Precision Measurements with the *HyperCP* Spectrometer at Fermilab

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HyperCP Physics Goals

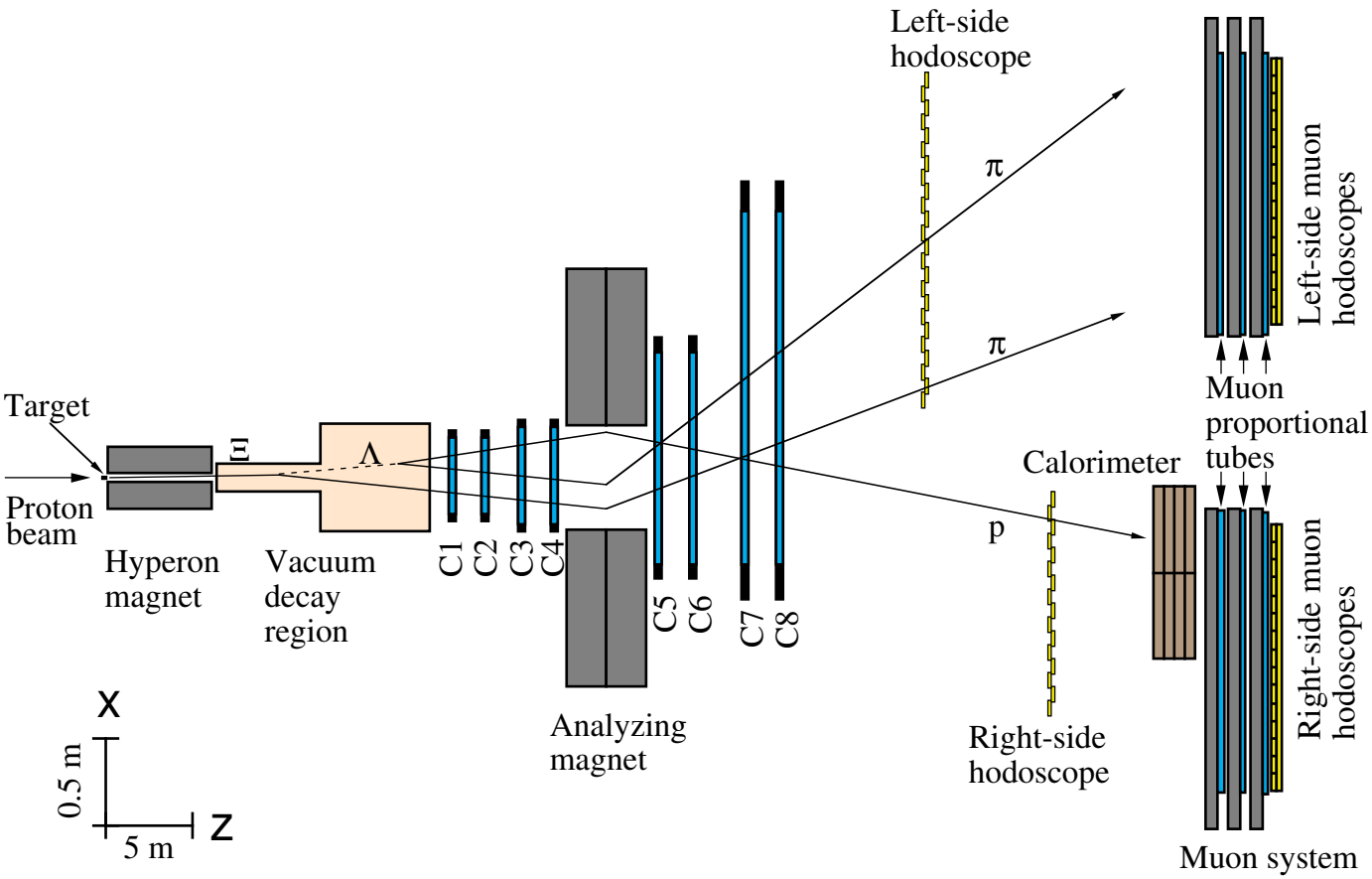
Primary Goal:

- A search for direct CP violation in $\Xi^- \to \Lambda\pi^-$, $\Lambda \to \mathrm{p}\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$, $\overline{\Lambda} \to \overline{p}\pi^+$ decays.

Secondary Goals:

- Search for CP violation in $\mathrm{K}^\pm \to 3\pi$ 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: $\Sigma^+ \to p\mu^+\mu^-$, $K^\pm \to \pi^\pm\mu^+\mu^-$.
  - $\Delta S = 2$ 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 Ξ^- decays.
  - α decay parameter in $\Omega^\pm \to \Lambda K^\pm$ decays.
  - Hyperon production cross sections.

The *HyperCP* Spectrometer



- 8 fast, low-gain, narrow-pitch wire chambers.
- Very high-rate DAQ:
  - 7–8 GHz protons, 10–15 MHz channeled beam, 50-80 KHz evts/spill-s to tape.
  - Up to 27 MB/s on 27 Exabyte 8705 tape drives.
- Simple, low-bias trigger using hodoscopes and calorimeter.
- Muon system for rare and forbidden hyperon and kaon decays.

HyperCP Yields

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

Events			
	Year		
Trigger	1997	1999	Total
Cascade	39×10^9	81×10^9	120×10^9
All	58×10^9	173×10^9	231×10^9

Number of Reconstructed Events			
	Channeled beam polarity		
Type	$+$	$-$	Total
$\Xi \to \Lambda\pi$	458×10^6	$2\,032 \times 10^6$	$2\,490 \times 10^6$
$K \to \pi\pi\pi$	391×10^6	164×10^6	555×10^6
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6

- We expect a statistical precison of:

$$\delta A_{\Xi\Lambda} \approx 2{\times}10^{-4}$$

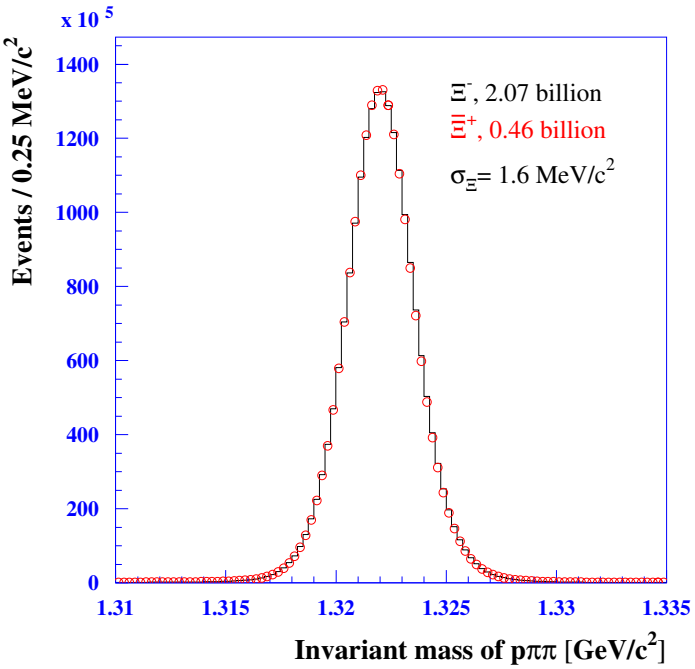
The Primary Event Reconstruction is Finished!

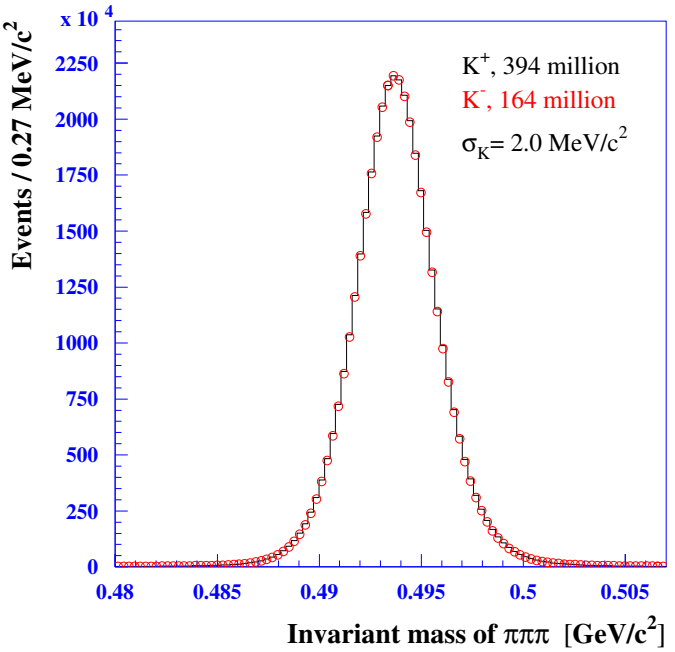
- Data volume compared to other, much larger experiments:

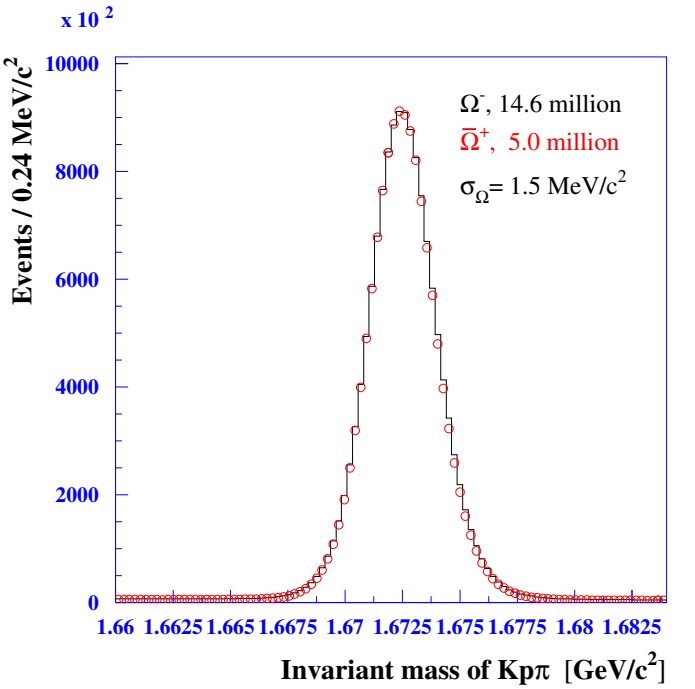
Parameters	Aleph	Babar	*HyperCP*	CDF	CMS
Event Size (KB)	250	50	0.5	250	1000
Events/yr (10^9)	0.004	2	240	2	2
Data/yr (TB)	1	100	120	450	2000
Manpower	300	500	42	600	2000

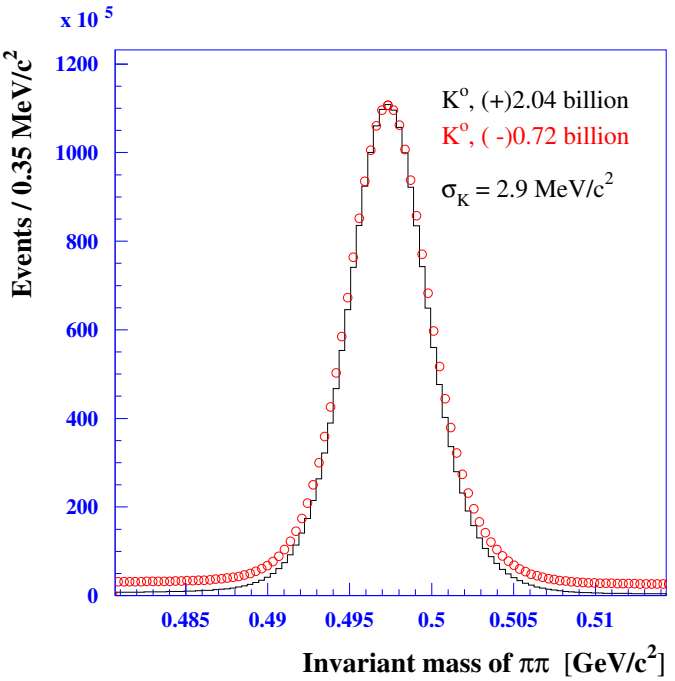
- All the data reconstructed on the Fermilab computer farm.
- Processing 30,000 tapes and keeping track of the data is a non-trivial task!
  - There are a total of 1,013 runs and 144,997 spills.
  - For each run and spill we plot 462 and 244 different parameters, respectively, for a total of 35,847,274 histograms.
  - Large (Postgres-SQL) database used to keep track of flow of information.
- It took about 11 months to reconstruct the data.
- Data sample is being used by computer scientists to study innovative data-mining techniques.
- Note: it would take 576 years to download all this data at 56 kbaud.

Masses from the Farm Analysis



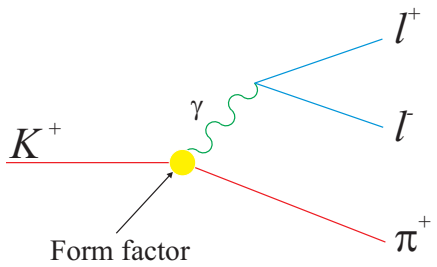






Rare Decay Physics: the Measurement of the Branching Ratio of $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$

- Importance of Rare Decays
  - Test the Standard Model: where it predicts a small effect, look for a bigger effect.
  - Test of Chiral Perturbation theory.
  - $K^{+} \to \pi^{+}l^{+}l^{-}$ also gives an estimate of the indirect CP-violating amplitude in $K_{\mathrm{L}} \to \pi^{\circ}e^{+}e^{-}$.
- In the Standard Model this FCNC decay is dominated by long-distance one-photon exchange:



- Recent Chiral Perturbation theory calculations unambiguously relate $K^{+} \to \pi^{+}\mu^{+}\mu^{-}$ to $K^{+} \to \pi^{+}e^{+}e^{-}$:

$$R = \frac{(K^{+} \to \pi^{+}\mu^{+}\mu^{-})}{(K^{+} \to \pi^{+}e^{+}e^{-})} > 0.23$$

Experimental Problems

1. The two experimental results on $K^+ \to \pi^+\mu^+\mu^-$ don't agree!

$$(5.0\pm0.4\pm0.7\pm0.6) \times 10^{-8} \qquad \text{BNL-787}$$
$$(9.22\pm0.60\pm0.49) \times 10^{-8} \qquad \text{BNL-865}$$

$$\Rightarrow 3.3\sigma \text{ discrepancy!}$$

2. The BNL-E787 result on R is too low:

$$R = 0.17\pm0.03 \qquad \text{BNL-787}$$
$$R = 0.32\pm0.03 \qquad \text{BNL-865}$$

(where the well-measured $K^+ \to \pi^+e^+e^-$ branching ratio has been used)

Measuring the $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ Branching Ratio

- Use $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ for normalization.
- Simply a counting experiment with a few acceptances and efficiencies thrown in:

$$B(K^{\pm}_{\pi\mu\mu}) = \frac{1}{200}\frac{N^{obs}_{K^{\pm}_{\pi\mu\mu}}}{N^{obs}_{K^{\pm}_{\pi 3}}}\frac{A_{K^{\pm}_{\pi 3}}}{A_{K^{\pm}_{\pi\mu\mu}}}\frac{\epsilon_{K^{\pm}_{\pi 3}}}{\epsilon_{K^{\pm}_{\pi\mu\mu}}}\frac{B(K^{\pm}_{\pi 3})}{\epsilon_{\mu^{+}\mu^{-}} \cdot \epsilon^{trig}_{rel}}$$

where:

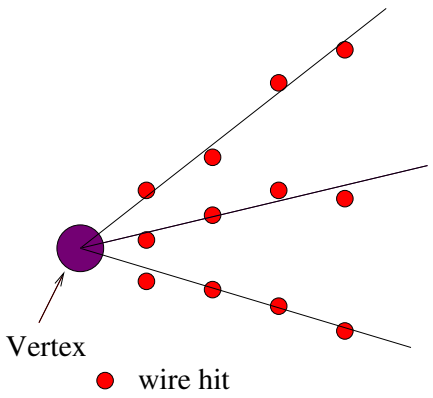
$$\begin{aligned} N^{obs} &= \text{number of observed events} \\ A_i &= \text{geometrical acceptances} \\ \epsilon_i &= \text{event selection efficiencies} \\ \epsilon^{trig}_{rel} &= \text{relative trigger efficiencies} \\ B(K^{\pm}_{\pi 3}) &= \mathrm{B}(K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}) = (5.59 \pm 0.05)\% \end{aligned}$$

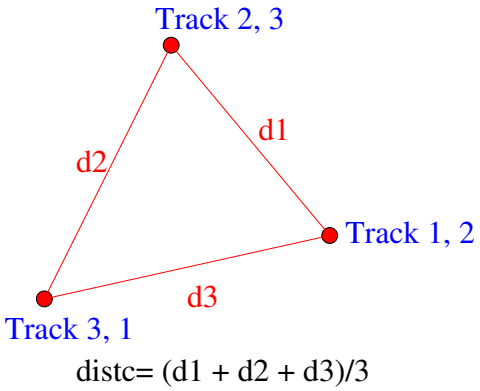
- Note: acceptances and efficiencies all high! This is not the case with BNL-787 and BNL-865.

Event Selection Cuts

Cuts common to signal and normalization samples:

- Three-track topology: two SS and one OS tracks.
- Target pointing: $\pm 5\,\mathrm{mm}$ in x and y.
- Decay vertex: within vacuum decay region.
- Decay consistent with single vertex:
  1) Good fit: $\chi^2/ndf \;<\; 2.5$.
  2) Small lateral separation at z_{vertex} $distc \;<\; 2\,\mathrm{mm}$.

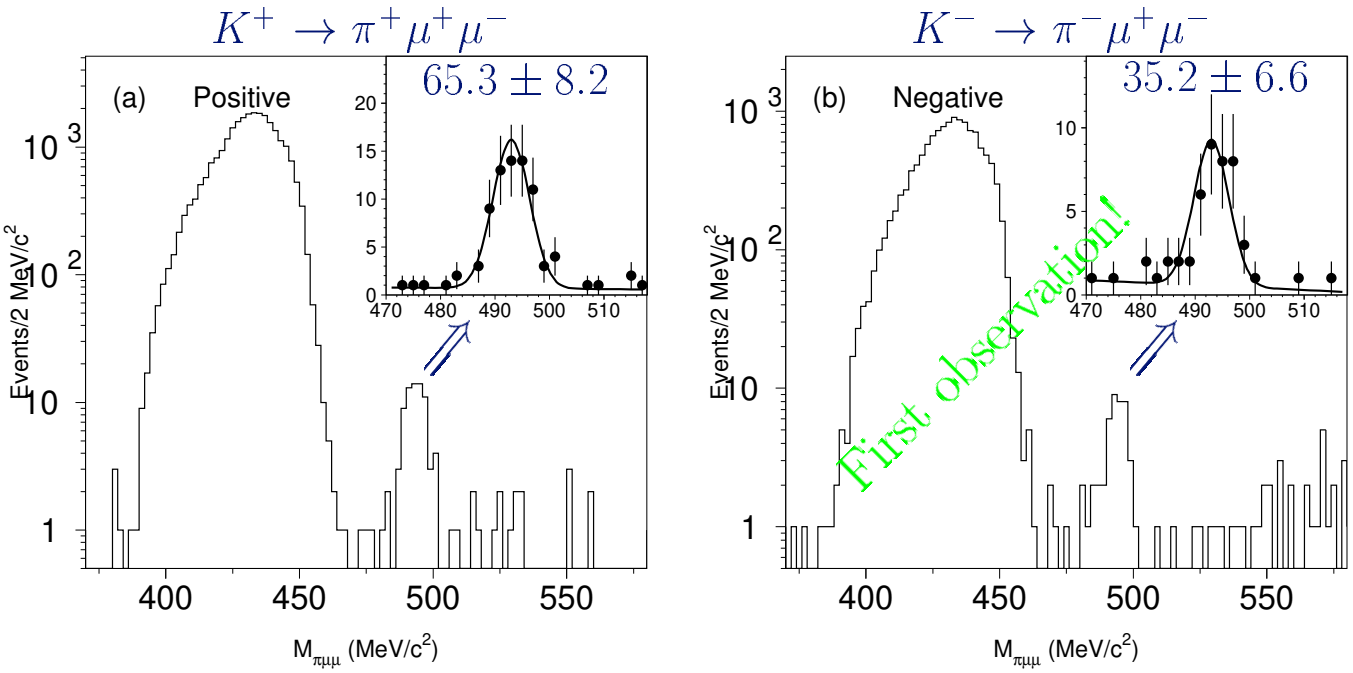




Cuts applied to just signal events — muon identification:

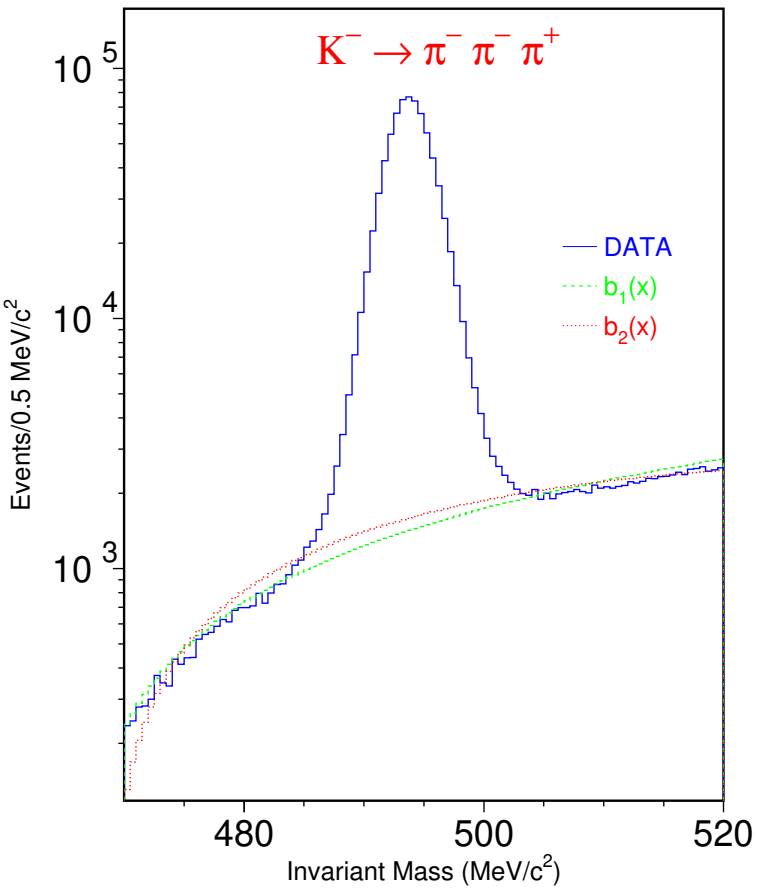
- Hits in 2/3 muon chambers in both x and y.
- Correlated in-time hits in muon hodoscopes.

Estimating the Number of $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ Events



- Signal is clean with minimum of cuts.
- Large peak to the left of the signal is from $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays reconstructed with the $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ hypothesis.
- First observation of $K^{-} \to \pi^{-}\mu^{+}\mu^{-}$!

Estimating the Number of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Events



- Try linear and quadratic fits to the background in the side-bands:

$$b_1(m) = c_1 + c_2 m$$
$$b_2(m) = c_1 + c_2 m + c_3 m^2$$

- Estimated number of events in the 1997 run:

$$N(K^+ \to \pi^+\pi^+\pi^-) = (4.446 \pm 0.010) \times 10^5$$
$$N(K^- \to \pi^-\pi^+\pi^-) = (2.318 \pm 0.008) \times 10^5$$

Summary of Systematic Errors

Source	σ_B/B (%)	$\sigma_B/B(K^{\pm}_{\pi\mu\mu})$ (%)
Beam targeting	1.1 (0.9)	1.0
Magnetic field	0.5 (0.4)	0.5
Trigger efficiency	3.1 (3.1)	3.1
Muon identification	0.3 (0.3)	0.3
Background Estimation ($K^{\pm}_{\pi 3}$)	0.2 (0.3)	0.2
Background Estimation ($K^{\pm}_{\pi\mu\mu}$)	2.4 (6.4)	3.6
Data and MC disagreement	0.4 (0.4)	0.4
Dalitz parameter	0.3 (0.3)	0.3
Slope parameter (δ)	0.2 (0.3)	0.2
$B(K^+ \to \pi^+\pi^+\pi^-)$	0.9 (0.9)	0.9
Total	4.2 (7.3)	5.0

The systematic error is less than the statistical error and is dominated by:

1. Uncertainty in the relative trigger efficiency.
2. Background to the $K^{\pm} \to \pi^{\mp}\mu^+\mu^-$ peak.

HyperCP $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ **Results**

- Separate branching ratios:

$$B(K^{+} \to \pi^{+}\mu^{+}\mu^{-}) = [9.7 \pm 1.2(\text{stat}) \pm 0.4(\text{syst})]\times 10^{-8}$$
$$B(K^{-} \to \pi^{-}\mu^{+}\mu^{-}) = [10.0 \pm 1.9(\text{stat}) \pm 0.7(\text{syst})]\times 10^{-8}$$

- Combined result:

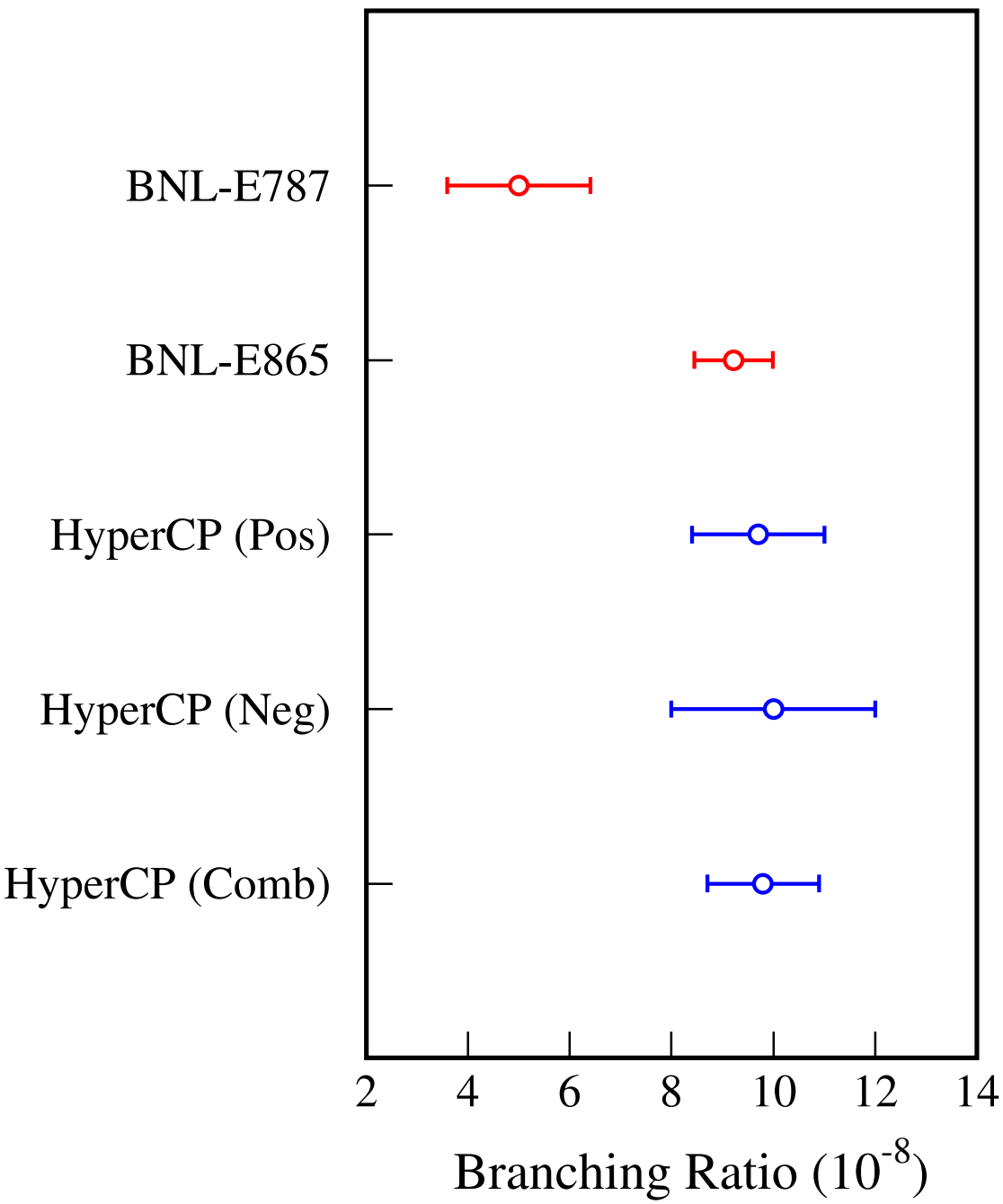
$$B(K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}) = (9.8 \pm 1.0 \pm 0.5)\times 10^{-8}$$

- CP asymmetry:

$$\Delta(K^{\pm}_{\pi\mu\mu}) = \frac{\Gamma(K^{+}_{\pi\mu\mu}) - \Gamma(K^{-}_{\pi\mu\mu})}{\Gamma(K^{+}_{\pi\mu\mu}) + \Gamma(K^{-}_{\pi\mu\mu})}$$
$$= -0.02 \pm 0.11(\text{stat}) \pm 0.04(\text{syst})$$

- Our result is consistent with the Chiral Perturbation theory calculation of $R = (K^{+} \to \pi^{+}\mu^{+}\mu^{-})/(K^{+} \to \pi^{+}e^{+}e^{-})$.
- Our result is dominated by statistical errors: expect 3X more data from the 1999 data set. Systematic error will also decrease.

Summary of Experimental Results on BR($K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$)



Why Search for CP Violation in Hyperon Decays?

- After 35 years of intense experimental effort — and many beautiful experiments — we still know little about CP violation: the origin of CP violation remains unknown and there is little hard evidence that it is explained by the Standard Model.
- The asymmetry can be 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.
- Hyperons are sensitive to sources of CP violation that, for example, kaons are not.
- 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

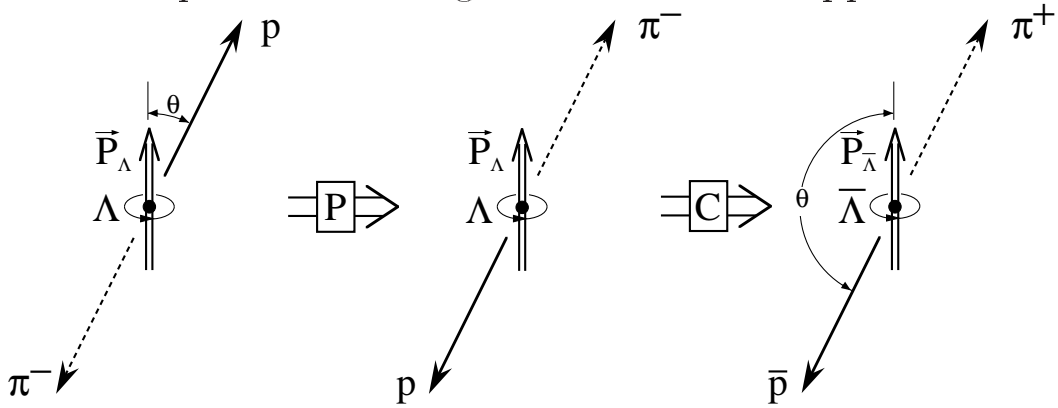
How to Search for *CP* Violation in Λ Decays?

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

Due to parity violation the proton likes to go in the direction of the Λ spin:

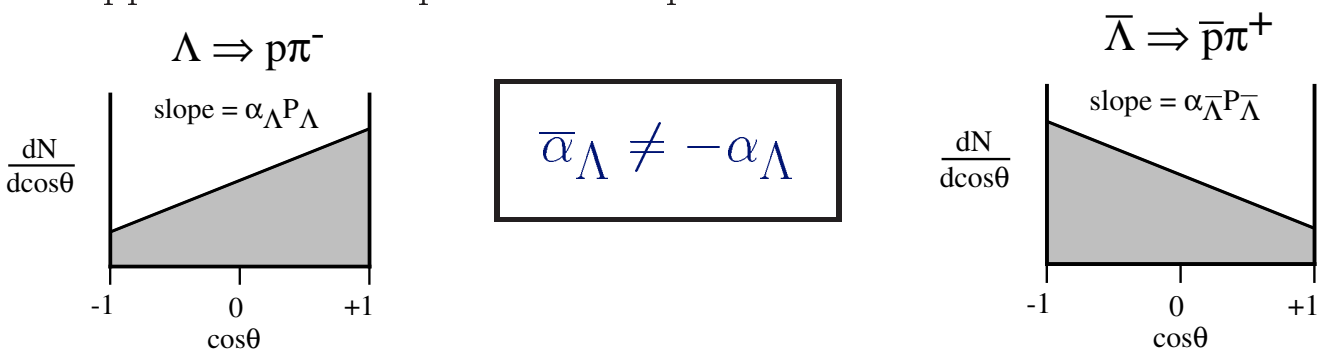
$$\frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta)$$

Under CP the antiproton likes to go in the direction opposite to the $\overline{\Lambda}$ spin:



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

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:



Problem: 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:

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

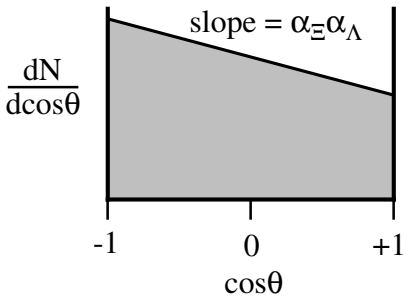
If the Ξ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the Λ is found in a helicity state:

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

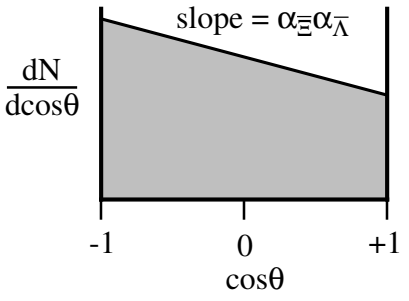
$$\frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta)$$

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

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



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



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

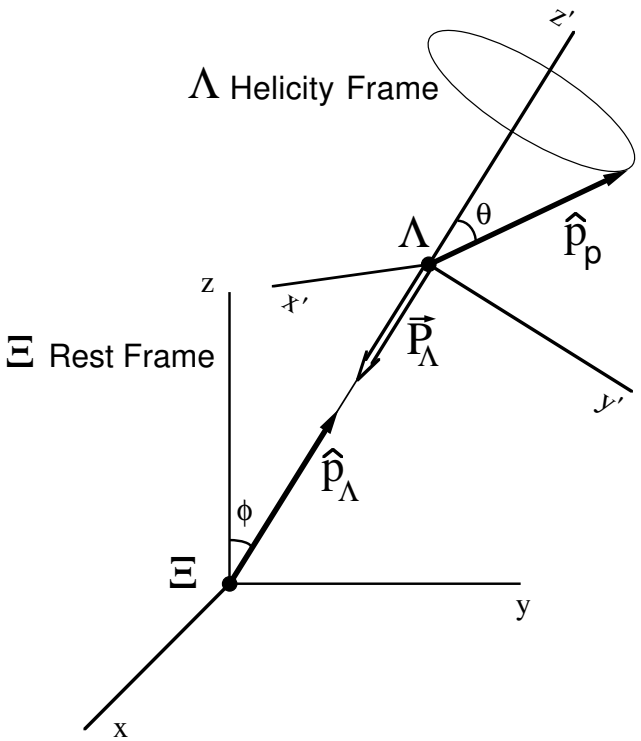
$$\alpha_\Xi \alpha_\Lambda = \overline{\alpha}_\Xi \overline{\alpha}_\Lambda$$

We are sensitive to CP violation in Ξ and Λ decays

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

where: $A_\Xi = \dfrac{\alpha_\Xi + \alpha_{\overline{\Xi}}}{\alpha_\Xi - \alpha_{\overline{\Xi}}}$ and $A_\Lambda = \dfrac{\alpha_\Lambda + \alpha_{\overline{\Lambda}}}{\alpha_\Lambda - \alpha_{\overline{\Lambda}}}$

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 Lambda helicity frame.



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

- There is a new measurement of $A_{\Xi\Lambda}$, based on the *HyperCP* technique.

Mode	Method	Limit	Exp	Date
$A_{\Xi\Lambda}$	$\mathrm{pN} \to \Xi\pi \to \Lambda\pi \to p\pi\pi$	0.012 ± 0.014	E756	2000

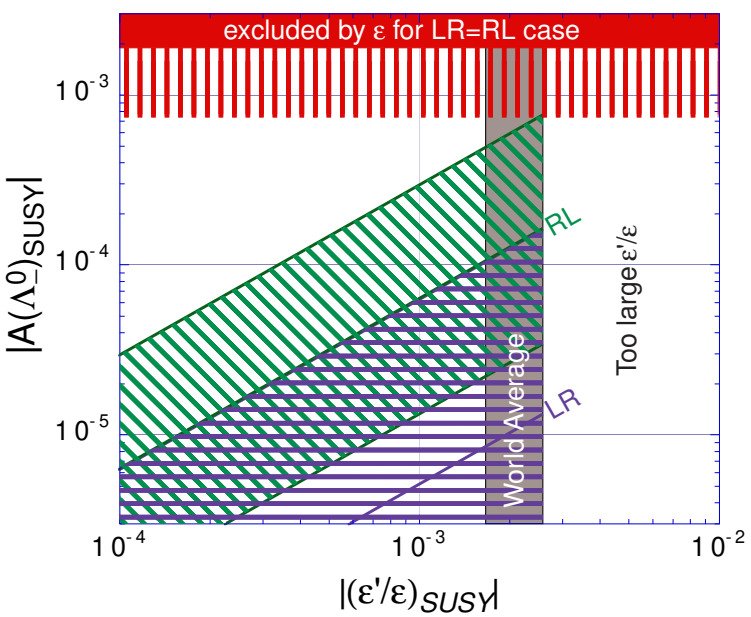
- This measurement of $A_{\Xi\Lambda}$ can be used with measurements of A_Λ to infer a limit on A_Ξ.
- None of these measurements is in the regime of testing theory.
- ***HyperCP* intends to push two orders of magnitude beyond the best limit.**

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.

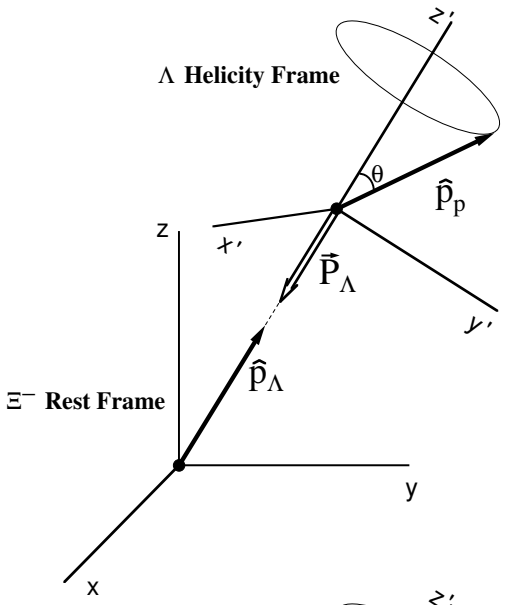
  > *"Given our crude estimate of the hadronic matrix elements involved, all our numerical results should be viewed with caution."*
  >
  > He and Valencia, PRD52 (1995) 5257.

- Standard Model predictions range from about $10^{-4} - 10^{-5}$.
- Hyperon CP violation not the same as kaon CP violation!
- For example, some supersymmetric models that do not generate ϵ'/ϵ can lead to A_Λ of $O(10^{-3})$.



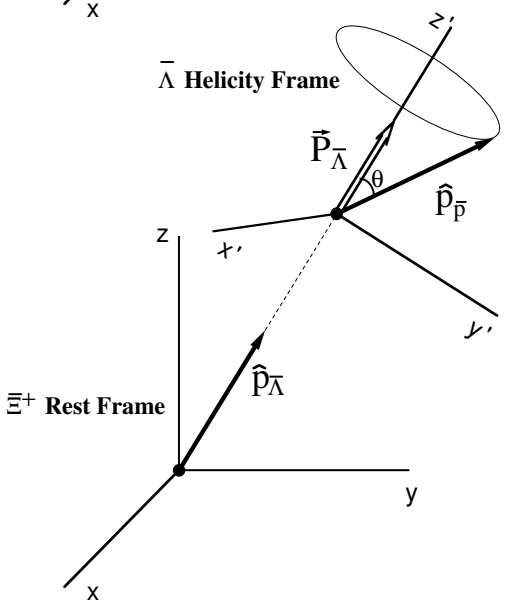
He *et al.*,PRD61:071701 (2000).

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



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

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



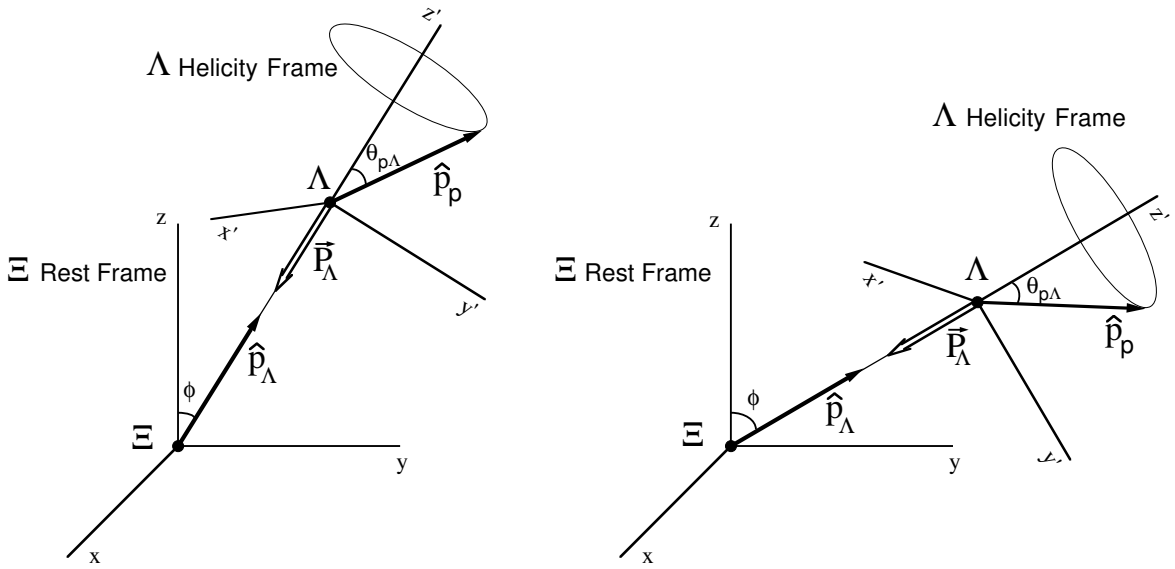
$$\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \overline{p}\pi^+\pi^+$$

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

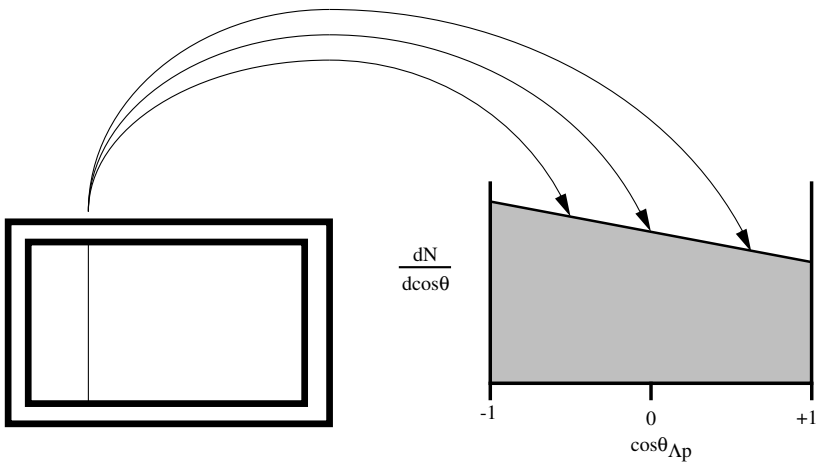
As long as we exactly flip the hyperon and spectrometer magnetic fields we have a CP invariant apparatus.

Analysis Method Naturally Minimizes Biases

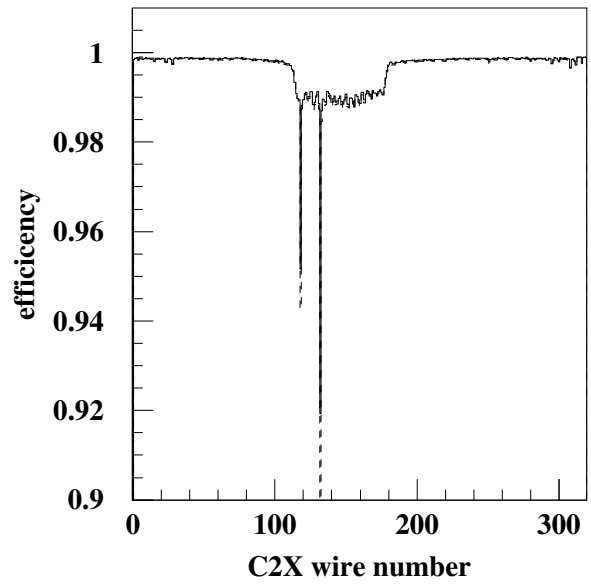
- The helicity frame axes changes from event to event since we always define the polar axis to be the direction of the Λ momentum in the Ξ rest frame.

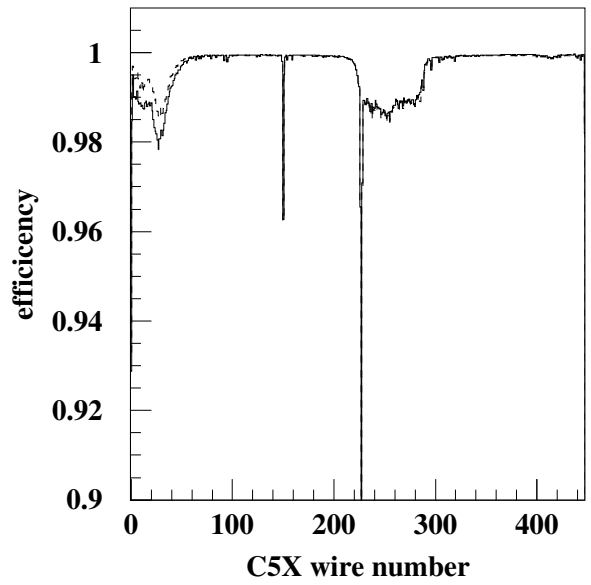


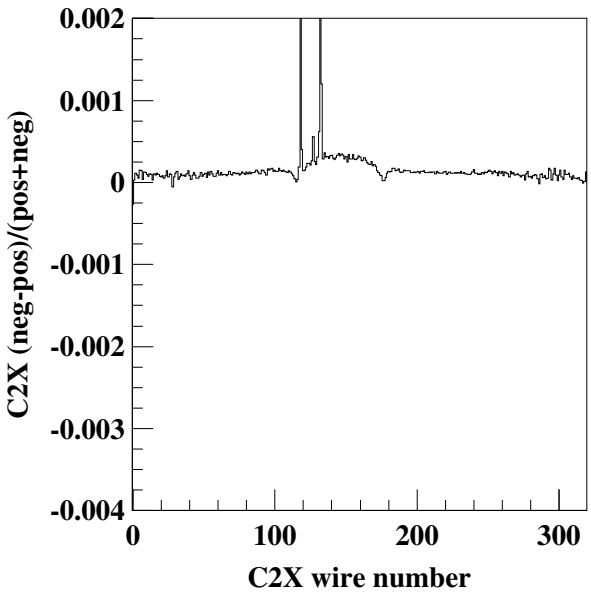
- Acceptance differences localized in a particular part of the apparatus do **not** map into a particular part of the proton (antiproton) $\cos\theta$ distribution.

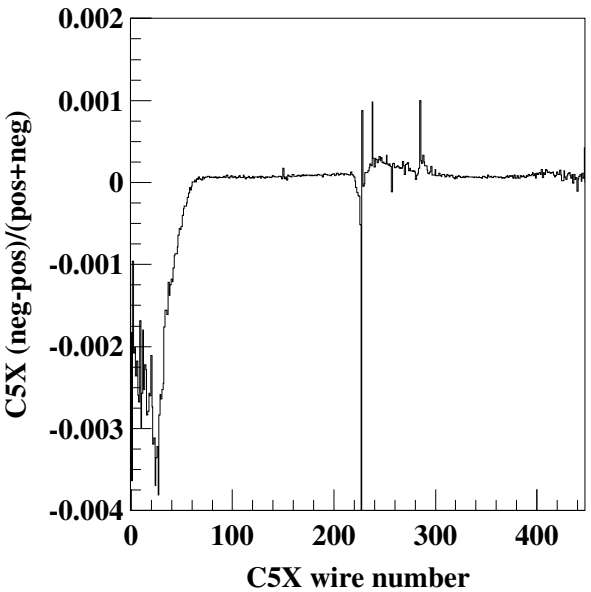


Chamber Efficiencies from Positive and Negative Running





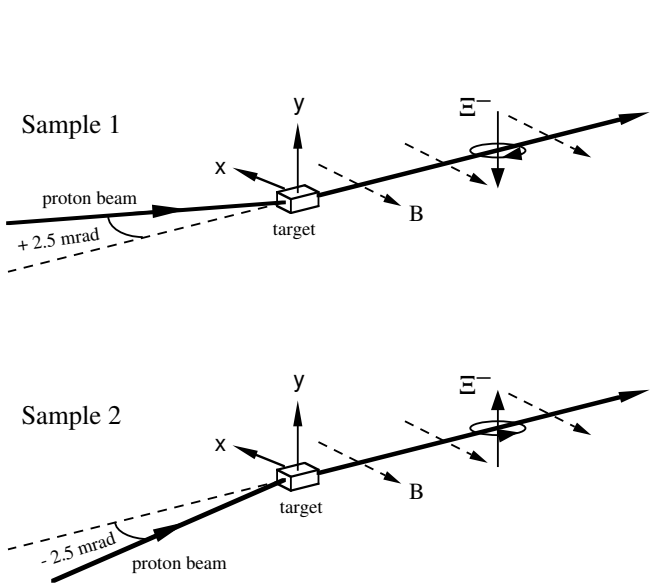


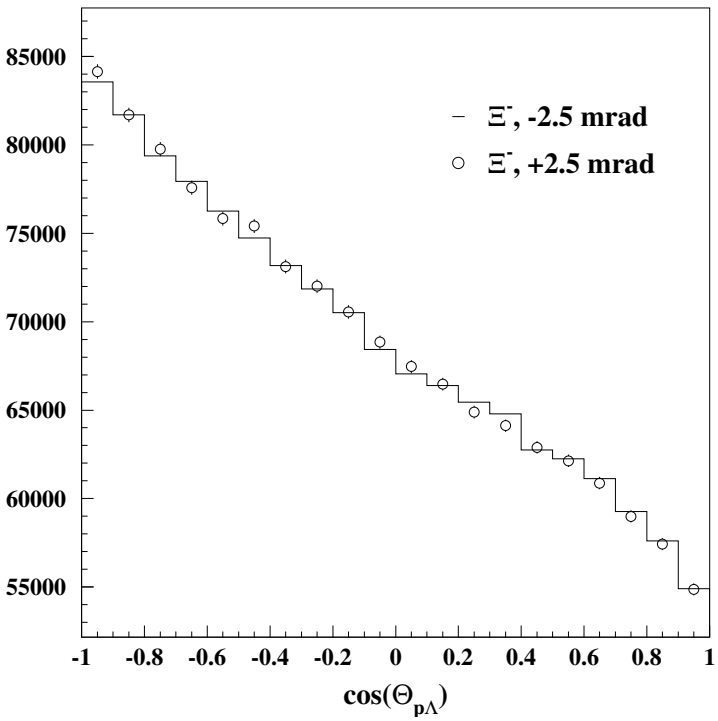


- Top plots are absolute efficiencies, bottom plots are differences.
- Solid lines are negative data, dashed are positive.

Bias: Effect of Polarization and Targetting on Asymmetry

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

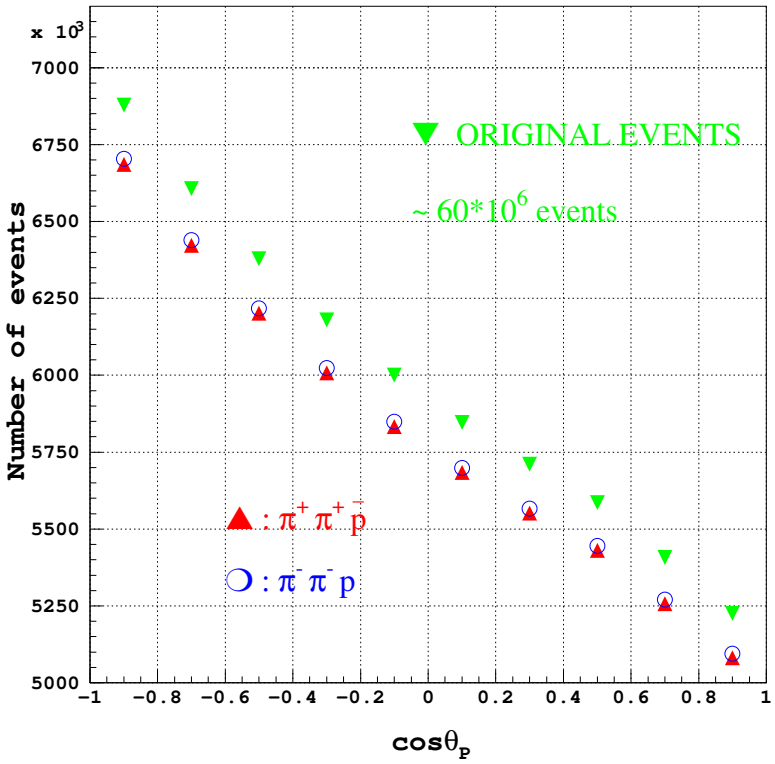




- No statistically significant effect at the several times 10^{-3} level, with no attempt of correction!

Bias: Effect of Interactions on $A_{\Xi\Lambda}$

- Because the pA and $\overline{p}A$, and the $\pi^- A$ and $\pi^+ A$ cross sections have a different momentum dependence, events lost to interactions in the spectrometer will affect the p and $\overline{p}$ $\cos\theta$ distributions differently.
- This has been studied by taking real Ξ^- events and interacting the decay products in a MC simulation of the apparatus.

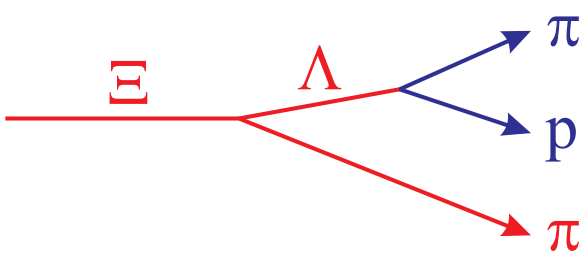


- This gives an upper limit on the bias due to interactions:

$$\delta A_{\Xi\Lambda} < 0.9 \times 10^{-4}$$

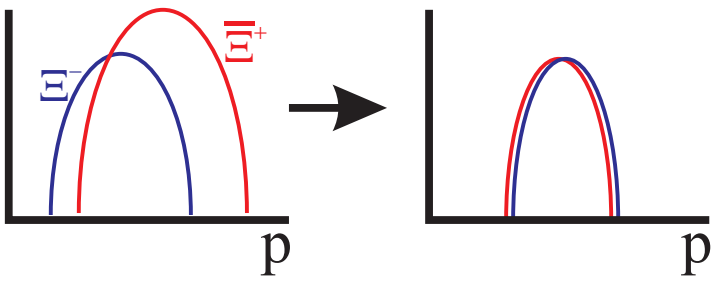
Two Different Analyses Being Done in Parallel

West Coast (LBL): Hybrid Monte Carlo Method



- Measure and correct for acceptance.
- Take a real $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$ event, discard proton and pion, generate 10 new unpolarized Λ decays.
- Advantage: well-tested and understood method. Absolute measurement of $\alpha_\Lambda\alpha_\Xi$.
- Disadvantage: Huge ($\sim$20 billion) number of events must be generated an reconstructed.

East Coast (UVa): Weighting Method



- Direct comparison of the proton and antiproton $\cos(\theta)$ distributions.
- Force the Ξ and $\overline{\Xi}$ events to have similar momentum and spatial distributions by appropriate weighting.
- Advantage: No Monte Carlo needed to measure apparatus acceptance.
- Disadvantage: no absolute measurement of $\alpha_\Lambda\alpha_\Xi$.

A Preliminary *CP* Violation Study

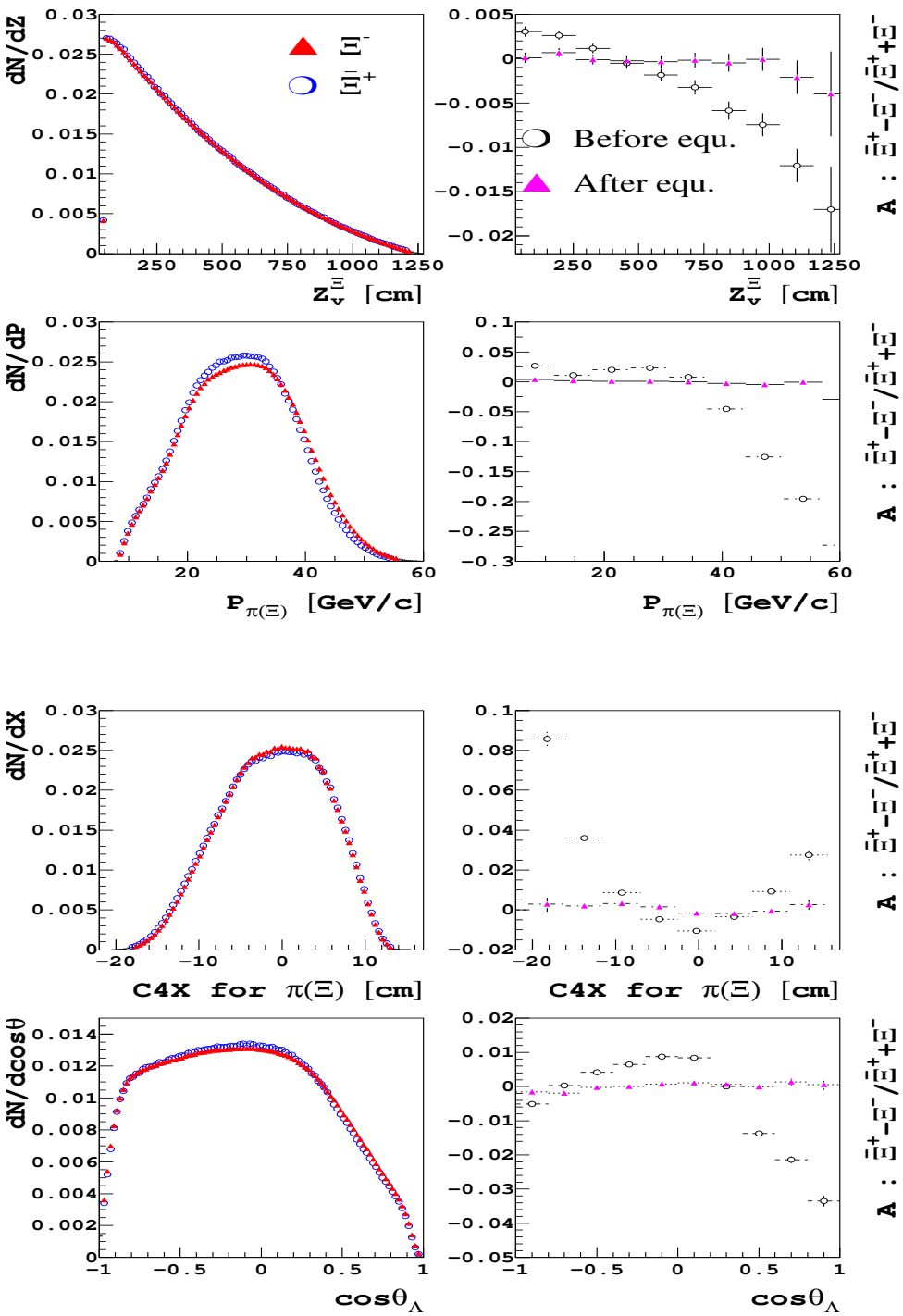
- Four sets of 1997 runs widely separated in time were used.
- 5.9×10^6 $\overline{\Xi}^+$ events : 1.2%
  37.2×10^6 Ξ^- events : 1.9%
  } of 1997 data set after all cuts
- The positive and negative data sets were normalized to each other in five variables:

  Ξ x target origin
  Ξ y target origin
  Ξ x collimator exit position
  Ξ y collimator exit position
  Ξ momentum
  } 12×10^6 cells

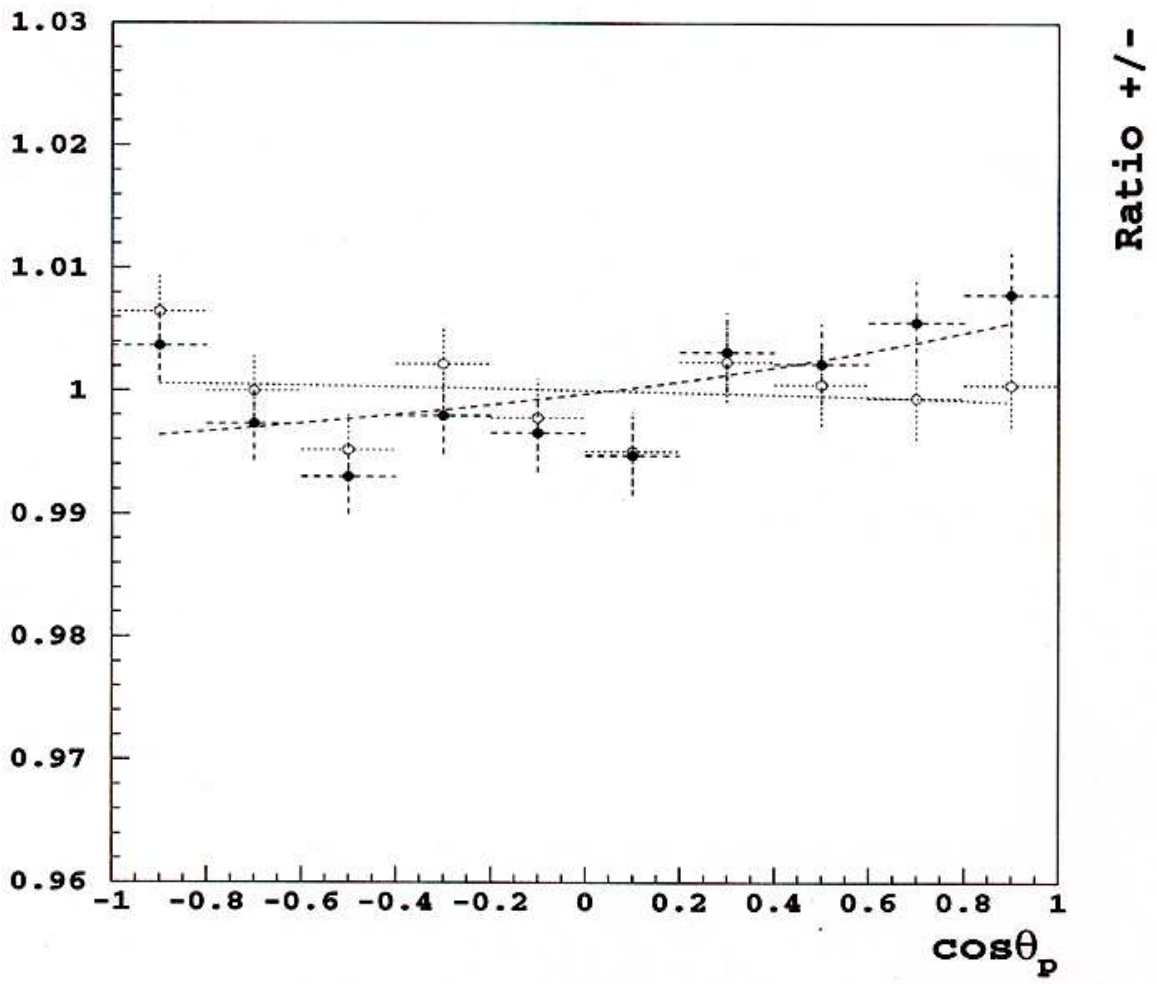
- The effect of the normalization scheme on any real asymmetry was tested with a Hybrid Monte Carlo:
  - 20×10^6 $\overline{\Xi}^+$ MC events
    150×10^6 Ξ^- MC events
  - MC Input: $\rightarrow A_{\Xi\Lambda} = -17.1\times10^{-3}$
    Analysis Output: $\rightarrow A_{\Xi\Lambda} = (16.9 \pm 0.4)\times10^{-3}$
- 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

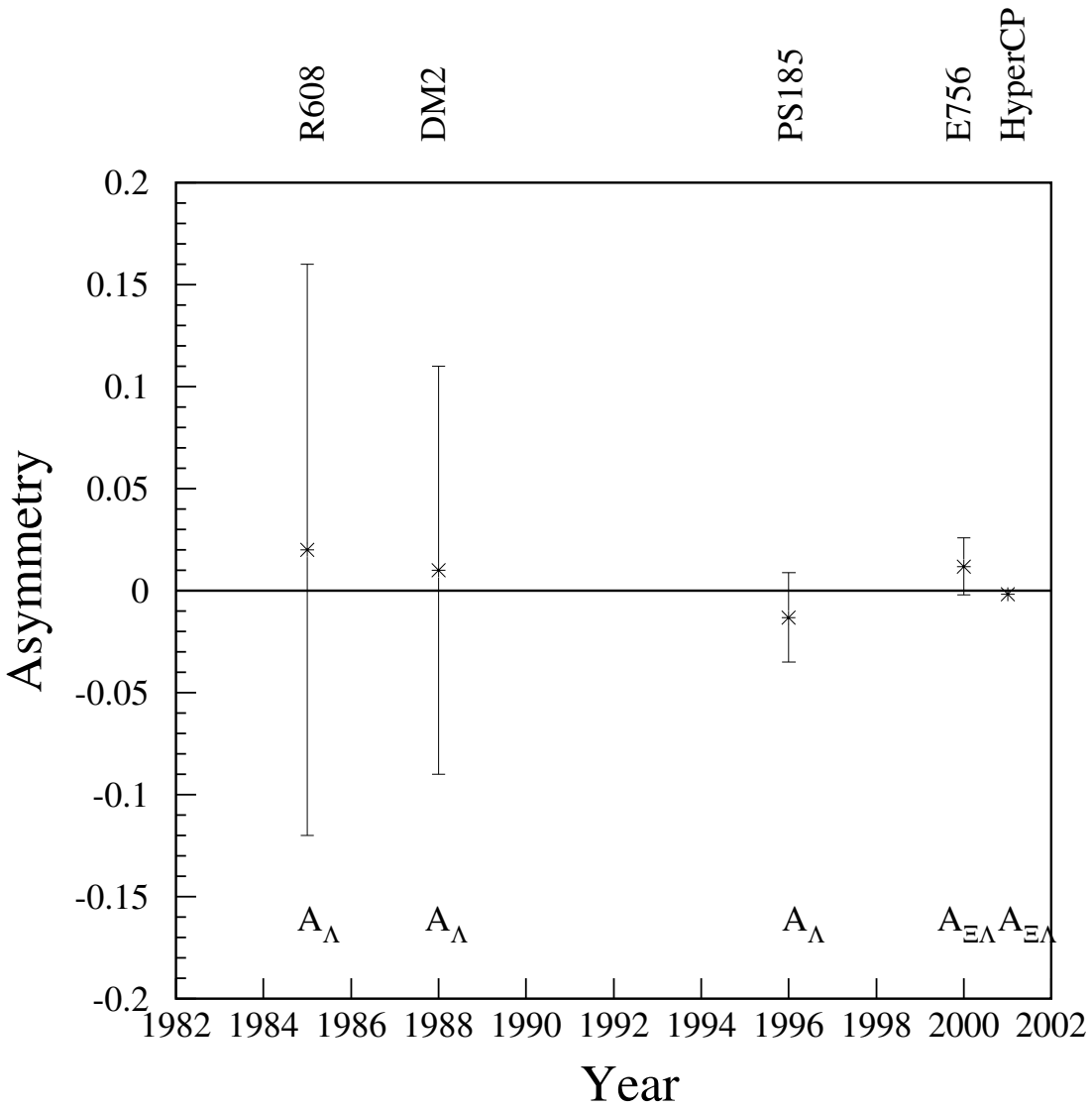


Helicity Frame cos(θ) From Set I



- RAW: $\Delta\alpha_\Lambda\alpha_\Xi = (4.7 \pm 1.7)\times10^{-3}$
- WEIGHTED: $\Delta\alpha_\Lambda\alpha_\Xi = (-0.8 \pm 1.7)\times10^{-3}$

Preliminary Study



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

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

Conclusions and Outlook

- *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 have observed the FCNC decay $K^- \to \pi^-\mu^+\mu^-$ for the first time.
- Our branching ratio result is consistent with Chiral Perturbation theory and resolves an experimental discrepancy.
- The hyperon CP-violation 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 — assaulting CP violation from a different direction than the kaon and B experiments.
- Stay tuned for more results!