Results from the *HyperCP* Experiment at Fermilab: The Search for Direct CP Violation in Hyperon Decays

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HyperCP Physics Goals

Primary Goal:

- Perform a sensitive search for direct *CP* violation by comparing the decay process $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ with its anti-process $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$, $\overline{\Lambda} \to \overline{p}\pi^+$.

Secondary Goals:

- Search for *CP* violation in $K^\pm \to 3\pi$ decays.
- Search for rare and forbidden hyperon and charged kaon decays:
  - Lepton number nonconservation in kaon and hyperon decays: $\Xi^- \to p\mu^-\mu^-$, $\Sigma^- \to p\mu^-\mu^-$, $K^+ \to \pi^-\mu^+\mu^+$.
  - Flavor changing neutral currents in hyperon and charged kaon decays: $\Sigma^+ \to p\mu^+\mu^-$, $K^+ \to \pi^+\mu^+\mu^-$.
  - $\Delta S = 2$ decays: $\Xi^- \to p\pi^-\pi^-$, $\Omega^- \to \Lambda\pi^-$, $\Omega^- \to pK^-\pi^-$.
- Measure various hyperon production and decay properties:
  - $\Xi^-(\overline{\Xi}^+)$ and $\Omega^-(\overline{\Omega}^+)$ polarization.
  - β decay parameter in $\Xi^-(\overline{\Xi}^+)$ decays.
  - α decay parameter in $\Omega^-(\overline{\Omega}^+)$ decays.
  - Hyperon production cross sections.

Why Search for CP Violation in Hyperon Decays?

- After 35 years of intense experimental effort — and many beautiful experiments — we still know very little about CP violation:
  - The origin of CP violation remains unknown. There is little hard evidence that it is explained by the standard model.
  - There is no compelling evidence of CP violation outside of the decays of the K_L.
- The asymmetry is relatively large: up to several $\times 10^{-3}$.
- The experiment is relatively easy to do:
  - No new accelerators needed.
  - Apparatus is modest in scope and cost.
- Hyperon CP violation is not the same as CP violation in kaon decays!
- CP violation is too important, and experimental evidence is too meagre, not to examine every possible manifestation of the effect.

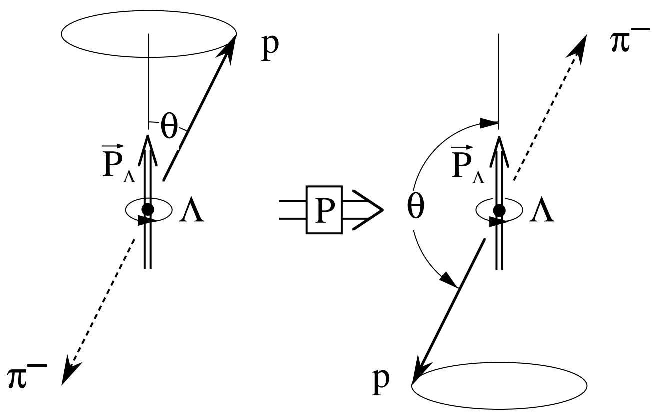
> *"To extract useful information and constraints on new physics, results from hyperon decays, K-decays, and B-decays will have to be pooled and confronted with models on a case by case basis."*
>
> S. Pakvasa

A Very Short Primer on Nonleptonic Hyperon Decays

$$\Xi^- \to \Lambda\pi^- \qquad \Lambda \to p\pi^-$$

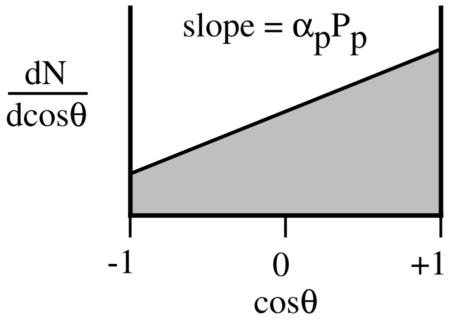
- **Their decay violates parity.** Hence the angular distribution of daughter baryons is not isotropic (if the parent hyperon is polarized)

$$\boxed{\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_p P_p \cos\theta)}$$



- **The magnitude of the parity violation is given by α_p.** It is very large!
- The slope of the daughter baryon $\cos\theta$ distribution is given by the product:

$$\alpha_p P_p$$



- **The daughter is polarized:**

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

$$\text{where :} \qquad \alpha_p = \frac{2\mathrm{Re}(S^*P)}{|S|^2 + |P|^2} \qquad \beta_p = \frac{2\mathrm{Im}(S^*P)}{|S|^2 + |P|^2} \qquad \gamma_p = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

- **Important note!** If the parent hyperon is unpolarized the daughter baryon is found in a helicity state:

$$\boxed{\vec{P}_d = \alpha_p \hat{p}_d}$$

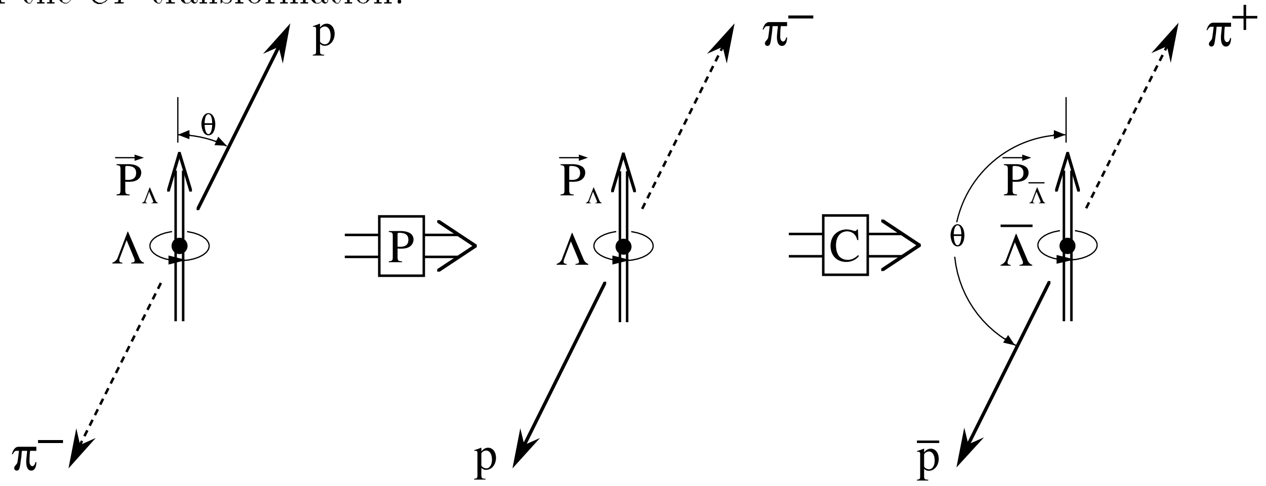
How Does One Search for CP Violation in Λ Decays?

$$\Lambda \rightarrow \mathrm{p}\pi^{-}$$

In the Λ rest frame, the angular distribution of the proton is given by:

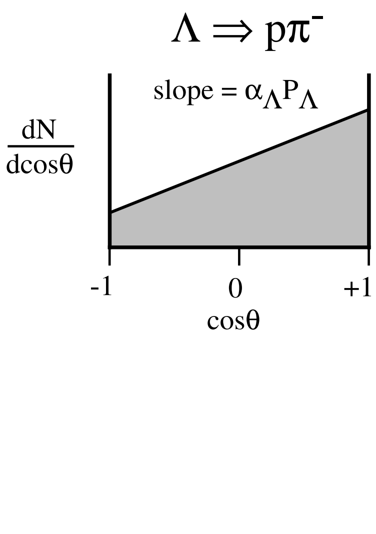
$$\frac{d\mathrm{N(p)}}{d\cos\theta} = \frac{\mathrm{N}_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta)$$

Under the *CP* transformation:

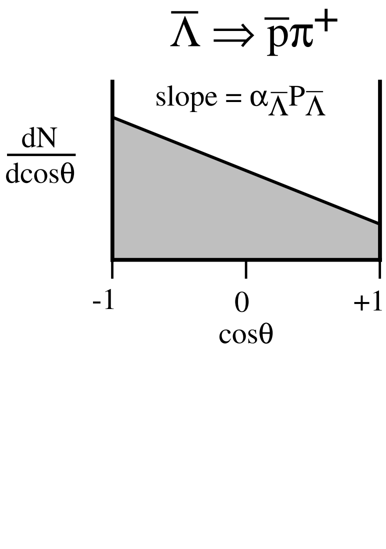


$$\alpha_\Lambda \quad \overset{\mathrm{CP}}{\Longrightarrow} \quad \overline{\alpha}_\Lambda = -\alpha_\Lambda$$

Hence *CP* is violated if the slope of the proton $\cos\theta$ distribution is *not* the *exact* opposite of the slope of the antiproton $\cos\theta$ distribution:



$$\boxed{\overline{\alpha}_\Lambda \neq -\alpha_\Lambda}$$



Producing Λ's of Known Polarization

Λ's and $\overline{\Lambda}$'s of precisely know polarization can be produced through the decay of **unpolarized** Ξ^- and $\overline{\Xi}^+$ hyperons:

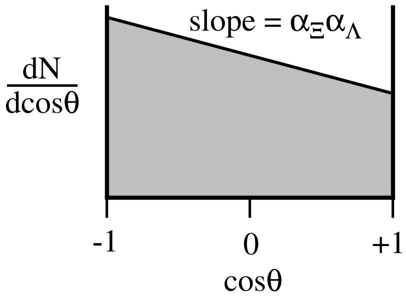
$$\Xi^- \to \Lambda\pi^- \qquad\qquad \overline{\Xi}^+ \to \overline{\Lambda}\pi^+$$

If the Ξ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the Λ is found in a helicity state:

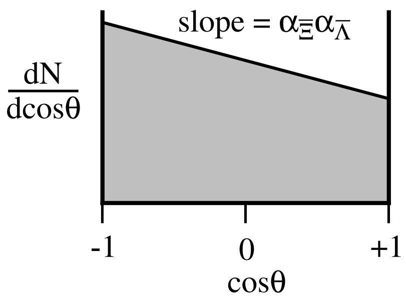
$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad\qquad \vec{P}_{\overline{\Lambda}} = \overline{\alpha}_\Xi \hat{p}_{\overline{\Lambda}}$$

$$\boxed{\frac{d\mathrm{N(p)}}{d\cos\theta} = \frac{\mathrm{N}_0}{2}(1+\alpha_\Lambda\alpha_\Xi\cos\theta)} \qquad \boxed{\frac{d\mathrm{N(\bar{p})}}{d\cos\theta} = \frac{\mathrm{N}_0}{2}(1+\overline{\alpha}_\Lambda\overline{\alpha}_\Xi\cos\theta)}$$

$\Xi^- \to \Lambda\pi^- \quad \Lambda \to p\pi^-$



$\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \quad \overline{\Lambda} \to \bar{p}\pi^+$



If CP is good, the slopes of the proton and antiproton $\cos\theta$ distributions are identical:

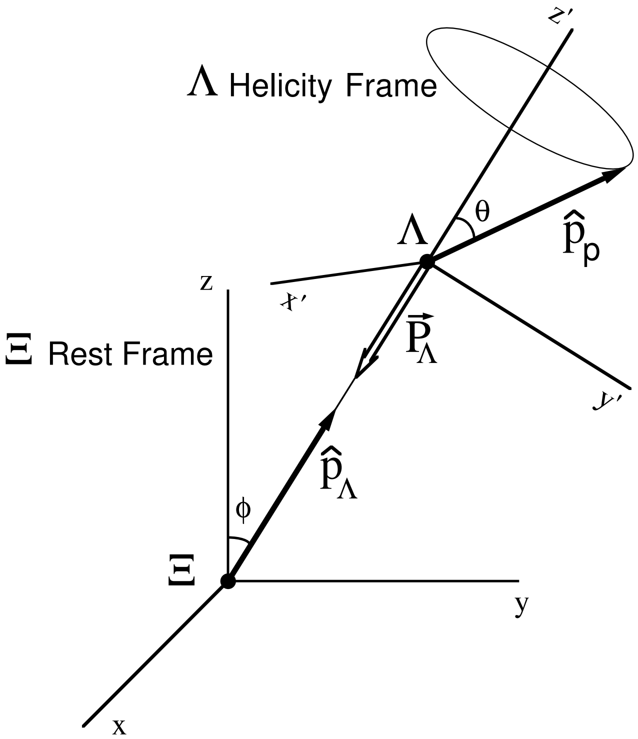
$$\boxed{\alpha_\Xi\alpha_\Lambda = \overline{\alpha}_\Xi\overline{\alpha}_\Lambda}$$

We are sensitive to CP violation in both Ξ and Λ decays

$$\boxed{A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}}}{\alpha_\Xi \alpha_\Lambda + \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}}} \approx A_\Xi + A_\Lambda}$$

where: $$A_\Xi = \frac{\alpha_\Xi + \alpha_{\overline{\Xi}}}{\alpha_\Xi - \alpha_{\overline{\Xi}}} \quad \text{and} \quad A_\Lambda = \frac{\alpha_\Lambda + \alpha_{\overline{\Lambda}}}{\alpha_\Lambda - \alpha_{\overline{\Lambda}}}$$

What we experimentally measure is the slope of the proton (antiproton) $\cos(\theta)$ distribution in the special Λ rest frame where the Λ momentum direction in the Ξ rest frame defines the polar axis: the Λ ($\overline{\Lambda}$) helicity frame.



Phenomenology of CP Violation in Ξ and Λ Decay

- CP violation in Ξ and Λ decays is manifestly direct with $\Delta S = 1$.
- Three ingredients are needed to get a non-zero asymmetry:
  1. At least two channels in the final state: the S-and P-wave amplitudes.
  2. The CP violating weak phases must be different in the two channels.
  3. Their must be unequal final-state scattering phase shifts in the two channels.
- The CP asymmetry is:

$$\begin{aligned} A_\Lambda &\cong -\tan\left(\delta_1^P - \delta_1^S\right)\sin\left(\phi_1^P - \phi_1^S\right), \\ A_\Xi &\cong -\tan\underbrace{\left(\delta_2^P - \delta_2^S\right)}_{\text{strong phases}}\sin\underbrace{\left(\phi_{12}^P - \phi_{12}^S\right)}_{\text{weak phases}}. \end{aligned}$$

- The $p\pi$ phase shifts have been measured to a precison of about one degree:

$$\Lambda \left\{ \begin{array}{lcr} \delta_1^P &=& -1.1 \pm 1.0^\circ \\ \delta_1^S &=& 6.0 \pm 1.0^\circ \end{array} \right.$$

- The $\Lambda\pi$ phase shifts have never been measured, and theoretical predictions disagree.

$$\Xi^- \left\{ \begin{array}{lcr} \delta_2^P &=& -2.7^\circ \\ \delta_2^S &=& -18.7^\circ \end{array} \right\} 1965 \qquad \begin{array}{cr} = & -1^\circ \\ = & 0^\circ \end{array} \Bigg\} \text{recent}$$

- By measuring β_Ξ *HyperCP* will be able to measure the strong phase shifts in Ξ decay to a precision of about one degree through the relationship:

$$\boxed{\frac{\beta}{\alpha} = -\tan(\delta_S - \delta_P)}$$

What do we Expect: Theoretical Predictions

- Beware of theorist's predictions. Calculations are notoriously difficult, and results are not reliable to better than an order of magnitude.

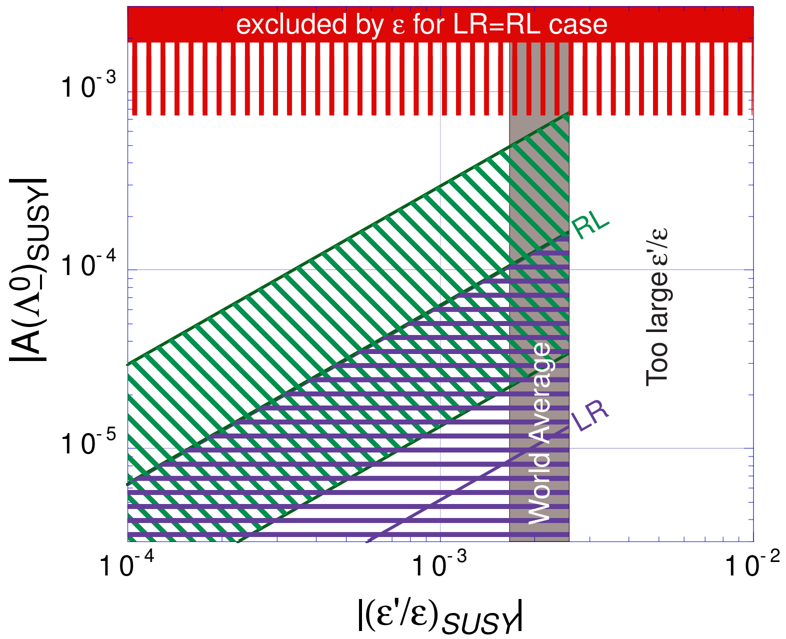
  "Given our crude estimate of the hadronic matrix elements involved, all our numerical results should be viewed with caution."

  He and Valencia, PRD52 (1995) 5257.

- However, in almost all calculations the sign of A_Λ and A_Ξ are the same.
- A summary of recent predictions (from Pakvasa's KAON99 talk) is:

Model	A_Ξ $[10^{-4}]$	A_Λ $[10^{-4}]$
SM (CKM)	-0.04	-0.4
2-Higgs	-3	-0.2
Superweak	0	0
L-R-S (isoconjugate)	0.2	-0.1
L-R-S (with mixing)	1	6

- It has been pointed out that supersymmetric models which have been invoked to explain the large value of ϵ'/ϵ reported by KTeV can generate a large value of A_Λ.

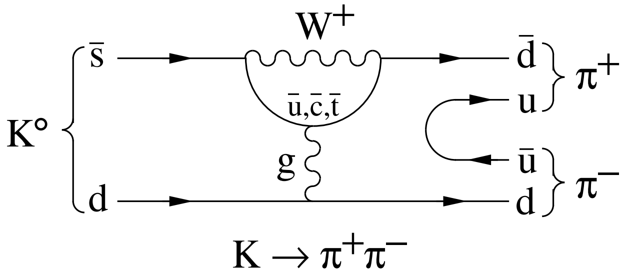


He *et al.*, PRD61:071701 (2000).

Comparison of ϵ'/ϵ and A_Ξ, A_Λ

ϵ'/ϵ

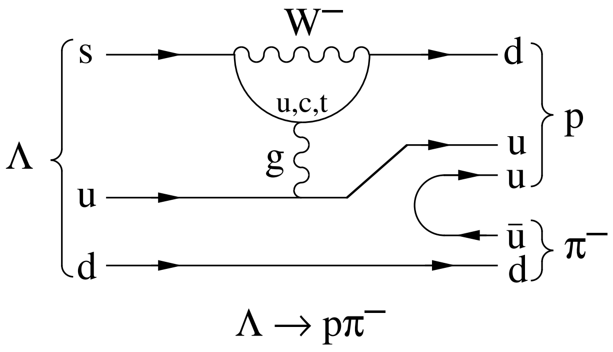
- Thought to be due to the Penguin diagram in the Standard Model.



- Expressed through a different CP-violating phase in the $I = 0$ and $I = 2$ amplitudes.
- Probes only parity violating amplitudes.
- Sensitive to the top quark mass.

$A_{\Xi\Lambda}$

- Thought to be due to the Penguin diagram in the Standard Model.



- Expressed through a different CP-violating phase in the S- and P-wave amplitudes.
- Probes parity violating and conserving amplitudes.
- Not sensitive to the top quark mass.

"Our results suggest that this measurement is complementary to the measurement of ϵ'/ϵ, in that it probes potential sources of CP violation at a level that has not been probed by the kaon experiments."

He and Valencia, PRD52 (1995) 5257.

What is the experimental situation?

- There are no limits on A_Ξ.
- A_Λ has been measured to 2×10^{-2}.

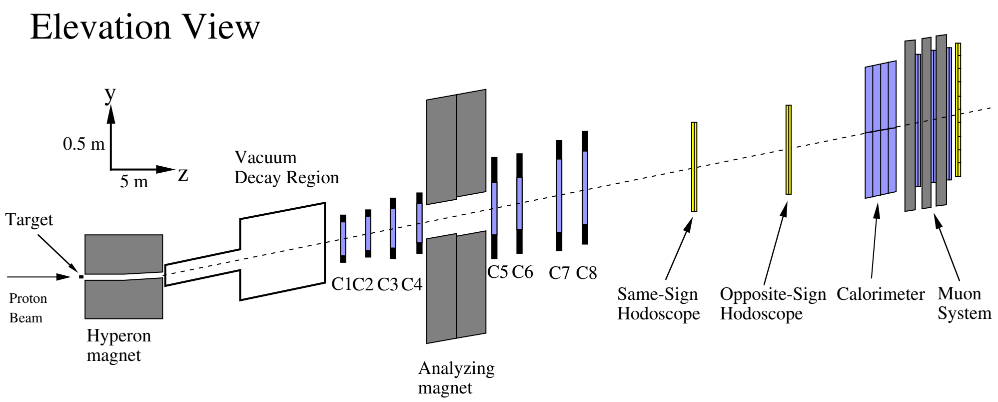
Mode	Method	Limit	Exp	Date
A_Λ	$\mathrm{p\overline{p}} \to \Lambda X$, $\mathrm{p\overline{p}} \to \overline{\Lambda} X$	-0.02 ± 0.14	R608	1985
A_Λ	$\mathrm{e^+e^-} \to \mathrm{J}/\psi \to \Lambda\overline{\Lambda}$	0.01 ± 0.10	DM2	1988
A_Λ	$\mathrm{p\overline{p}} \to \Lambda\overline{\Lambda}$	0.010 ± 0.022	PS185	1998

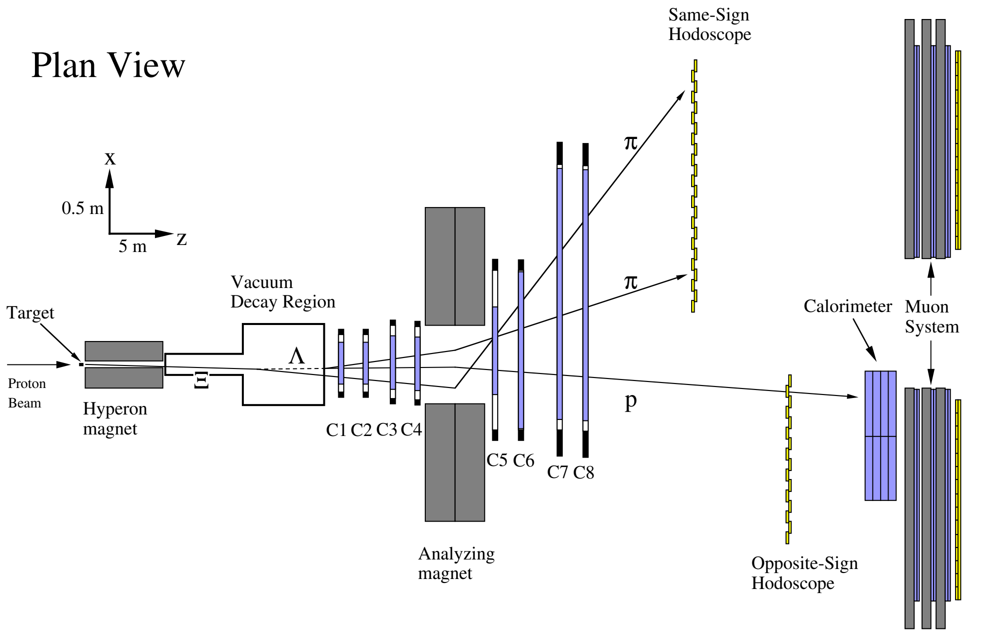
- There are two new measurements of $A_{\Xi\Lambda}$, both based on the *HyperCP* technique.

Mode	Method	Limit	Exp	Date
$A_{\Xi\Lambda}$	$\mathrm{e^+e^-} \to \Xi_c^\circ\overline{\Xi}_c^\circ \to \Xi^-\pi^+\overline{\Xi}^+\pi^-$	$-0.057 \pm 0.064 \pm 0.039$	CLEO	1998
$A_{\Xi\Lambda}$	$\mathrm{pN} \to \Xi\pi \to \Lambda\pi \to \mathrm{p}\pi\pi$	0.012 ± 0.014	E756	2000

- These first two measurements of $A_{\Xi\Lambda}$ can be used with measurements of A_Λ to infer a limit on A_Ξ.
- **All of these measurements are still not in the regime of testing theory.**

The *HyperCP* spectrometer is extremely fast





- 8 fast, low-gain, narrow-pitch wire chambers.
- Very high-rate DAQ:
  - 100,000 events/s to tape.
  - 27 MB/s on 27 Exabyte 8705 tape drives.
- Simple, low-bias trigger using hodoscopes and calorimeter.
- Muon system for rare and forbidden K and hyperon decays.

HyperCP Yields

- In two years of running, 1997 and 1999, we took the largest data sample ever by a particle physics experiment: **226 billion** events on **28,214** tapes in 1997 and 1999: **109 TB** of data.

Events			
	Channeled beam polarity		
Trigger	+	−	Total
Cascade	80×10^9	40×10^9	120×10^9
All	157×10^9	69×10^9	226×10^9

Projected Number of Reconstructed Events			
	Channeled beam polarity		
Type	+	−	Total
$\Xi \rightarrow \Lambda\pi$	0.5×10^9	2×10^9	2.5×10^9
$\mathrm{K} \rightarrow \pi\pi\pi$	0.32×10^9	0.13×10^9	0.45×10^9
$\Omega \rightarrow \Lambda\mathrm{K}$	5.3×10^6	14×10^6	19×10^6

- We expect a statistical precison of:

$$\boxed{\delta A_{\Xi\Lambda} \approx 1.4 \times 10^{-4}}$$

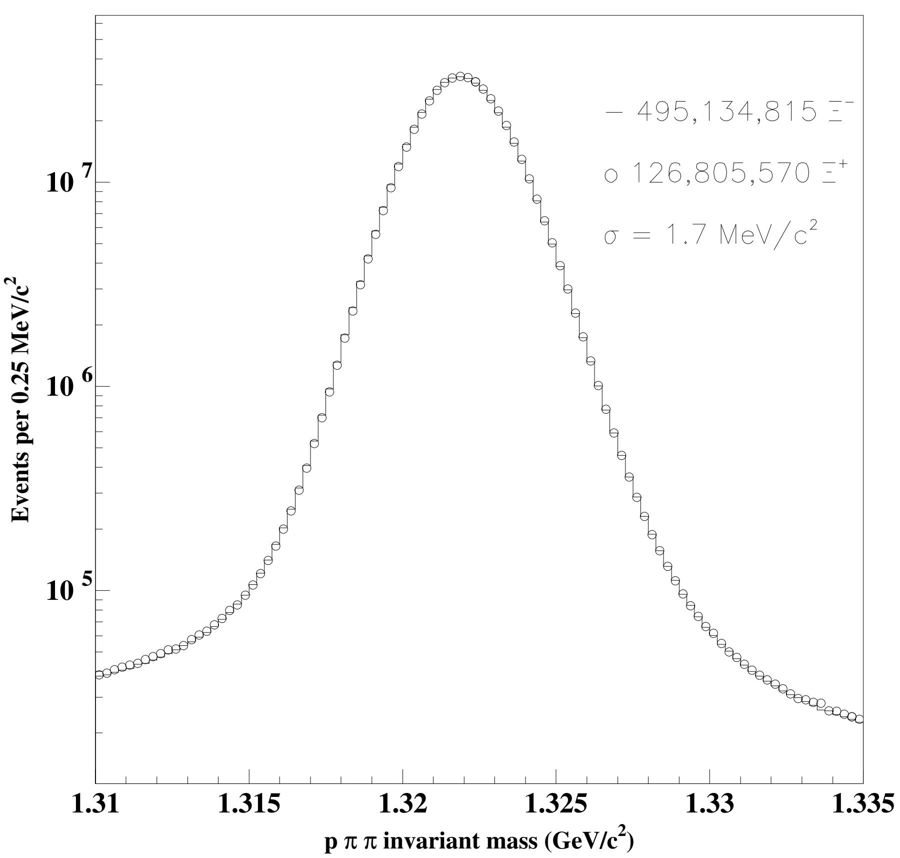
- We also took a significant amount of polarized data.

Polarized Data Yields		
Angle	$\overline{\Xi}^+$	Ξ^-
+3.0 mrad	113×10^6	22×10^6
−3.0 mrad	93×10^6	17×10^6
+2.5 mrad	10×10^6	2×10^6
−2.5 mrad	8×10^6	1.6×10^6

Status of the Data Analysis

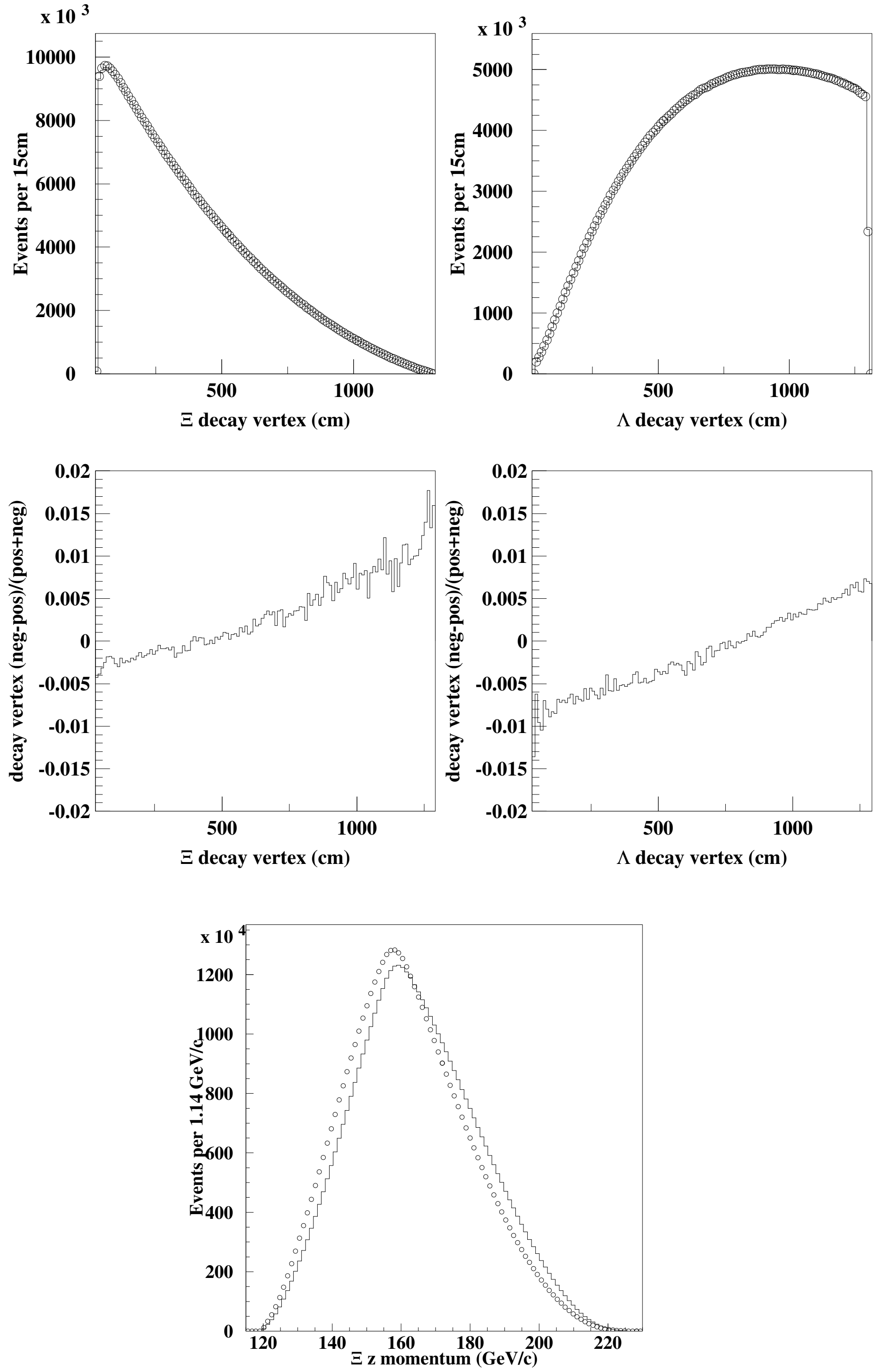
- Laborius alignment and calibration of the spectrometer complete.
- Reduction of the data is well underway on the Fermilab PC farms.
  - Enormous bookkeeping operation with hundreds of parameters plotted on a spill-by-spill basis.
  - Over **16 million** histograms will be produced and stored in a database.
  - About 25% complete and going at about 90 tapes/day.
- Several physics analyses in progress:
  - CP violation in Ξ and Λ decays.
  - CP violation in $K \rightarrow \pi\pi\pi$ decays.
  - Rare and forbidden hyperon and kaon decay searches.
  - Measurement of β decay parameter in $\Xi^{-}(\overline{\Xi}^{+})$ decays.
  - Measurement of α decay parameter in $\Omega^{-}(\overline{\Omega}^{+}) \rightarrow \Lambda(\overline{\Lambda}) + K^{-}(K^{+})$ decays.
  - Production polarization of $\Xi^{-}(\overline{\Xi}^{+})$ and $\Omega^{-}(\overline{\Omega}^{+})$.
  - Hyperon production cross sections.

The Ξ^- and $\overline{\Xi}^+$ masses from the farm analysis

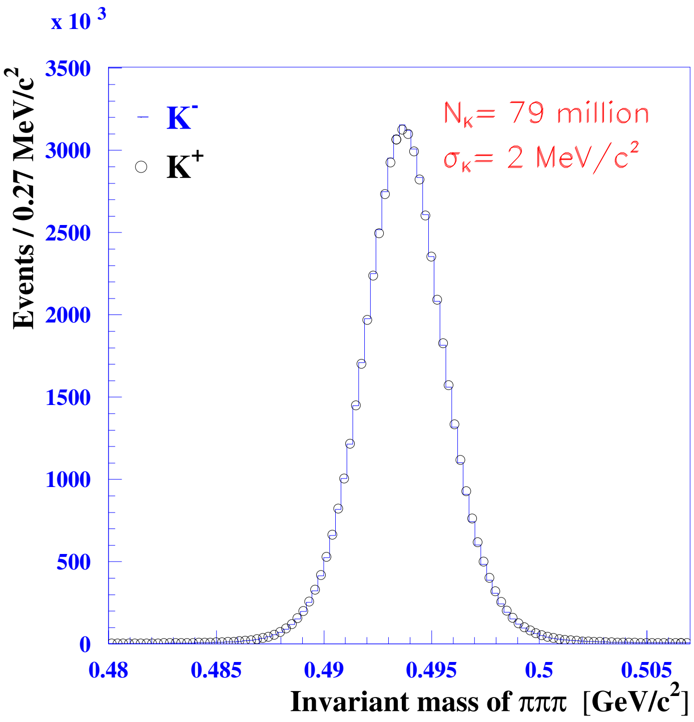


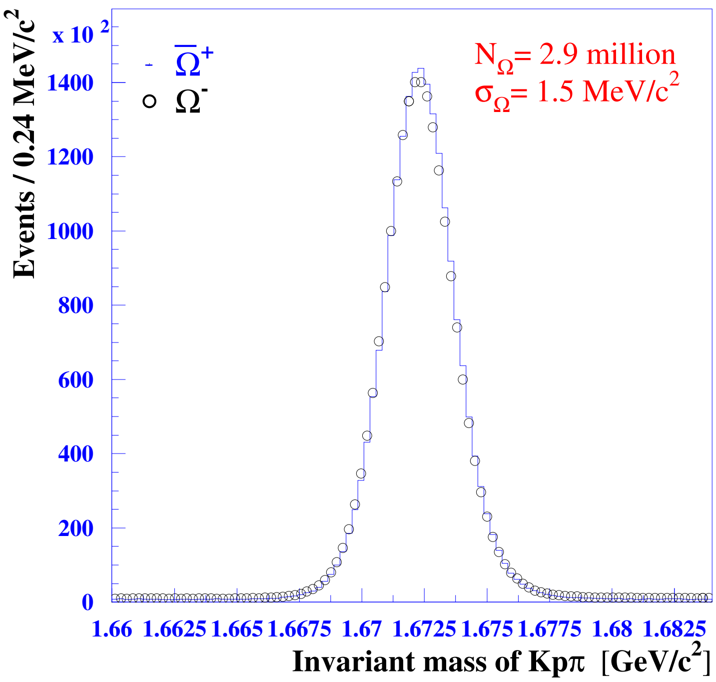
- Very loose cuts have been applied.
- Tighter cuts can reduce the B/S to 10^{-4}.

Comparison between the Ξ^- and $\overline{\Xi}^+$ and Λ and $\overline{\Lambda}$ decay vertices from the farm analysis. No attempt has been made to normalize the two distributions in momentum.



The $K^+(K^-)$ and $\Omega^-(\overline{\Omega}^+)$ masses from the farm analysis





Systematics

Any effect which adds or subtracts events unequally from the Ξ^- and $\overline{\Xi}^+$ proton and antiproton $\cos\theta$ distributions will cause a false asymmetry **if not corrected for**.

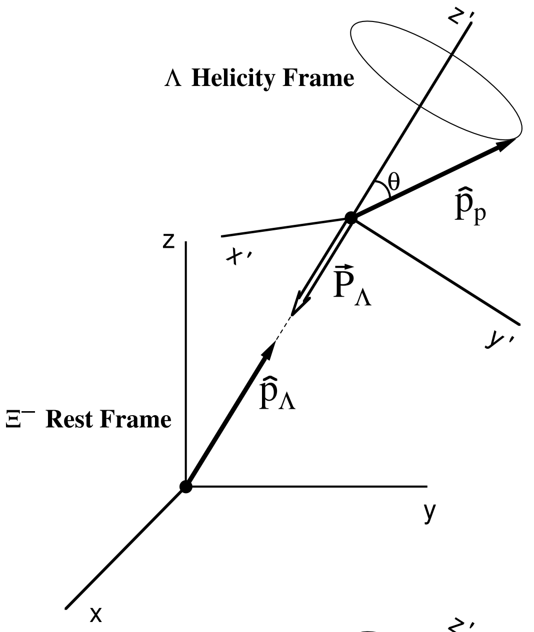
There are three classes of biases.

1. Acceptance differences:
   - Targetting differences.
   - Magnetic field differences.
   - Chamber and trigger efficiency differences.
   - Different reconstruction efficiencies due to different interaction cross sections with the material in the spectrometer between the π^- and π^+ and between the p and $\overline{p}$.
2. Different Ξ^- and $\overline{\Xi}^+$ polarization.
   - This means that the Λ is no longer found in a simple helicity state with the polarization magnitude given by α_Ξ, but rather by:

   $$\vec{P}_\Lambda = \frac{(\alpha + \vec{P}_\Xi \cdot \hat{p}_\Lambda)\hat{p}_\Lambda + \beta(\vec{P}_\Xi \times \hat{p}_\Lambda) + \gamma(\hat{p}_\Lambda \times (\vec{P}_\Xi \times \hat{p}_\Lambda))}{(1 + \alpha \vec{P}_\Xi \cdot \hat{p}_\Lambda)}$$

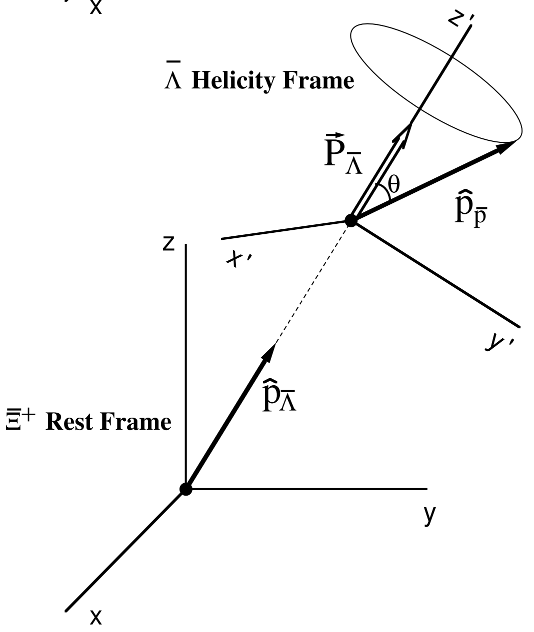
   - This results in the Λ and $\overline{\Lambda}$ inhabiting different regions of phase space.
   - Note: in the limit of perfect Λ acceptance the polarization averages to zero in the helicity frame analysis. Also nonzero Ξ polarization can in principal be corrected for.
3. Different backgrounds under the Λ and $\overline{\Lambda}$ and the Ξ^- and $\overline{\Xi}^+$ mass peaks.

If CP is not violated then the Ξ^- and $\overline{\Xi}^+$ decays appear identical



$$\boxed{\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-}$$

$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Xi \alpha_\Lambda \cos\theta)$$

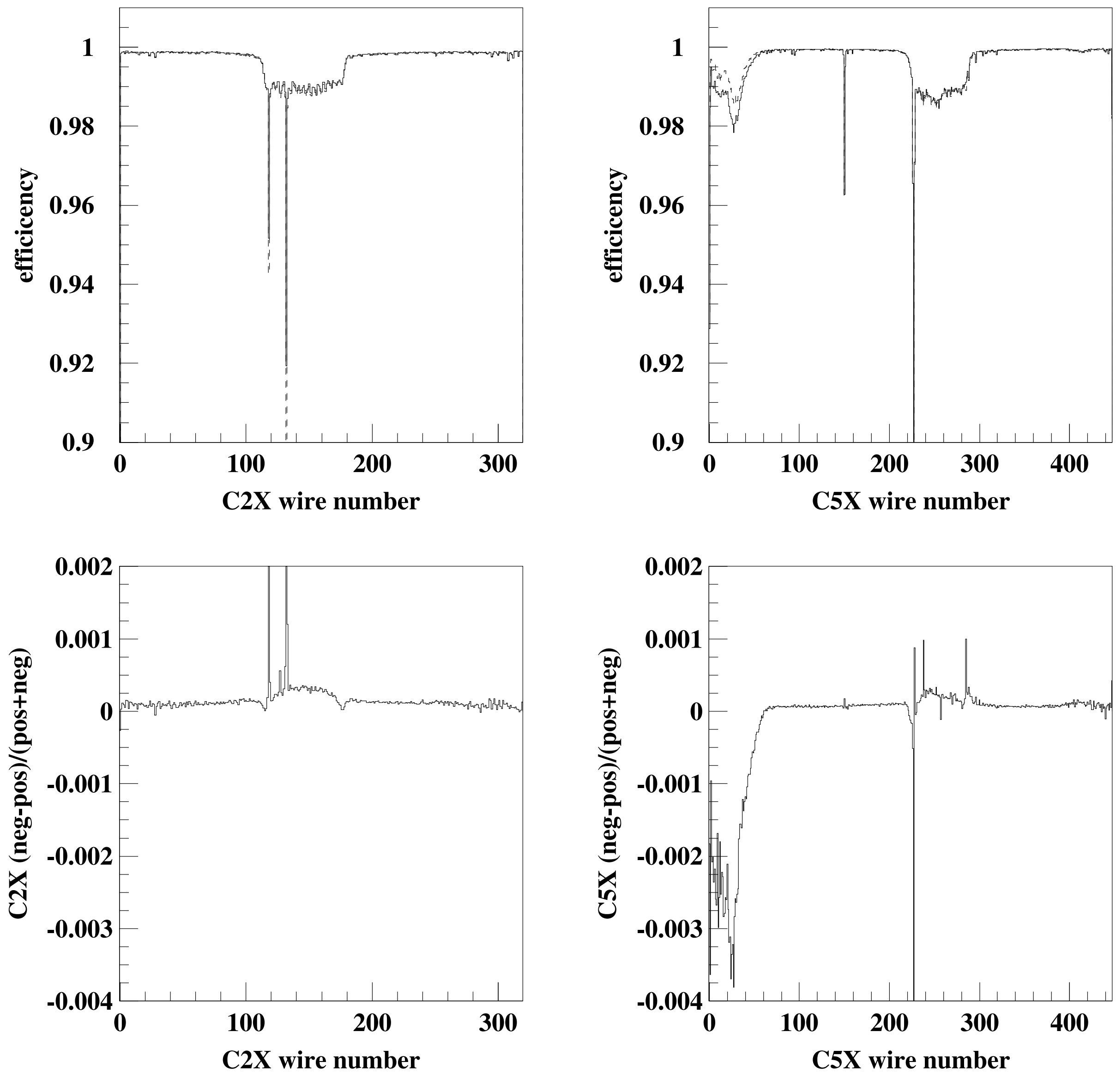


$$\boxed{\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \overline{p}\pi^+\pi^+}$$

$$\begin{aligned} \frac{dP}{d\cos\theta} &= \frac{1}{2}(1 + \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}} \cos\theta) \\ &= \frac{1}{2}(1 + (-\alpha_\Xi)(-\alpha_\Lambda) \cos\theta) \\ &= \frac{1}{2}(1 + \alpha_\Xi \alpha_\Lambda \cos\theta) \end{aligned}$$

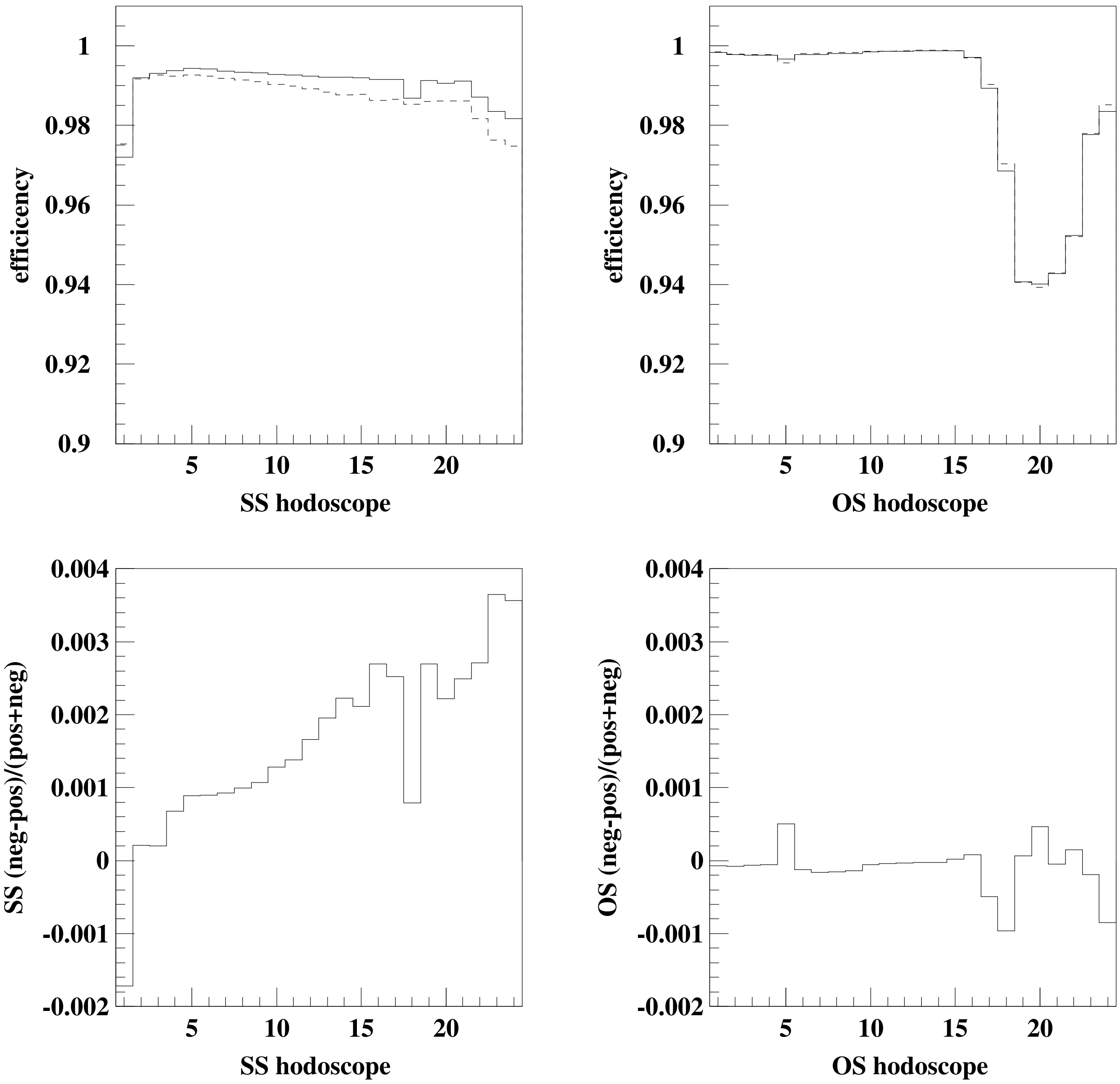
As long as we exactly flip the hyperon and spectrometer magnetic fields we have a CP invariant apparatus.

To a very good approximation the apparatus is CP invariant



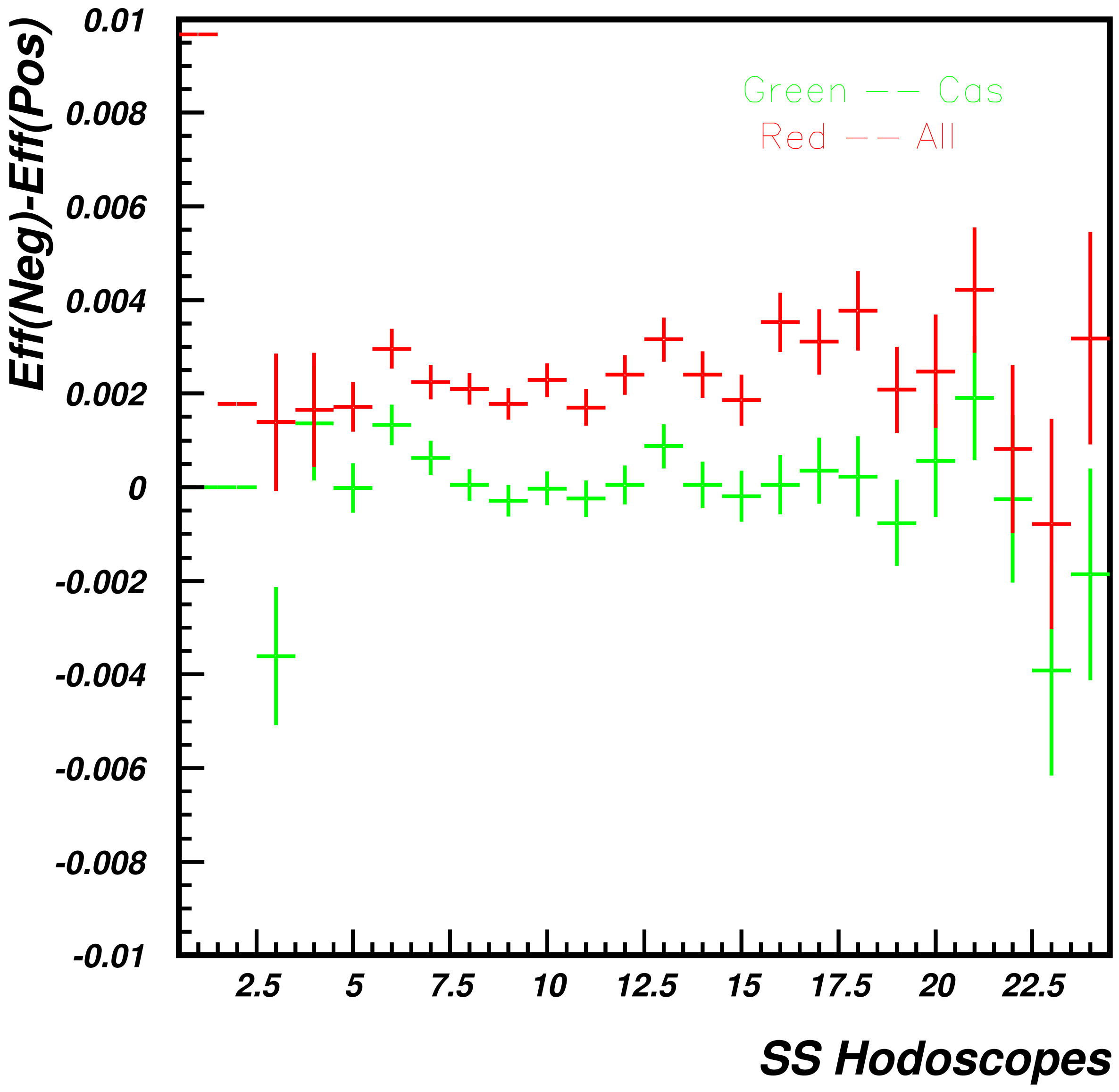
Chamber efficiencies from positive and negative running. Solid lines are negative data, dashed are positive.

Hodoscope efficiencies from the farm analysis. Solid lines are negative data, dashed are positive.



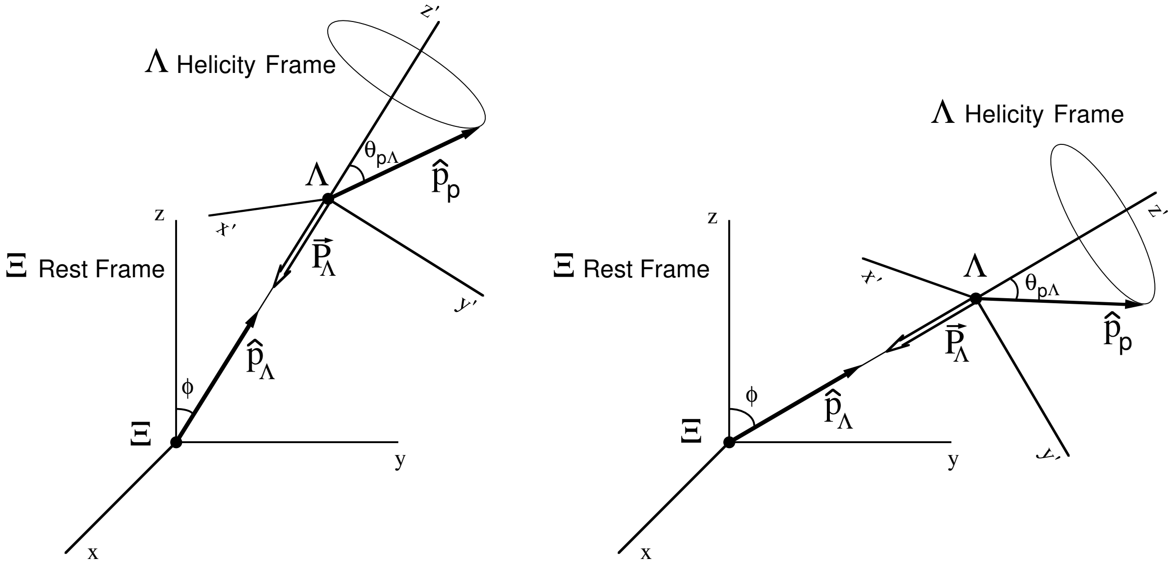
- **Note:** over **one billion** events in the OS plot and over **two billion** events in the SS plot.
- Only one of two possible hits of each of the counters is required by the trigger.

The difference in efficiencies is less than 10^{-3} when only Ξ^- and $\overline{\Xi}^+$ events, and not all events, are compared.

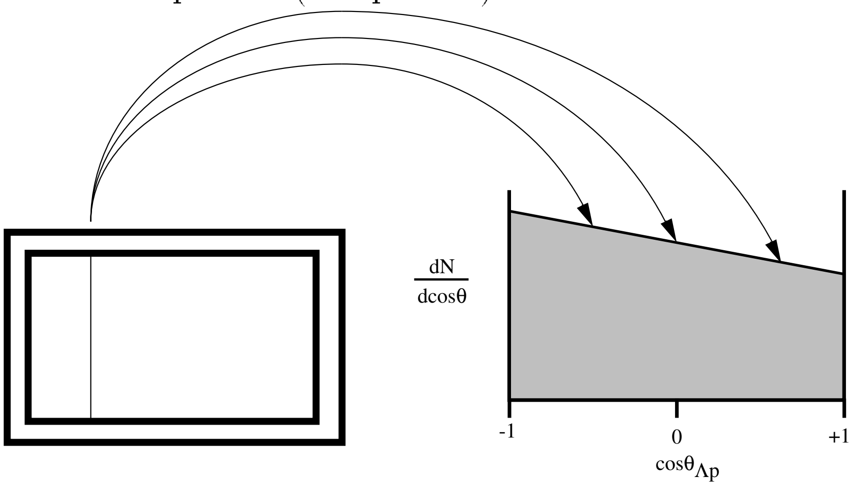


Our analysis method naturally minimizes potential biases

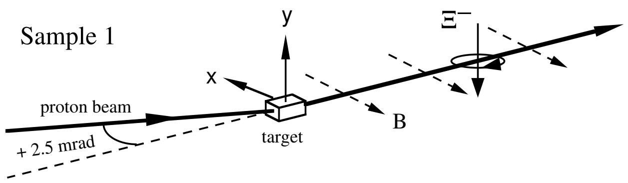
- The analysis frame axes changes from event to event since we always define the $\hat{z}$ axis to be the direction of the Λ momentum in the Ξ rest frame.



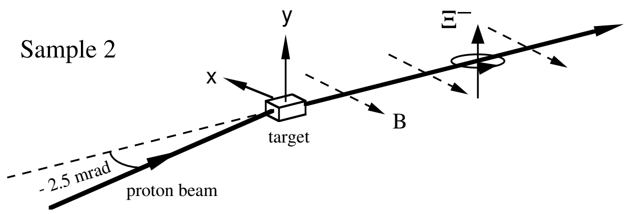
- Acceptance differences localized in a particular part of the apparatus do **not** map into a particular part of the proton (antiproton) $\cos\theta$ distribution.



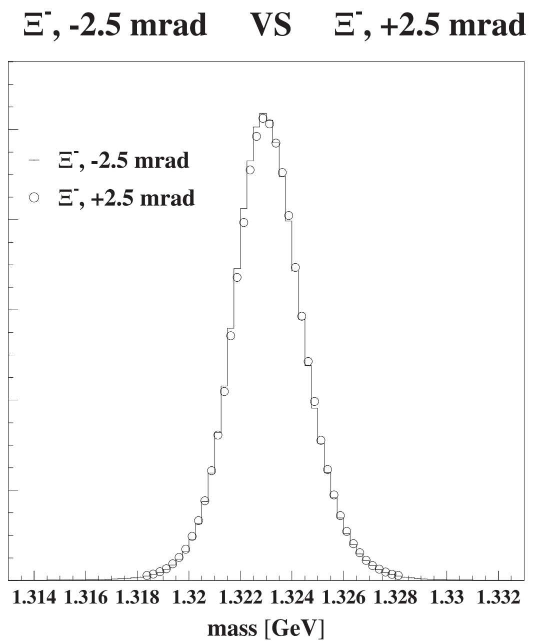
To illustrate the power of the helicity frame analysis in minimizing biases we have analyzed two sets of Ξ^- hyperons with different polarizations



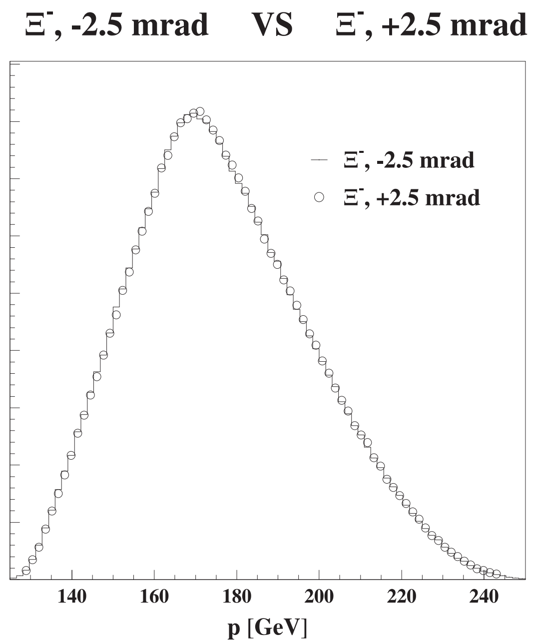
$$\mathrm{p} + \mathrm{Cu} \rightarrow \Xi^- \Uparrow + \mathrm{X}$$



- The two samples have polarization of about 14% in equal and opposite directions.
- The two samples also have different acceptances. Neverthless the two sets have very similar masses and momenta:

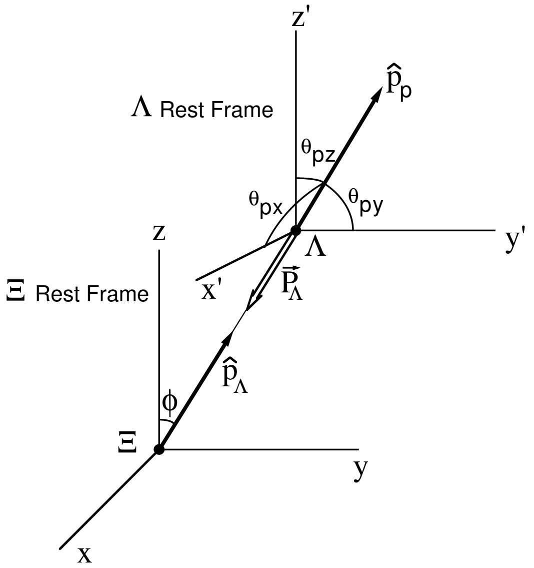


The $p\pi^-\pi^-$ invariant mass comparison

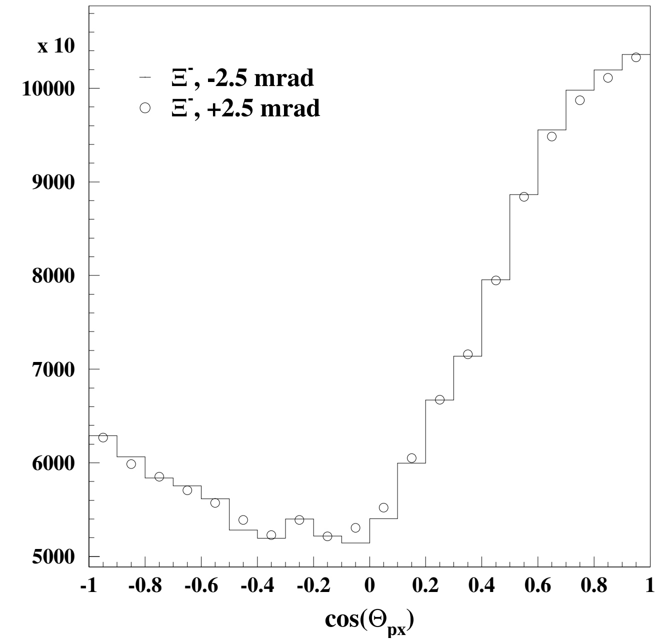


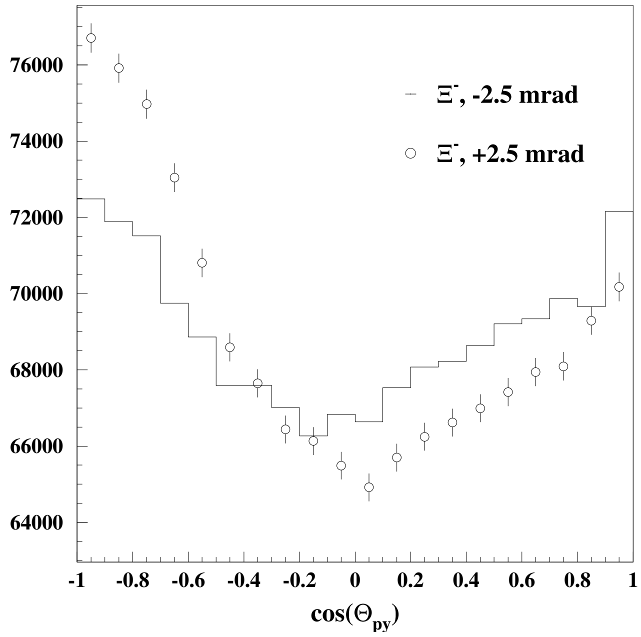
The Ξ^- momentum comparison

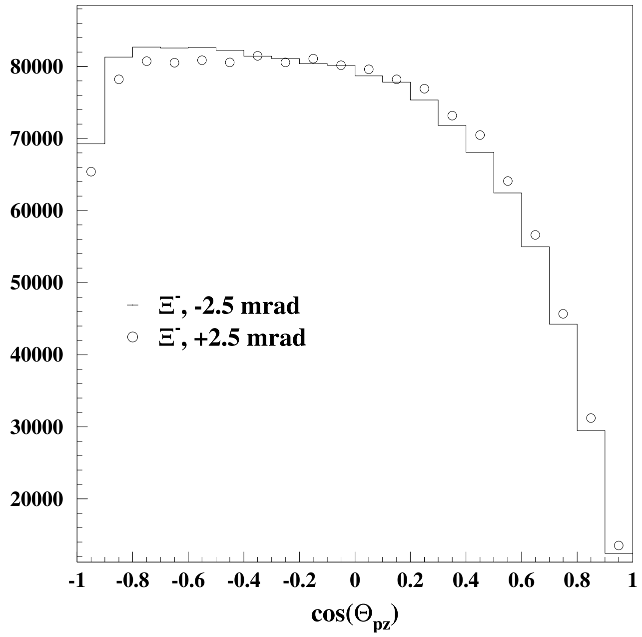
Effect of Polarization on Fixed Axis Analysis



The fixed axis analysis frame.



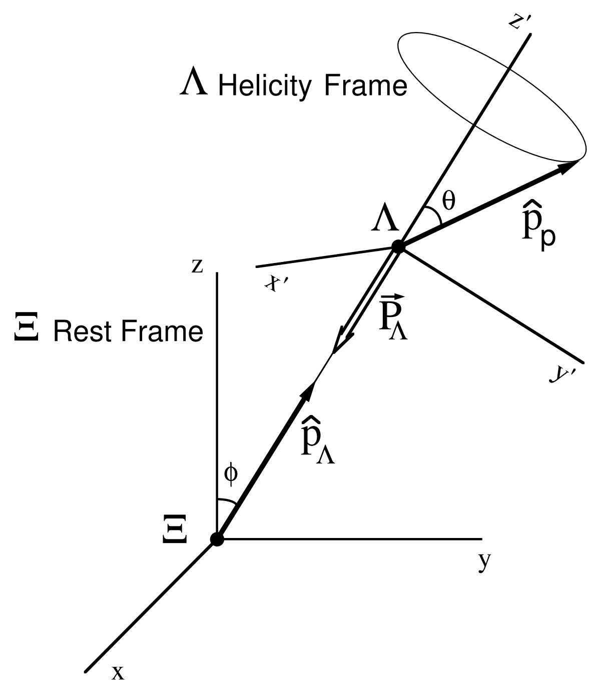


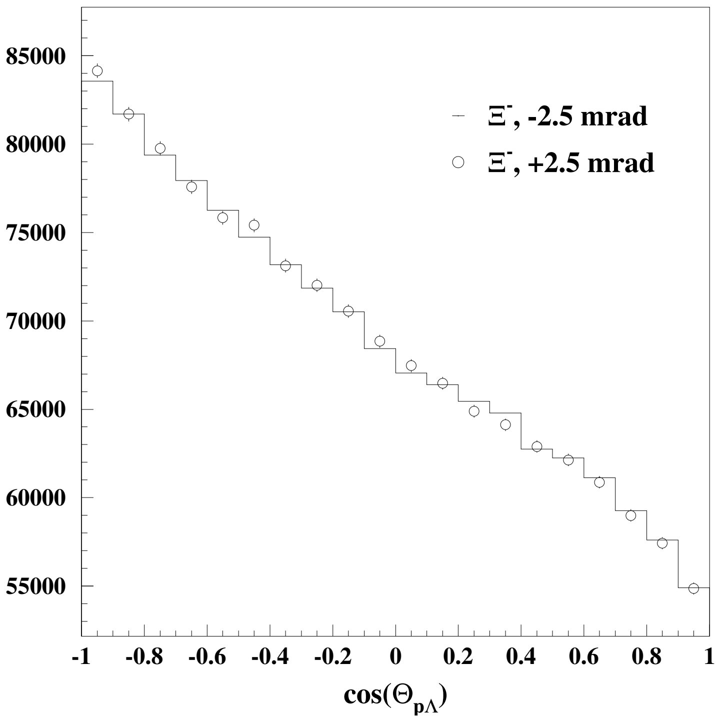


- Effect on the $\cos\theta_p$ distribution is huge!

Effect of Polarization on Helicity Frame Analysis

Ξ^- $(-2.5$ mrad$)$ vs Ξ^- $(+2.5$ mrad$)$





No statistically significant effect at the several times 10^{-3} level!

A preliminary CP violation study, including a careful examination of systematic errors, has been done with a small fraction of the data

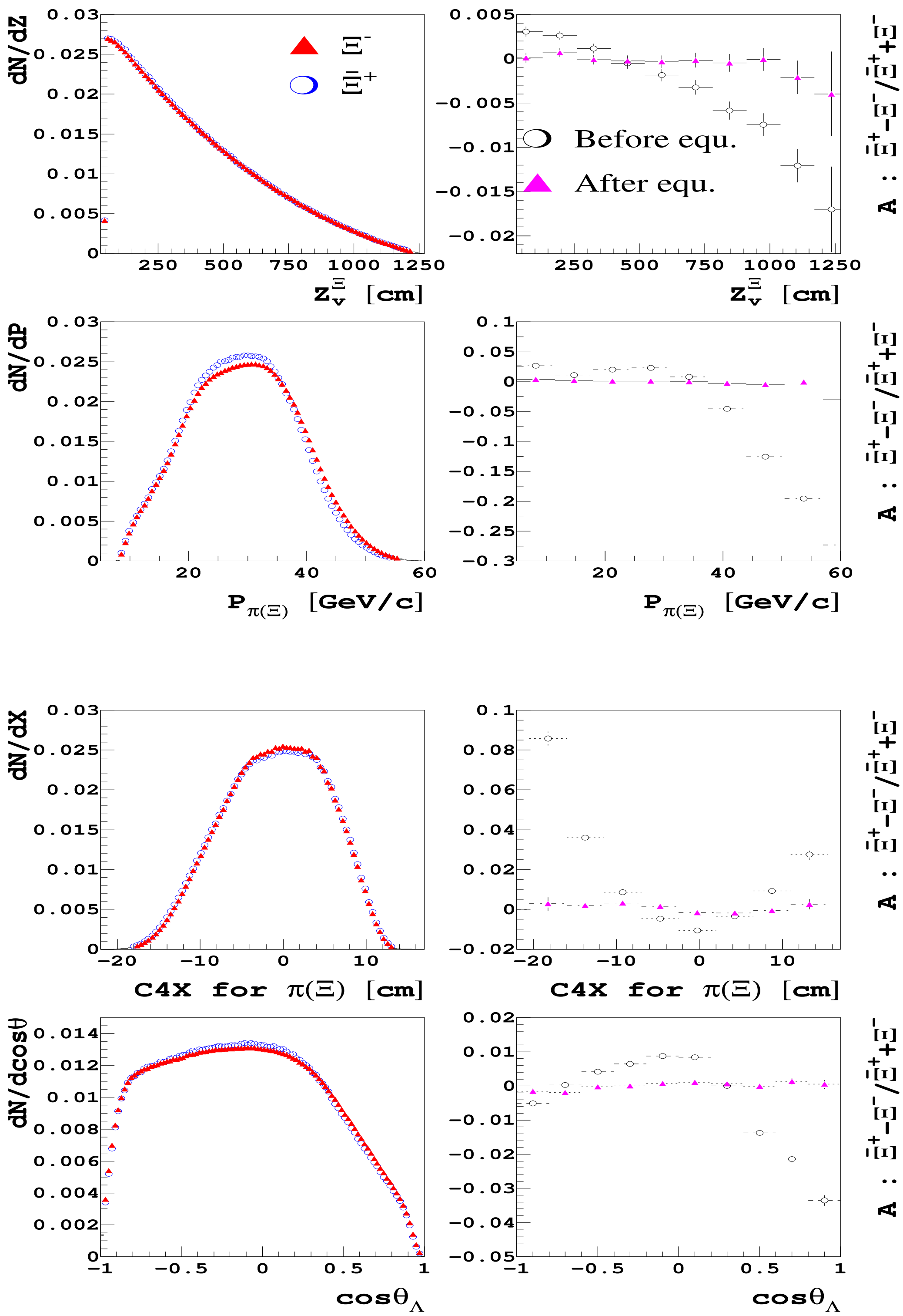
- Four sets of 1997 runs widely separated in time were used.
- $$\left.\begin{array}{rlcl} 5.9\times10^{6} & \Xi^{+} \text{ events} & : & 1.2\% \\ 37.2\times10^{6} & \Xi^{-} \text{ events} & : & 1.9\% \end{array}\right\}\text{of 1997 data set after all cuts}$$
- The positive and negative data sets were normalized to each other in five variables:

$$\left.\begin{array}{r} \Xi \text{ x target origin} \\ \Xi \text{ y target origin} \\ \Xi \text{ x collimator exit position} \\ \Xi \text{ y collimator exit position} \\ \Xi \text{ momentum} \end{array}\right\} 12\times10^{6} \text{ cells}$$

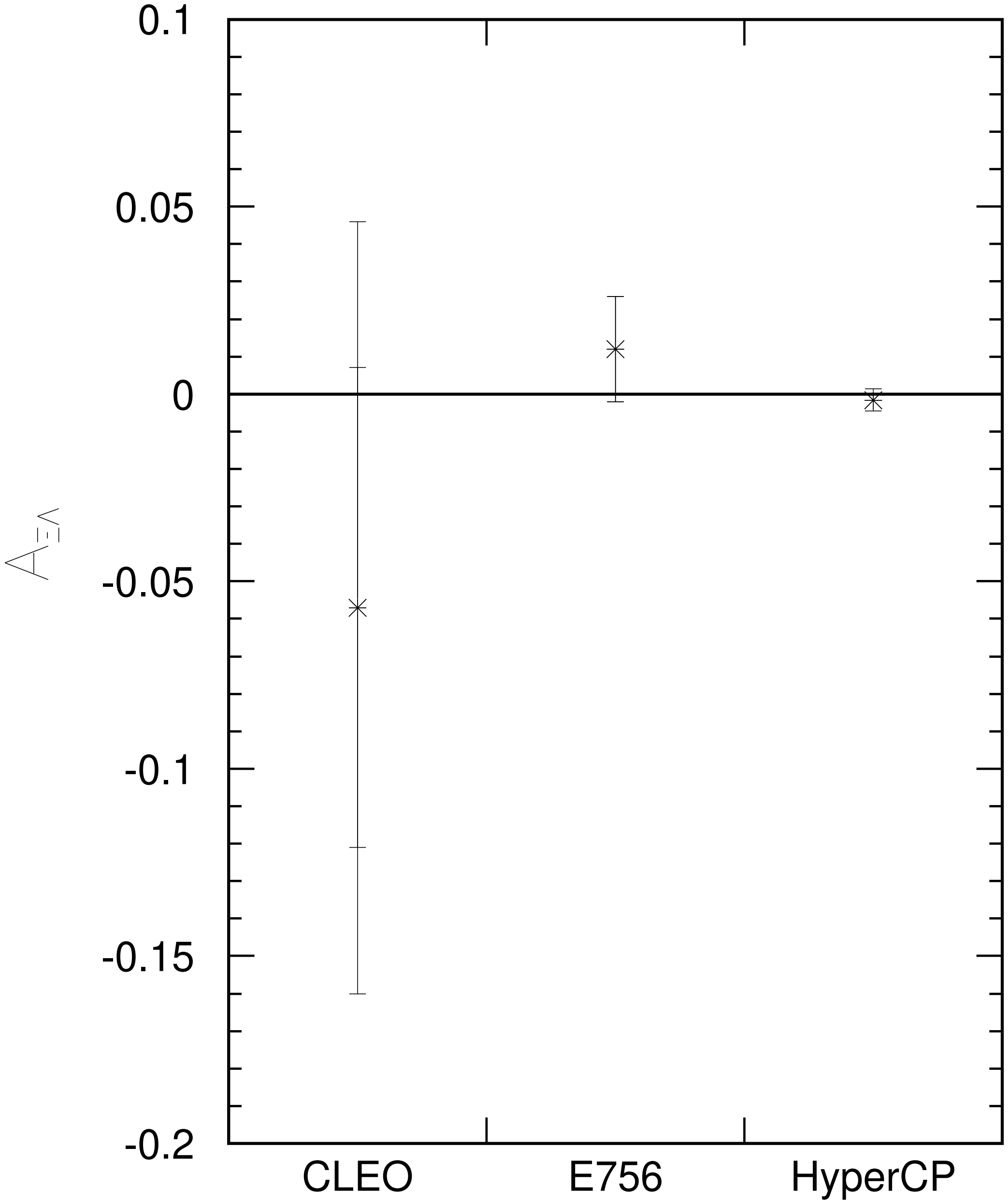
- The effect of the normalization scheme on any real asymmetry was tested with a Hybrid Monte Carlo:
  - $$\begin{array}{r} 20\times10^{6}\ \Xi^{+} \text{ MC events} \\ 150\times10^{6}\ \Xi^{-} \text{ MC events} \end{array}$$
  - $$\begin{array}{rl} \text{MC Input:} & \rightarrow A_{\Xi\Lambda} = -17.1\times10^{-3} \\ \text{Analysis Output:} & \rightarrow A_{\Xi\Lambda} = (16.9 \pm 0.4)\times10^{-3} \end{array}$$
- Biases from interactions, backgrounds, and the normalization process were studied and found to be consistent with zero with a precision of:

$$\delta A_{\Xi\Lambda} < 1.6\times10^{-3}$$

EFFECTS OF THE EQUALIZATION



Preliminary Study



This *preliminary HyperCP* study, based on an analysis of 1.7% of the 1997 data gives:

$$\boxed{A_{\Xi\Lambda} = (-1.6 \underset{\text{stat}}{\pm 1.3} \underset{\text{syst}}{\pm 1.6}) \times 10^{-3}}$$

Conclusions and Outlook

- *HyperCP* has ammassed by far the most hyperons ever recorded.
- The data looks good: a preliminary study of 1.7% of the data gives:

$$\delta A_{\Xi\Lambda} = (-1.6 \pm 1.3 \pm 1.6)\times 10^{-3}$$

- We are confident that we will be able to test CP conservation in Ξ and Λ decays to $\delta A_{\Xi\Lambda} \approx 2\times 10^{-4}$ — two orders of magnitude better than the present limit — assulting CP violation from a different direction than the kaon and B experiments.
- A rich program of charged hyperon and kaon physics is in progress, including the first high-sensitivity searches for rare and forbidden hyperon decays.

> *"We must continue to seek the origin of the CP symmetry violation by all means at our disposal. We know that improvements in detector technology and quality of accelerators will permit even more sensitive experiments in the coming decades. We are hopeful, then, that at some epoch, perhaps distant, this cryptic message from nature will be deciphered."*
>
> J. Cronin, 1981