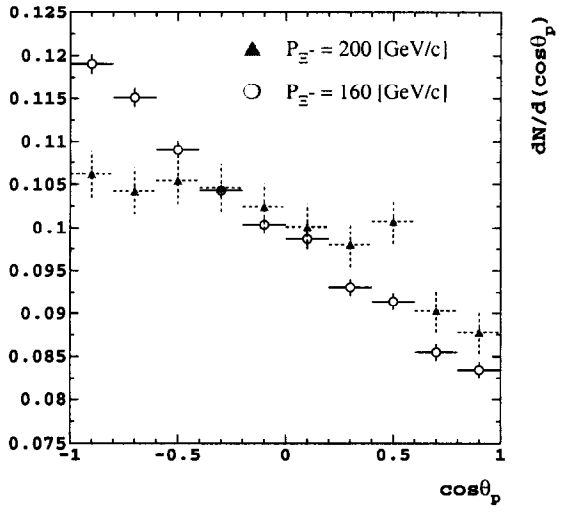

Figure 3. *For Ξ^-, comparison of normalized $cos(\theta_p)$ distributions for two momentum bands of 1 GeV/c at 160 and 200 GeV/c*

5.1. Equalization

These differences between Ξ^- and $\overline{\Xi}^+$ production require corrections. Samples of positive and negative data, as close as possible in time, have to be compared in order to extract the asymmetry. We use reconstructed events of both polarities to set up a process of equalization. This implies that acceptance and trigger efficiency are independent of tiny effects like CP non conservation or differences between particle antiparticle interaction in the spectrometer.

Five independent variables are necessary to define completely the trajectory of a secondary beam particle. In this work we have used the momentum (P_Ξ), the two transverse coordinates of the particle at the production target (x_t,y_t) and the two transverse coordinates of the particle at the exit of the selection magnet (x_c,y_c). For each reconstructed event, we have therefore a point in this five-dimensional space. The density distribution in this space is slightly different for particles and antiparticles. To compare equivalent sets of particles and antiparticles, we weight the two distributions in this five-dimensional space. Table 2 summarizes the bin size and range for each variable.

Table 2
Binning for the equalization variables

Variable	N° of bins	Bin width
x_t	30	0.23 mm
y_t	40	0.20 mm
x_c	20	0.72 mm
y_c	20	0.52 mm
P_Ξ	25	5.2 GeV/c

The five-dimensional space was therefore decomposed into 1.2×10^7 cells. A weighting factor is computed for each cell : the ratio of the number of $\overline{\Xi}^+$ to the number of Ξ^- found in the cell and its 242 neighbors. Whenever no events were found for one sign, the corresponding number of events of the other sign are removed from the sample. With typically 1×10^6 positive events and 5×10^6 negative events per data set analysed, only a few events are lost near the edge of the space. The average number of events per cell is around 20 $\overline{\Xi}^+$ and 100 Ξ^-. The weighting factor, wich defines the density phase space in a cell, is then very precisely computed. The bin size in momentum is not small enough, but with a number of cells 5 to 10 times bigger we lose events because densities become too small. A supplementary equalization on thinner momentum bins, integrating over all other variables, is applied at the end.

Figure 4 illustrates the effect of this equalization procedure. It shows the normalized distributions of the transverse coordinate y_c at the exit of the collimator for negative and positive data. Before equalization, clear differences are observed. After equalization the weighted $\overline{\Xi}^+$ distribution nicely fits the Ξ^- distribution. Two more examples are given in figure 5, for reconstructed quan-

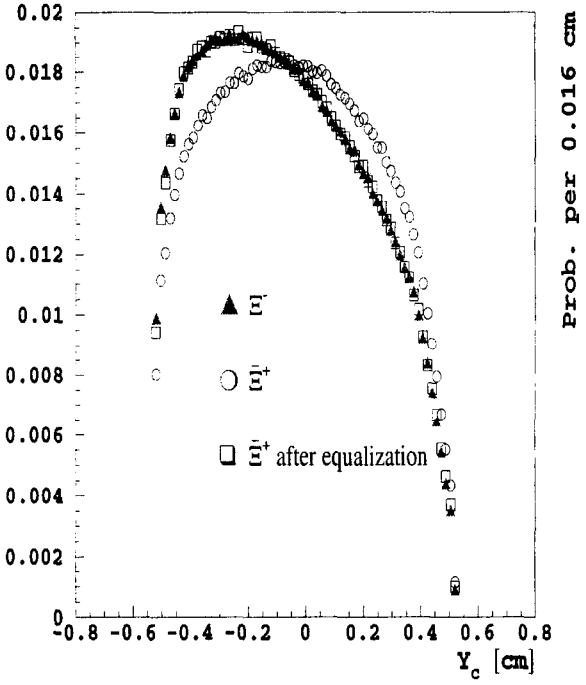

Figure 4. *y_c coordinate distributions at the exit of the collimator, before and after equalization procedure*

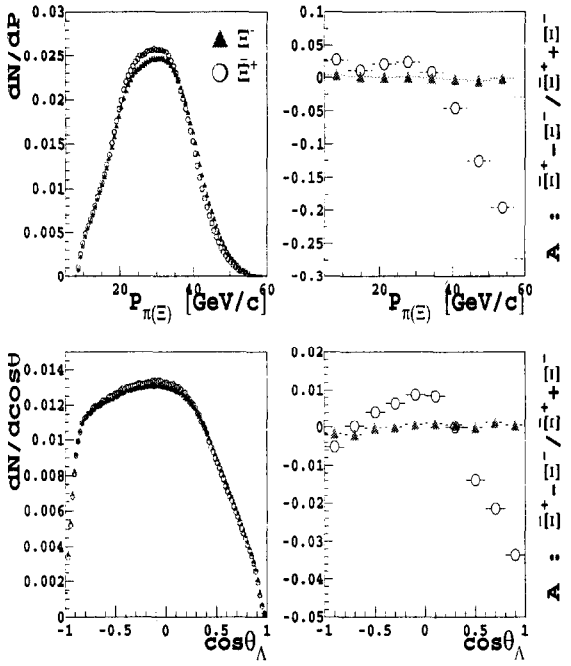

Figure 5. *The momentum distribution of the π from the Ξ decay and the angular distribution of the Λ in the Ξ rest frame are shown for both polarities, before equalization on the left. On the right, the corresponding asymmetry is shown as open circles and triangles show the asymmetry after equalization*

tities which are not used in the equalization process : the momentum distribution of the π from Ξ decay and the angular distribution of the Λ in the rest frame of the Ξ. The normalized distributions are compared on the left. The corresponding asymmetries are plotted as open circles on the right. For both quantities, the asymmetries completely disappear when equalization is applied. This is shown by filled triangles on the right. Asymmetries disappear for all other production sensitive quantities as well.

We still have to prove that the process of equalization does not kill a hypothetical CP violation effect. To investigate this issue, three sets of data, each involving about 1×10^6 $\bar{\Xi}^+$ and 6×10^6 Ξ^-, have been used. The decay and path through the spectrometer is simulated by Monte-Carlo for 100 Ξ having the same transverse coordinates and the same momentum at the exit of the selecting magnet as each reconstructed Ξ. For each set, about 20×10^6 $\bar{\Xi}^+$ and 150×10^6 Ξ^- are found within the acceptance of the spectrometer that pass cuts applied to real events. In the decay simulation, a difference in slope $\Delta\alpha = \alpha_{\bar{\Xi}}\,\alpha_{\bar{\Lambda}} - \alpha_{\Xi}\,\alpha_{\Lambda}$ has been included. Each set is then analyzed to recover the asymmetry. For the analysis shown in

figure 6, $\Delta\alpha$ was -10×10^{-3} corresponding to an asymmetry $\mathcal{A} = -17.2 \times 10^{-3}$. $\Delta\alpha$ values without equalization are shown as black dots together with their average shown on the right; the simulated asymmetry is not apparent. After equalization, it is recovered as shown by the open circles. We obtain $\Delta\alpha = (-9.9 \pm 0.2) \times 10^{-3}$ or $\mathcal{A} = (-16.9 \pm 0.4) \times 10^{-3}$. The asymmetry is recovered within the statistical accuracy given by the size of our simulation. The accuracy should improve if the same procedure is applied to an increased number of data sets.

5.2. Background

$\bar{\Xi}^+$ and Ξ^- mass spectra normalized to the same number of entries are shown in figure 7 for different sets of cuts. Only Ξ with mass between 1.3163 GeV/c^2 and 1.3263 GeV/c^2 were used to measure the asymmetry $\mathcal{A}_{\Xi\Lambda}$. The signal-to-noise ratio has been estimated by extrapolation under the peak of the tails at low mass and at high mass. Three effects do contribute to the shape of these invariant mass spectra : combinatorial background due to association of accidental tracks, true decays with similar topology which fake a Ξ decay, and finally reconstruction errors associated with the presence of extra tracks or hits. In figure 7a, the background for positive runs is seen to be about two times bigger than for negative runs. This is due to kaon decays into three pions, since K^+ are more abundantly produced than K^- in proton-nucleon collisions. Three-standard-deviation cuts on the coordinates of the particle at target, cuts on the position at the exit of the collimator, restricting decay vertices to be inside of the vacuum region, and elimination of the $K \to 3\pi$ decays give the spectrum of figure 7b. The fraction of background within a $\pm 3\sigma$ window around the Ξ mass (σ =1.6 MeV/c^2) is reduced by about a factor of 20 for $\bar{\Xi}^+$ and a factor of 10 for Ξ^-. The background left is 3×10^{-3} and tail differences between positive and negative data have almost disappeared. Further cuts on momenta, angles and elimination of most of the $\Omega \to K + \Lambda$ decays do not change the background-to-signal ratio but strongly reduce the tails as shown in figure 7c. Spectra for positive and negative data

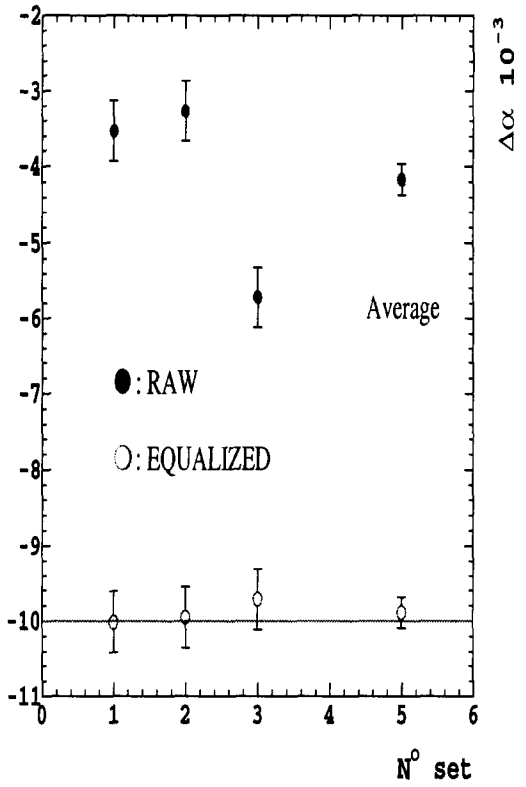

Figure 6. *Difference in slope $\Delta\alpha$ before (black dots) and after (open circle) equalization. The simulated $\Delta\alpha = -10 \times 10^{-3}$ is recovered after the equalization process.*

are now in excellent agreement over more than 5 orders of magnitude. At this level, a fraction less than 3×10^{-5} $\Omega \to K + \Lambda$ events are left within the mass window and differences in production cross-sections for Ω^+ and Ω^- produce a negligible contribution to the asymmetry ($\Delta\alpha < 10^{-5}$). A few semi-leptonic $\Xi \to \Lambda + e + \nu_e$ and $\Xi \to \Lambda + \mu + \nu_\mu$ decays contribute to the high-mass tail. All the remaining background is due

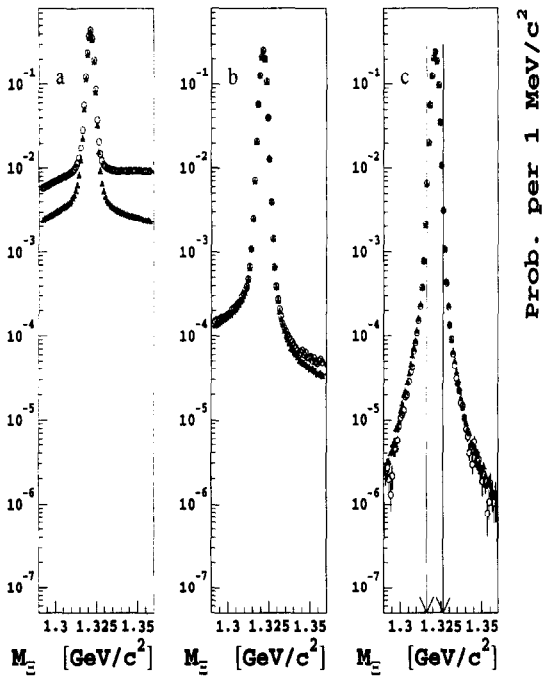

Figure 7. *Invariant mass spectra for different sets of cuts. Open circles are used for $\overline{\Xi}^+$ and black triangles for Ξ^-. Events between the arrows were used to measure the asymmetry $\mathcal{A}_{\Xi\Lambda}$*

to either mistakes made in the reconstruction or combinatorial background (the latter being probably due to a true Λ or K_s decay combined with an extra track). Slope differences $\Delta\alpha$ between positive and negative data have been studied for two side bands, below and above the Ξ mass. No difference is seen at low mass $\Delta\alpha$=0.001±0.01 but a slight effect of 0.034±0.011 at high mass. After equalization these differences become respectively 0.005 ± 0.01 and -0.009 ± 0.011. With the fraction of 3×10^{-3} mentioned above this gives an upper limit of 1.2×10^{-4} on $\Delta\alpha$ and 2.1×10^{-4} to the measured asymmetry. This is negligible for the present study but will necessitate further study and corrections for the final analysis involving the entire HyperCP data sample and aiming to achieve a sensitivity at the 1.4×10^{-4} level.

5.3. Residual polarization

In principle, a zero polarization of the parent hyperon is not absolutely necessary for the CP measurement. According to equation 2 above, a correction can be made to remove any bias resulting from the parent polarization. Effects due to differences in polarization between $\overline{\Xi}^+$ and Ξ^- are expected to be very small. However polarized samples were taken for both polarities by varying the production angle by ± 3 mrad. The data are being analyzed, and a correction to the asymmetry will be made if necessary.

5.4. Beam displacement on target

Displacements on target are in principle corrected by the equalization process, provided that the stability of the spectrometer allows a precise reconstruction of the transverse position at the target. The small spectrometer instabilities give a present precision of 100 μm to the x reconstruction. Monte-Carlo has shown that such displacement induce no change in the asymmetry, at the statistical level of 1.4×10^{-3}. This statistical limit can be reduced with an increased number of MC events. Furthermore, it will also decrease as $1/\sqrt{N}$ with the number N of analysed data sets. The limit for our four data sets is less than 1.0×10^{-3}.

6. PRELIMINARY RESULT

Four sets of data from the 1997 run have been analyzed. These sets constitute a sampling over the whole running period and represent about 3% of the 1997 data. Positive and negative data for each set were collected within a short period of time. The asymmetry for each set with its statistical uncertainty is presented in figure 8 as open circles. The weighted average is shown as a black dot, it is compared to the result of a previous experiment E756 which is now available[12]. This preliminary analysis is based on a sample of 5.9×10^6 $\overline{\Xi}^+$ and 37.2×10^6 Ξ^-. We have found an asymmetry $\mathcal{A} = (-1.6 \pm 1.3) \times 10^{-3}$, where

the error is statistical only.

The contributions to the systematic uncertainty are as follows:

x and y displacement at target	$< 1.0 \times 10^{-3}$
Equalization	$< 0.4 \times 10^{-3}$
Interactions	$< 0.9 \times 10^{-4}$
Drift of spectrometer	$< 0.5 \times 10^{-4}$
Background	$< 2.1 \times 10^{-4}$

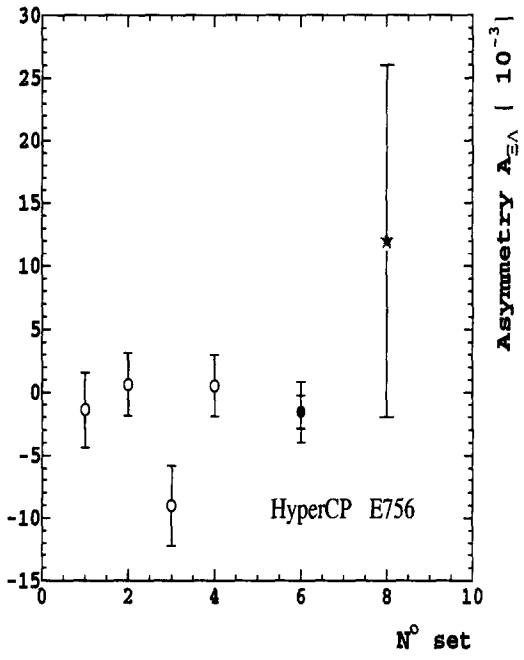

Figure 8. *CP asymmetry for four sets of data. The average of the four data sets values expressed with the systematic error, and the result of E756*

The systematic error is dominated by the effect of the displacement of the beam on the target but has so far has been studied with very low statistics. Summing quadratically all the contributions to the systematic error leads to the following result for the asymmetry:

$$\mathcal{A}_{\Xi\Lambda} = (-1.6 \pm 1.3^{stat.} \pm 1.1^{syst.}) \times 10^{-3}$$

7. CONCLUSION

HyperCP had successful 1996/7 and 1999 runs and has collected the largest samples of Ξ^- and $\overline{\Xi}^+$ decays in the world. A preliminary analysis of 1.7% of the data has led to an asymmetry compatible with CP conservation at the 10^{-3} level. More data and analysis are necessary to push down the present systematic limit of 1.1×10^{-3} to the level of the projected statistical sensitivity of 1.4×10^{-4}.

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