FNAL E871 - HyperCP

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Physics Goals

Primary Goal:

A search for exotic sources of CP violation in hyperon decays.

Secondary Goals:

- Search for rare and forbidden hyperon and charged kaon decays:
  - Lepton number nonconservation in $\Xi^- \rightarrow p\, \mu^- \mu^-$
  - Flavor changing neutral currents in hyperon and charged kaon decays:
    $K^{+/-} \rightarrow \pi^{+/-} \mu^+ \mu^-$ and $\Sigma^+ \rightarrow p^+ \mu^+ \mu^-$ and Ω decays

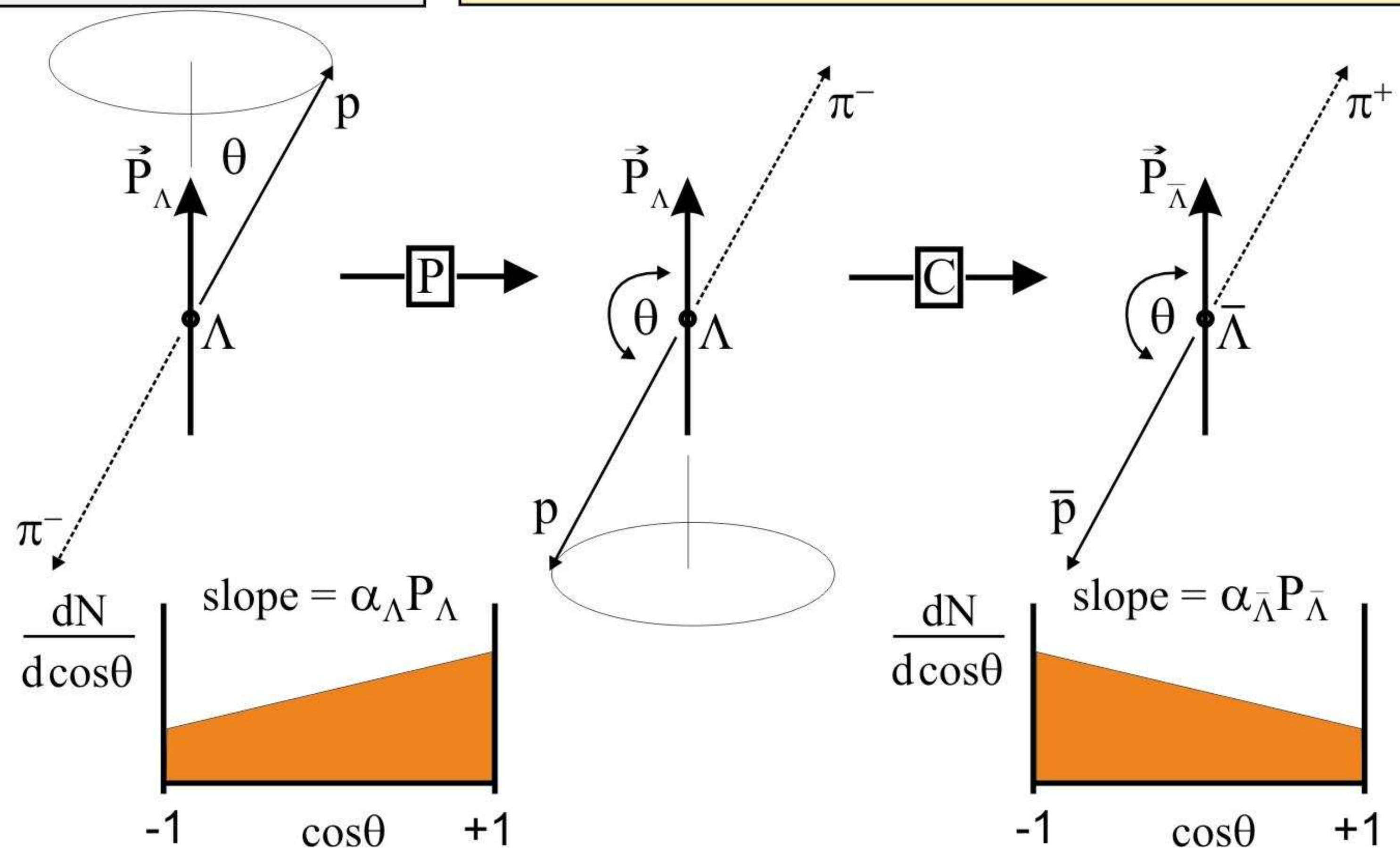
- Measure various hyperon production and decay properties:
  - Hyperon production cross sections
  - Hyperon polarization
  - Measurements of β decay parameter
  - Measurements of α decay parameter

Theory

$$\Xi^- \rightarrow \Lambda\pi^-$$
$$\hookrightarrow p\pi^-$$

$$\frac{dN}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta)$$

$$\vec{P}_\Lambda = \frac{(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{p}_\Lambda)\hat{p}_\Lambda + \beta_\Xi(\vec{P}_\Xi \times \hat{p}_\Lambda) + \gamma_\Xi(\hat{p}_\Lambda \times (\vec{P}_\Xi \times \hat{p}_\Lambda))}{(1+\alpha_\Xi \vec{P}_\Xi \cdot \hat{p}_\Lambda)}$$



$\Lambda \rightarrow p\pi^-$ $\qquad$ $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

HyperCP Measurement

$\Lambda/\bar{\Lambda}$'s of known polarization can be produced through the decay of unpolarized $\Xi^-/\bar{\Xi}^+$'s.

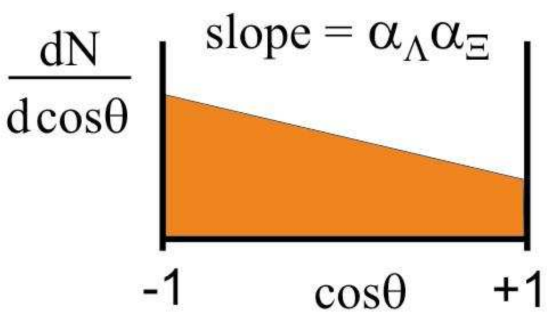
If the Ξ is produced unpolarized - which can simply be done by targeting at 0 degrees the Λ is found in a helicity state:

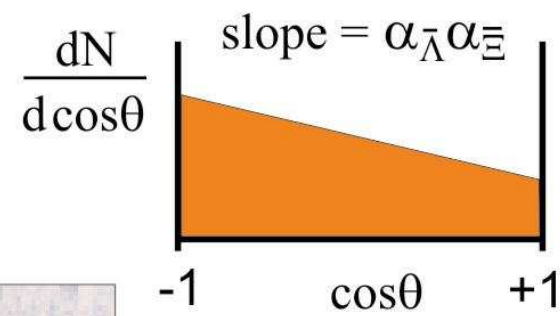
$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad\qquad \vec{P}_{\bar{\Lambda}} = \alpha_{\bar{\Xi}} \hat{p}_{\bar{\Lambda}}$$

$$\frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta)$$

$$\alpha_\Lambda \alpha_\Xi \overset{CP}{\Rightarrow} \alpha_{\bar{\Lambda}} \alpha_{\bar{\Xi}}$$

$$\frac{dN(\bar{p})}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_{\bar{\Lambda}} \alpha_{\bar{\Xi}} \cos\theta)$$





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

If CP is good, the slopes of the proton and antiproton cosθ distributions are identical…

Phenomenology

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.

$$A_\Lambda = (\alpha_\Lambda + \alpha_{\bar{\Lambda}})/(\alpha_\Lambda - \alpha_{\bar{\Lambda}}) \cong -\tan(\delta_P - \delta_S)\sin(\phi_P - \phi_S)$$

$$A_\Xi = (\alpha_\Xi + \alpha_{\bar{\Xi}})/(\alpha_\Xi - \alpha_{\bar{\Xi}}) \cong -\tan(\delta_P - \delta_S)\sin(\phi_P - \phi_S)$$

strong phases   weak phases

Beware of theorist's predictions. Calculations are notoriously difficult…

"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.

Ø Standard Model predictions for the asymmetry range from about 10^{-4} to 10^{-5}

Ø Hyperon CP violation not the same as kaon CP violation!

Ø Some super-symmetric models allow asymmetries as large as 10^{-3}

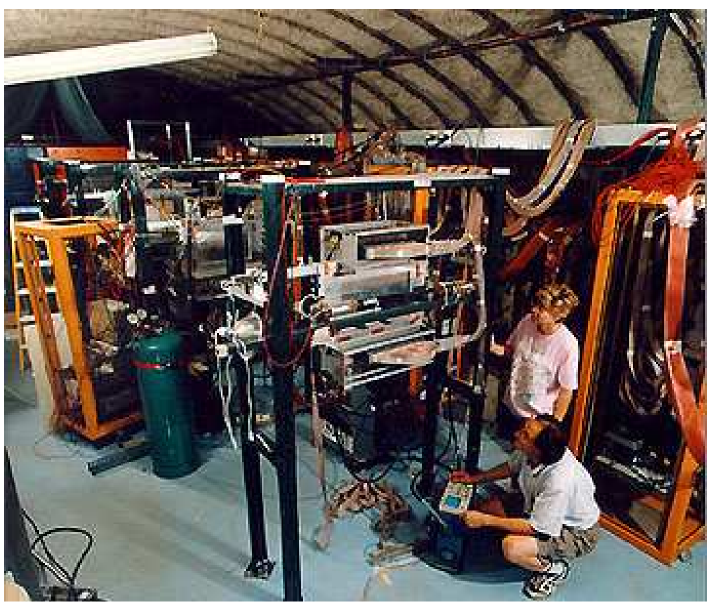
Experimental Situation

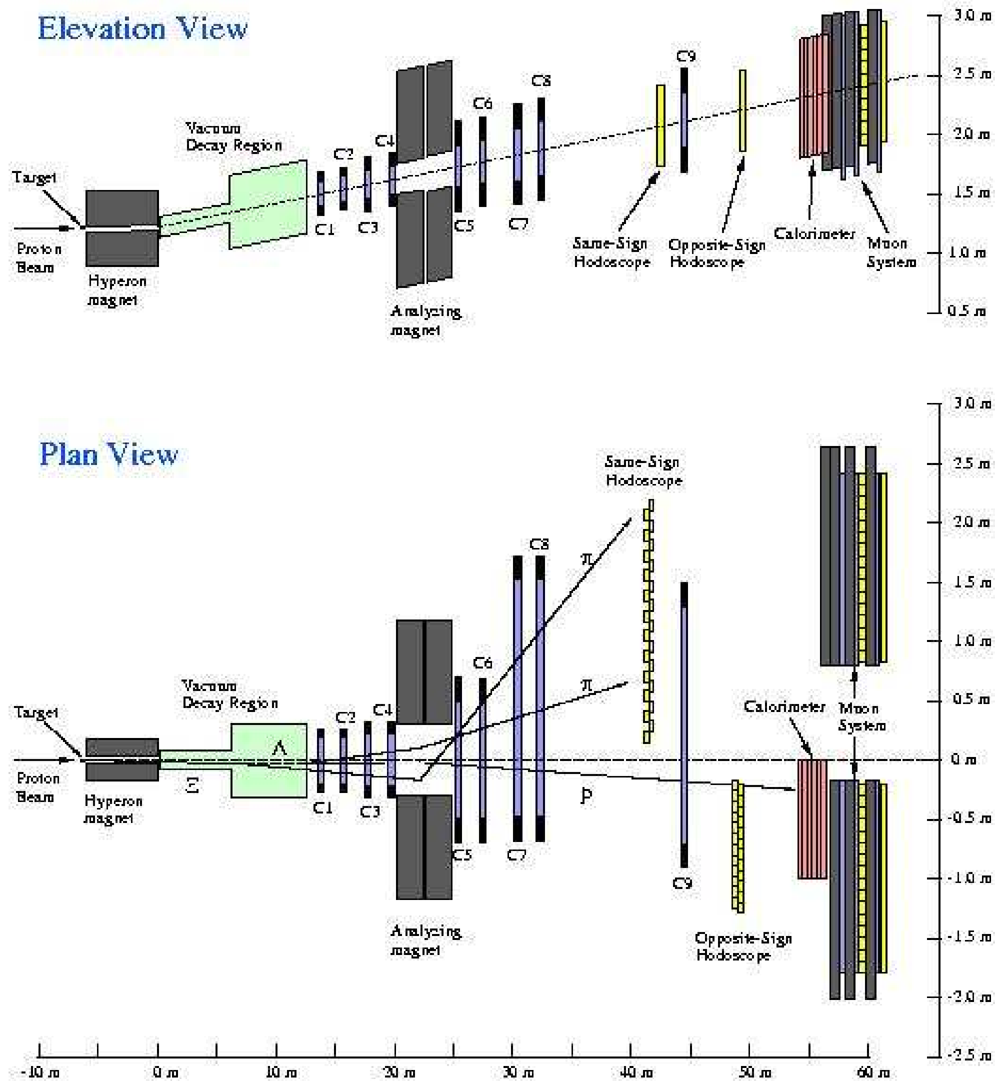
Experiment	Mode	A_Λ
R608 at ISR	$\bar{p}p \to \Lambda X,\ \bar{p}p \to \bar{\Lambda} X$	-0.02 ± 0.14
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	0.01 ± 0.10
PS185 at LEAR	$\bar{p}p \to \bar{\Lambda}\Lambda$	-0.013 ± 0.022

Experiment	Mode	$A_{\Xi\Lambda}$
FNAL E756	$\Xi \to \Lambda\pi,\ \Lambda \to p\pi$	0.012 ± 0.014
CLEO (unpublished)	$\Xi \to \Lambda\pi,\ \Lambda \to p\pi$	$-0.057 \pm 0.064 \pm 0.039$

- HyperCP will measure $A_{\Xi\Lambda}$ with unpolarized Ξ^- and Ξ^+ hyperons produced by 800 GeV protons to a precision of 10^{-4}.

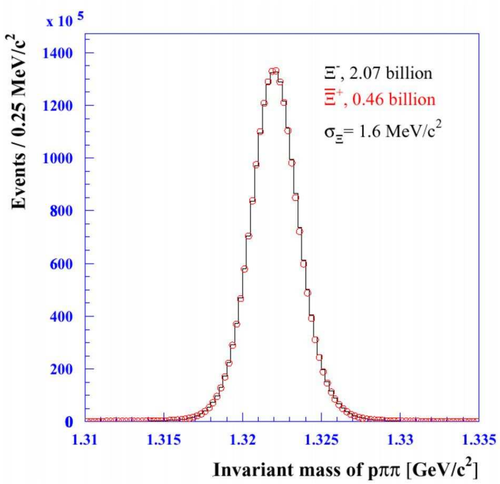
HyperCP Apparatus

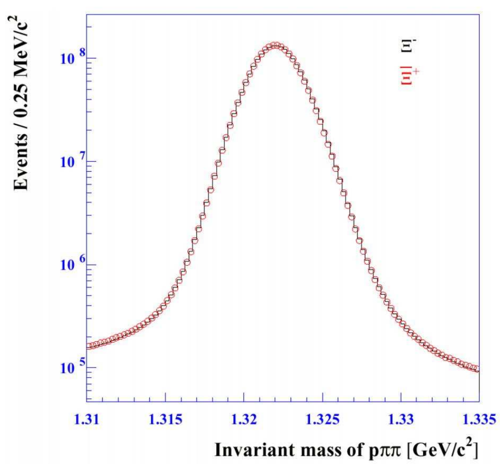




Data Summary

In 12 months of data taking we recorded one the largest data sample ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.





HyperCP Yields

Triggers

	1997	1999	Total
Total triggers (10^9)	58	173	231
Cascade triggers (10^9)	39	90	129
Negative cascade triggers (10^9)	15	29	44
Positive cascade triggers (10^9)	24	61	85
Data volume (TB)	38	82	120
Tapes (Exabyte)	8,980	20,421	29,401

Reconstructed Events: Total

Mode	Parent particle polarity +	Parent particle polarity −	Total
$\Xi \to \Lambda\pi$	458×10^6	2032×10^6	2490×10^6
$\Omega \to \Lambda K$	4.86×10^6	14.11×10^6	18.97×10^6
$K \to 3\pi$	391×10^6	164×10^6	555×10^6
$K_s \to \pi^+\pi^-$	2025×10^6	693×10^6	2718×10^6

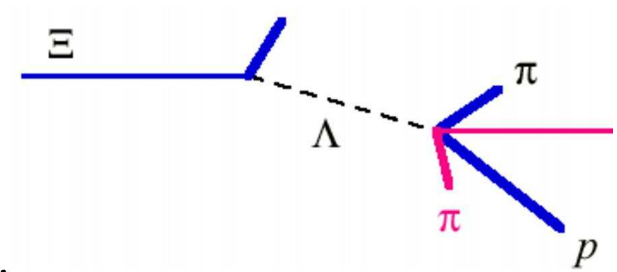
Reconstructed Events: Polarized

Angle	$\overline{\Xi}^+$	Ξ^-
+3.0 mrad	17.7×10^6	89.4×10^6
−3.0 mrad	10.2×10^6	75.1×10^6
+2.5 mrad	2.9×10^6	6.9×10^6
−2.5 mrad	2.1×10^6	6.0×10^6

Hybrid MC Method

- For a given input event, Monte Carlo events are created using all measured quantities from the input event except $\cos\theta_{p\Lambda}$ which is generated uniformly.

- The HMC events are then subjected to multiple scattering, detector simulation, track reconstruction and the same selection process as the input events.



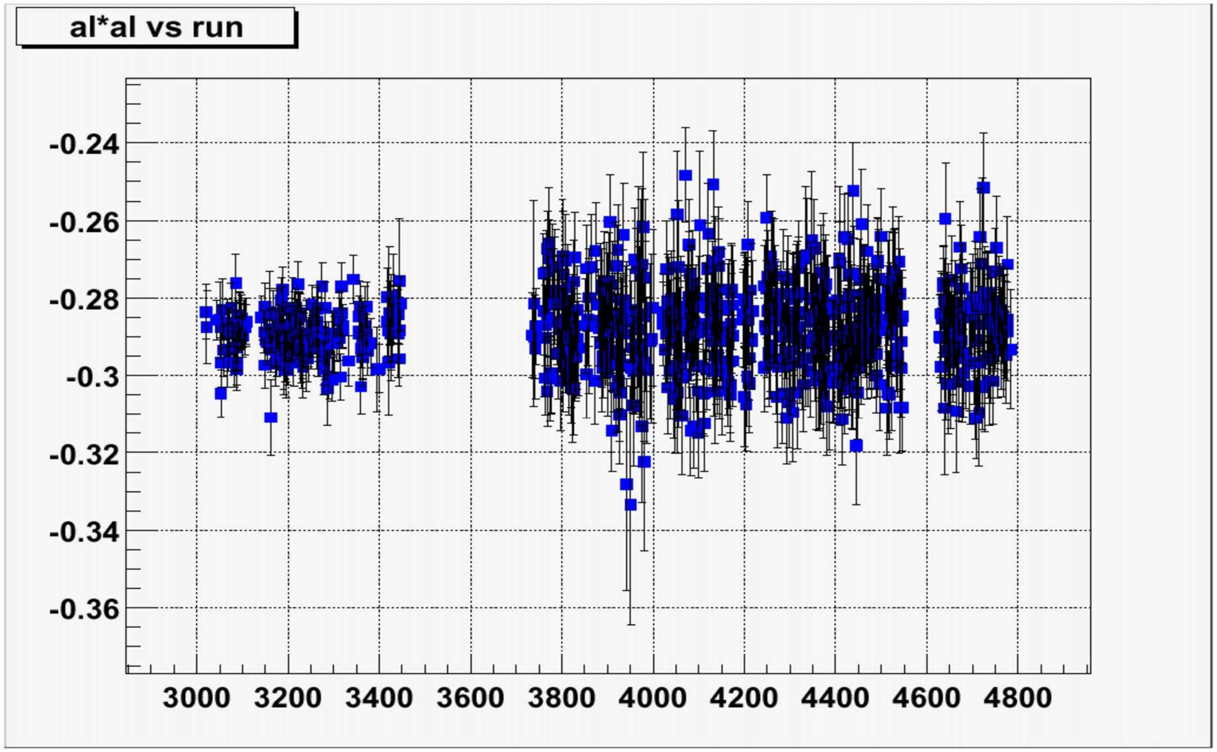
- The $\cos\theta_{p\Lambda}$ distribution of the accepted HMC events is then adjusted to match that of the input events with a weight which is a function of $\alpha_{\Xi}\alpha_{\Lambda}$ by minimization.

- Verification: PDG input $\alpha_{\Xi}\alpha_{\Lambda} = -0.2927\ (\pm\ 0.0070)$
  HMC: $\alpha_{\Xi}\alpha_{\Lambda} = -0.2953 \pm 0.0029$

DATA

HMC measurement of $\alpha_\Xi \alpha_\Lambda$ vs run

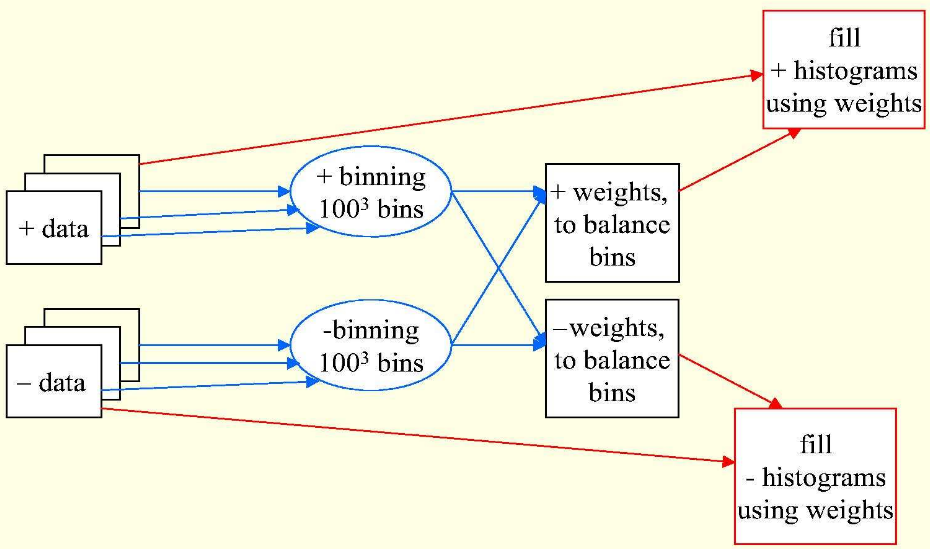
- Data sample: randomly selected Ξ events during data reduction; about 15×10^6 Ξ^- and 30×10^6 Ξ^+ events.



Average $\alpha_\Xi \alpha_\Lambda$ = -0.2880 ± 0.0004(stat) χ^2 = 26/19 dof
in agreement with PDG value

Weighting Technique

- Problem: Geometical acceptance identical for Ξ^- and $\overline{\Xi}^+$ decay products only if parent Ξ^- and $\overline{\Xi}^+$ have same momentum and inhabit the same phase space exiting the collimator.
- Solution: Weight the Ξ^- and $\overline{\Xi}^+$ events to force the two distributions to be identical.
- Take ratio of weighted proton and antiproton $\cos\theta$ distributions and look for a non-zero slope as a signature for CP violation.



- Fit follwing function:

$$\frac{\frac{1}{N_0}\frac{dN}{d\cos\theta}}{\frac{1}{\overline{N}_0}\frac{d\overline{N}}{d\cos\theta}} = C\frac{1+\alpha_\Xi\alpha_\Lambda\cos\theta}{1+\overline{\alpha}_\Xi\overline{\alpha}_\Lambda\cos\theta}$$

$$= C\frac{1+\alpha_\Xi\alpha_\Lambda\cos\theta}{1+(\alpha_\Xi\alpha_\Lambda-\delta)\cos\theta}$$

- To extract asymmetry δ:

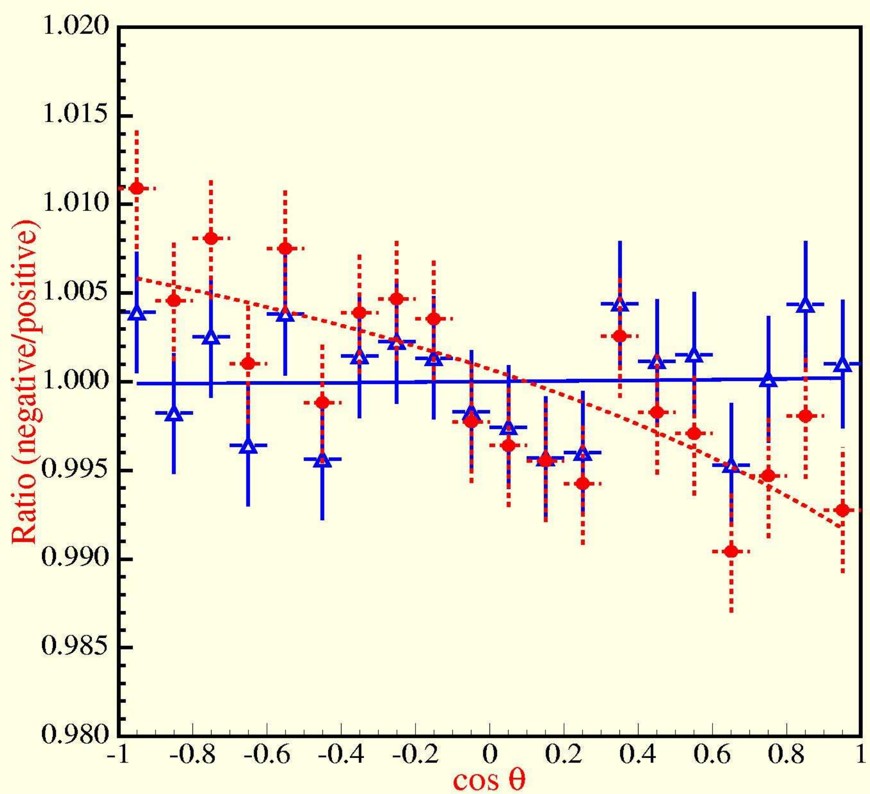
$$\delta = \alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda$$

$$A_{\Xi\Lambda} = \frac{\delta}{\alpha_\Xi\alpha_\Lambda + \overline{\alpha}_\Xi\overline{\alpha}_\Lambda}$$

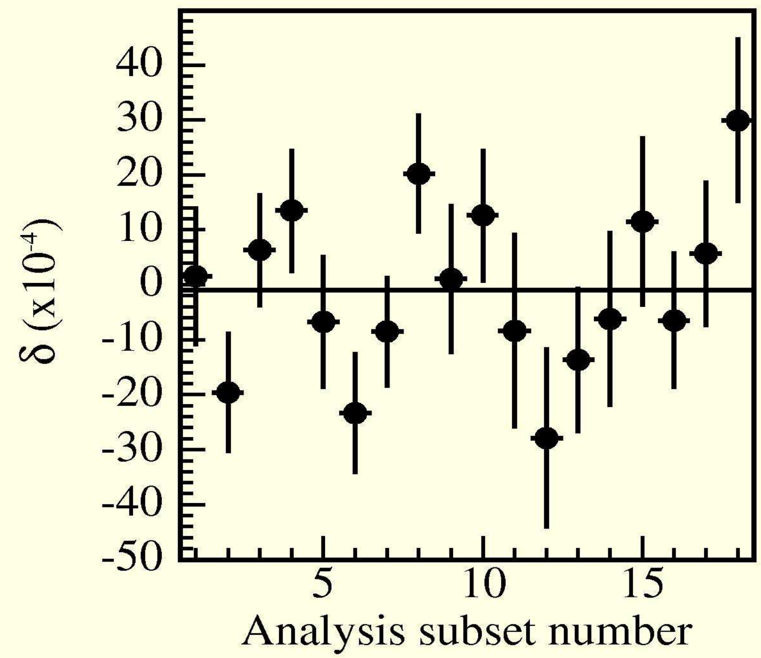
The *CP* Asymmetry $A_{\Xi\Lambda}$ from Weighting Method

$$\delta = \alpha_\Xi \alpha_\Lambda - \overline{\alpha}_\Xi \overline{\alpha}_\Lambda$$

$$\text{Fit ratio to :} \frac{1 + \alpha_\Xi \alpha_\Lambda \cos\theta}{1 + (\alpha_\Xi \alpha_\Lambda - \delta)\cos\theta}$$



Analysis set 1



Weighted average of all 18 data sets:

$$\delta = (-0.9 \pm 3.0) \times 10^{-4}$$
$$A_{\Xi\Lambda} = (1.5 \pm 5.1) \times 10^{-4}$$

$\chi^2/\text{ndf} = 1.4$

Conclusions

- HyperCP has amassed by far the largest data sample ever recorded, with which a rich program of charged hyperon and kaon physics is in progress.

- We find no evidence of CP violation in Ξ and Λ decays, with two independent analyses

$$\delta A_{\Xi\Lambda} = (1.5 \pm 5.1 \pm 4.5)\mathrm{x}10^{-4}$$
$$\delta A_{\Xi\Lambda} = (7 \pm 12 \pm 6.2)\mathrm{x}10^{-4}$$

- We will be able to push our limit to $\delta A_{\Xi\Lambda} \sim 2\mathrm{x}10^{-4}$ which is two orders of magnitude better than the present limit, assaulting CP violation from a different direction than the kaon and B experiments.

- We have the first evidence of parity violation in $\Omega^- \rightarrow \Lambda K^-$ decays.

- We are breaking new ground with our unique program of searches for rare and forbidden hyperon decays.

- Our $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ branching ratio result is consistent with Chiral Perturbation theory and favors the BNL-865 result.