Precision Measurements with the HyperCP Spectrometer at Fermilab

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Primary Goal:

- A search for exotic sources of CP violation in $\Xi^-/\Xi^+$ and $\Lambda/\bar{\Lambda}$ decays.

Secondary Goals:

- Search for CP violation in $K^{\pm} \to 3\pi$ and $\Omega^{\pm} \to \Lambda K^{\pm}$ decays.
- Search for rare and forbidden hyperon and charged kaon decays:
  - Lepton number nonconservation in $\Xi^- \to p\mu^-\mu^-$.  
  - Flavor changing neutral currents in hyperon and charged kaon decays:
    $\Omega^- \to \Xi^-\mu^+\mu^-, \Sigma^+ \to p\mu^+\mu^-, \Omega^- \to \Xi^-\mu^+\mu^-, K^\pm \to \pi^\pm\mu^+\mu^-$.  
  - $\Delta S > 1$ decays: $\Xi^- \to p\pi^-\pi^-, \Omega^- \to \Lambda\pi^-, \Omega^- \to pK^-\pi^-, \Omega^- \to p\pi^-\pi^-$.  
  - $\Omega^- \to \Xi^-\pi^+\pi^-$.  
- Measure various hyperon production and decay properties:
  - $\Xi^- (\Xi^+)$ and $\Omega^- (\Omega^+)$ polarization.  
  - $\beta$ decay parameter in $\Xi^-$ decays, and hence the $\Lambda\pi$ strong phase shift.  
  - $\alpha$ decay parameter in $\Omega^\pm \to \Lambda K^{\pm}$ decays.  
  - Hyperon production cross sections.
The HyperCP Spectrometer

- 800 GeV/c incident proton beam.
- 10–15 MHz, 167 GeV/c charged beam.
- 8 high-rate, narrow-pitch wire chambers.
- Muon system for rare and forbidden hyperon and kaon decays.

- Simple, low-bias trigger using hodoscopes and calorimeter.
  \[ SS(\geq 1 \text{ hit}) \cdot OS(\geq 1 \text{ hit}) \cdot Cal(\geq 40 \text{ GeV}) \]
Secondary Beam Rates Equalized by Target Interchange

- Target length changed to equalize channeled beam rates.
  - + polarity: 2.0 cm Cu
  - − polarity: 6.0 cm Cu

![Graph showing beam hodoscope rates and current in chamber 1 for + and - polarities.](image)
HyperCP Data Acquisition System

- All custom front ends: no CAMAC, Fastbus, or VME.
- Sustained data logging rate of 27MB/s onto 27 Exabyte 8705 tapes.
- Maximum trigger rate of about 100,000 events per second:

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

Events read out per spill-s x 10^2
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

<table>
<thead>
<tr>
<th>Events</th>
<th>Year</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trigger</td>
<td>1997</td>
</tr>
<tr>
<td>Cascade</td>
<td>39 (\times) 10^9</td>
<td>81 (\times) 10^9</td>
</tr>
<tr>
<td>All</td>
<td>58 (\times) 10^9</td>
<td>173 (\times) 10^9</td>
</tr>
</tbody>
</table>

### Reconstructed Events

<table>
<thead>
<tr>
<th>Reconstructed Events</th>
<th>Channeled beam polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type</td>
</tr>
<tr>
<td>(\Xi \to \Lambda \pi)</td>
<td>458 (\times) 10^6</td>
</tr>
<tr>
<td>(K \to \pi \pi \pi)</td>
<td>391 (\times) 10^6</td>
</tr>
<tr>
<td>(\Omega \to \Lambda K)</td>
<td>4.9 (\times) 10^6</td>
</tr>
</tbody>
</table>
### HyperCP Data Set Enormous!

- Data volume compared to other, much larger experiments (E. Augé, EPS HEP 2001).

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

- Note:
  - One copy of the *Encyclopaedia Britannica*: 1 GB.
  - The *World Wide Web* as of September 11, 2001: 5 TB.
  - A video store (5,000 videos): 8 TB.
  - The *Library of Congress* (not counting pictures): 20 TB.
  - The *Internet Archive* (from 1996 to October 2001): 100 TB.
  - It would take 576 years to download all this data at 56 kbaud.
Data Reconstructed on Fermilab Computer Farm

- Done by three people(!) using a web-based interface.
- Took 11 months at about a 364 GB/day rate.
- Called “Tour de Force — by a small experiment,” in summary talk at the International Conference on Computing in High Energy and Nuclear Physics
- PostgreSQL database used to keep track of data.
- A total of 35,847,274 histograms with information on reconstruction and detector performances were generated automatically in the farm processing.
Masses from the Farm Analysis

\[ \Sigma^+, \text{2.07 billion} \]
\[ \Sigma^0, \text{0.46 billion} \]
\[ \sigma_{\Sigma} = 1.6 \text{ MeV/c}^2 \]

\[ \Omega^+, \text{14.6 million} \]
\[ \Omega^0, \text{5.0 million} \]
\[ \sigma_{\Omega} = 1.5 \text{ MeV/c}^2 \]

\[ K^+, \text{394 million} \]
\[ K^0, \text{164 million} \]
\[ \sigma_K = 2.0 \text{ MeV/c}^2 \]

\[ K^0, (+)2.04 \text{ billion} \]
\[ K^0, (-)0.72 \text{ billion} \]
\[ \sigma_K = 2.9 \text{ MeV/c}^2 \]
Why Search for $CP$ Violation in Hyperon Decays?

- After 40 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 price is modest:
  - 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.

“We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of $CP$ violation will reveal the presence of New Physics.”

Bigi and Sanda, CP Violation
Short Primer on Nonleptonic Hyperon Decays

\[ \Xi^- \rightarrow \Lambda \pi^- \quad \Lambda \rightarrow p \pi^- \]

- **Decay violates parity.** Hence angular distribution of daughter not isotropic (if parent is polarized)

  \[
  \frac{dP}{d\cos \theta} = \frac{1}{2} (1 + \alpha_P P_p \cos \theta)
  \]

- The magnitude of the parity violation is given by \( \alpha_P \).

- The slope of the daughter baryon \( \cos \theta \) distribution given by:

  \[ \alpha_P P_p \]

- The daughter is polarized:

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

  \[ \Rightarrow \quad \vec{P}_d = \alpha_p \hat{p}_d \text{ if } \vec{P}_p = 0 \]
Hyperon $\alpha$ Parameters

- $\Omega^- \rightarrow \Xi^- \pi^0$
- $\Omega^- \rightarrow \Xi^0 \pi^{-}$
- $\Omega^- \rightarrow \Lambda K^-$
- $\Xi^- \rightarrow \Lambda \pi^-$
- $\Xi^0 \rightarrow \Lambda \pi^0$
- $\Sigma^- \rightarrow n \pi^-$
- $\Sigma^+ \rightarrow p \pi^0$
- $\Sigma^+ \rightarrow n \pi^+$
- $\Lambda \rightarrow n \pi^0$
- $\Lambda \rightarrow p \pi^-$

- All are non-zero except for the three in $\Omega^-$ decays.
How to Search for $CP$ Violation in $\Lambda$ Decays

Due to parity violation the proton likes to go in the direction of the $\Lambda$ spin:

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

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

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

- $\alpha \Lambda \rightarrow CP \Rightarrow \bar{\alpha}_\Lambda = -\alpha \Lambda$

If $CP$ is violated the slope of the proton $\cos \theta$ distribution is not the exact opposite of the slope of the antiproton $\cos \theta$ distribution.

$$\alpha \Lambda \neq -\alpha \Lambda$$
Problem: Producing Λ’s of Known Polarization

Λ/Λ’s of known polarization can be produced through the decay of unpolarized Ξ⁻/Ξ⁺’s:

\[ \Xi^- \rightarrow \Lambda \pi^- \quad \Xi^+ \rightarrow \Lambda \pi^+ \]

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:

\[ \vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \quad \vec{P}_\Lambda = \bar{\alpha}_\Xi \hat{p}_\Lambda \]

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

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

\[ \alpha_\Xi \alpha_\Lambda = \bar{\alpha}_\Xi \bar{\alpha}_\Lambda \]

\[ \Xi^- \rightarrow \Lambda \pi^- \quad \Lambda \rightarrow p \pi^- \]

\[ \Xi^+ \rightarrow \Lambda \pi^+ \quad \Lambda \rightarrow p \pi^+ \]
We are sensitive to both $\Xi$ and $\Lambda$ $CP$ violation

\[ A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \alpha_\Xi \bar{\alpha}_\Lambda}{\alpha_\Xi \alpha_\Lambda + \alpha_\Xi \bar{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda \]

where: \[ A_\Xi = \frac{\alpha_\Xi + \bar{\alpha}_\Xi}{\alpha_\Xi - \bar{\alpha}_\Xi} \quad \text{and} \quad A_\Lambda = \frac{\alpha_\Lambda + \bar{\alpha}_\Lambda}{\alpha_\Lambda - \bar{\alpha}_\Lambda} \]

What we experimentally measure is the slope of the proton (antiproton) $\cos(\theta)$ distribution in the special $\Lambda$ rest frame where the $\Lambda$ momentum direction in the $\Xi$ rest frame defines the polar axis: the Lambda Helicity Frame.
If \( CP \) is not violated \( \Xi^- \) and \( \Xi^+ \) decays appear identical

\[
\Xi^- \rightarrow \Lambda \pi^- \rightarrow p \pi^- \pi^-
\]

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

\[
\Xi^+ \rightarrow \Lambda \pi^+ \rightarrow p \pi^+ \pi^+
\]

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

If we exactly flip the spectrometer magnetic fields and we keep the chamber, hodoscope, and calorimeter efficiencies the same we have a \( CP \) invariant apparatus.
Spectrometer Magnetic Field Difference Small

- Hall probes measured field to $1 \times 10^{-4}$ T precision.
- When flipping polarity, field magnitude kept within $\sim 2 \times 10^{-4}$.
- This corresponds to a $\sim 0.3$ mm deflection difference at 10 m for the lowest momentum ($\sim 10$ GeV/c pions).

All 1999 spills
Chamber Efficiencies from Positive and Negative Running

- data: solid line
- + data: dashed line

![Graphs showing chamber efficiencies from positive and negative running.](image-url)
Hodoscope Efficiencies from Positive and Negative Running

- data: solid line.
- + data: dashed line.

- Differences where it matters <0.1%.
- Redundant counters make real inefficiencies vanishingly small.

- Two rows on OS side.
- Two particles on SS side.

### Absolute Efficiency

<table>
<thead>
<tr>
<th>SS Hodoscope Counter Number</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.90</td>
</tr>
<tr>
<td>10</td>
<td>0.92</td>
</tr>
<tr>
<td>15</td>
<td>0.94</td>
</tr>
<tr>
<td>20</td>
<td>0.96</td>
</tr>
<tr>
<td>25</td>
<td>0.98</td>
</tr>
<tr>
<td>30</td>
<td>1.00</td>
</tr>
</tbody>
</table>

### Relative Efficiency Difference (neg. - pos.)

<table>
<thead>
<tr>
<th>OS Hodoscope Counter Number</th>
<th>Efficiency Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.002</td>
</tr>
<tr>
<td>10</td>
<td>0.004</td>
</tr>
<tr>
<td>15</td>
<td>0.006</td>
</tr>
<tr>
<td>20</td>
<td>0.008</td>
</tr>
<tr>
<td>25</td>
<td>0.010</td>
</tr>
<tr>
<td>30</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Calorimeter Efficiencies from Positive and Negative Running

- Proton momentum has $x$ and $y$ dependence ⇒ Calorimeter efficiency has $x$ and $y$ dependence.
- No slope dependence in difference in calorimeter efficiency.
- Difference in positive and negative efficiencies due to different rates in calorimeter.

Trigger:

$$\text{CAS} = \text{SS}(\geq 1 \text{ hit}) \cdot \text{OS}(\geq 1 \text{ hit}) \cdot \text{Cal}(\geq 40 \text{ GeV})$$
Phenomenology of CP Violation in \(\Xi\) and \(\Lambda\) Decay

- CP violation in \(\Xi\) and \(\Lambda\) 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.

\[
A_\Lambda = \frac{\alpha_\Lambda + \alpha_\Xi}{\alpha_\Lambda - \alpha_\Xi} \approx -\tan (\delta_P - \delta_S) \sin (\phi_P - \phi_S),
A_\Xi = \frac{\alpha_\Xi + \alpha_\Xi}{\alpha_\Xi - \alpha_\Xi} \approx -\tan (\delta_P - \delta_S) \sin (\phi_P - \phi_S).
\]

- Asymmetry greatly reduced by the small strong phase shifts.
  - The \(p\pi\) phase shifts have been measured to a precision of about one degree:
    \[
    \Lambda \begin{cases} 
    \delta_P = -1.1 \pm 1.0^\circ \\
    \delta_S = 6.0 \pm 1.0^\circ
    \end{cases}
    \]
  - The \(\Lambda\pi\) phase shifts can’t be measured, and theoretical predictions disagree.
    \[
    \Xi^{-} \begin{cases} 
    \delta_P = -2.7^\circ \\
    \delta_S = -18.7^\circ
    \end{cases} 1965 = -1^\circ = 0^\circ \text{ recent } \chi PT
    \]
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.”


- 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 $\epsilon'/\epsilon$ can lead to $A_A$ of $O(10^{-3})$. 

[Susy Model Predictions Diagram]
### Comparison of $\epsilon'/\epsilon$ and $A_{\Xi}, A_{\Lambda}$

<table>
<thead>
<tr>
<th>$\epsilon'/\epsilon$</th>
<th>$A_{\Xi\Lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Thought to be due to the Penguin diagram in the Standard Model.</td>
<td>- Thought to be due to the Penguin diagram in the Standard Model.</td>
</tr>
</tbody>
</table>

```
\begin{align*}
K^0 \rightarrow \pi^+\pi^- \\
\begin{array}{c}
\bar{s} \\
\bar{d}
\end{array} \rightarrow \\
W^+ \\
\bar{u}, \bar{c}, \bar{t} \\
\bar{d} \\
\bar{u} \\
\pi^+
\end{align*}
```

```
\begin{align*}
\Lambda \rightarrow p\pi^- \\
\begin{array}{c}
\bar{d} \\
\bar{u}
\end{array} \rightarrow \\
W^- \\
u, c, t \\
\bar{u} \\
\pi^-
\end{align*}
```

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

- Expressed through a different $CP$-violating phase in the $S$- and $P$-wave amplitudes.
- Probes parity violating and conserving amplitudes.

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

Difference between HyperCP and $\epsilon'/\epsilon$ Experiments

- Kaon experiments measure simultaneously 4 different decays with 2 different apparatus:
  - $K_L \to 2\pi^0\ \{\ \text{calorimeter}\ \}$
  - $K_S \to 2\pi^0$
  - $K_L \to \pi^+\pi^-\ \{\ \text{wire chambers}\ \}$
  - $K_S \to \pi^+\pi^-$

$$\frac{(K_S \to 2\pi^0)/(K_L \to 2\pi^0)}{(K_S \to \pi^+\pi^-)/(K_L \to \pi^+\pi^-)} = 1 + 6\left(\frac{\epsilon'}{\epsilon}\right)$$

- $K_L \to 2\pi^0$, $\pi^-\pi^+$ have small branching ratios.

- HyperCP measures alternately 2 identical decays with identical apparatus:
  - $\Xi^- \to \Lambda\pi^-$
  - $\Xi^+ \to \bar{\Lambda}\pi^+$

- $\Xi^- \leftrightarrow p\pi^-$
- $\Xi^+ \leftrightarrow \bar{p}\pi^+$

- $\Xi \to \Lambda\pi$ and $\Lambda \to p\pi$ have large branching ratios.
What is the experimental situation?

- There are no limits on $A_{\Xi}$.
- $A_{\Lambda}$ has been measured to $2 \times 10^{-2}$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Method</th>
<th>Limit</th>
<th>Exp</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\Lambda}$</td>
<td>$p\bar{p} \to \Lambda X$, $p\bar{p} \to \bar{\Lambda}X$</td>
<td>$-0.02 \pm 0.14$</td>
<td>R608</td>
<td>1985</td>
</tr>
<tr>
<td>$A_{\Lambda}$</td>
<td>$e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$</td>
<td>$0.01 \pm 0.10$</td>
<td>DM2</td>
<td>1988</td>
</tr>
<tr>
<td>$A_{\Lambda}$</td>
<td>$p\bar{p} \to \Lambda\bar{\Lambda}$</td>
<td>$0.010 \pm 0.022$</td>
<td>PS185</td>
<td>1998</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Method</th>
<th>Limit</th>
<th>Exp</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{\Xi\Lambda}$</td>
<td>$pN \to \Xi\pi \to \Lambda\pi \to p\pi\pi$</td>
<td>$0.012 \pm 0.014$</td>
<td>E756</td>
<td>2000</td>
</tr>
</tbody>
</table>

- This measurement of $A_{\Xi\Lambda}$ can be used with measurements of $A_{\Lambda}$ to infer a limit on $A_{\Xi}$.
- None of these measurements is in the regime of testing theory.
- HyperCP is pushing two orders of magnitude beyond the best limit.
Two Different Analyses Being Done in Parallel

West Coast (LBL):
Hybrid Monte Carlo Method

- Compare corrected $\cos \theta$ distributions.
- Take a real $\Xi \rightarrow \Lambda \pi$, $\Lambda \rightarrow p\pi$ event, discard proton and pion, generate 10 new unpolarized $\Lambda$ decays.
- **Advantage:** Absolute measurement of $\alpha_\Lambda \alpha_\Xi$.
- **Disadvantage:** Monte Carlo must be very, very good, and fast: $\sim 20$ billion events needed.

East Coast (UVa):
Weighting Method

- Compare uncorrected $\cos(\theta)$ distributions.
- Force the $\Xi$ and $\bar{\Xi}$ events to have similar momentum and spatial distributions by appropriate weighting.
- **Advantage:** No Monte Carlo needed to measure apparatus acceptance, smaller statistical error.
- **Disadvantage:** inflexible, event-size dependent analysis.
Weighting Technique

- **Problem:** Geometrical acceptance identical for $\Xi^-$ and $\Xi^+$ decay products only if parent $\Xi^-$ and $\Xi^+$ have same momentum and inhabit the same phase space exiting the collimator.

- **Solution:** Weight the $\Xi^-$ and $\Xi^+$ events to force the two distributions to be identical.

![Diagram of weighting technique](image)

- **Diagram Explanation:**
  - **Pass 1: Data**
    - $++$ data
    - Bin data in $\Xi p, y, dy/dz$
    - 100 bins
    - Calculate + weights
  - $-\text{data}$
    - Bin data in $\Xi p, y, dy/dz$
    - 100 bins
    - Calculate - weights

- **Pass 2: Data**
  - Fill + histograms using + weights
  - Fill - histograms using - weights

- **Graph:**
  - Ratio of proton to antiproton momenta before and after weighting.
  - Proton z momentum (GeV/c)
  - Ratio
    - 1.75
    - 1.5
    - 1.25
    - 1.0
    - 0.75
  - Data points showing the ratio distribution.
Momentum, $y$ slope, $y$ Position at Collimator Exit Weighted

- Momentum magnitude, $y$ slope and $y$ position different.

<table>
<thead>
<tr>
<th>Variable</th>
<th># cells</th>
<th>Cell size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi$ momentum</td>
<td>100</td>
<td>2.25 GeV/c</td>
</tr>
<tr>
<td>$y$ position at collimator</td>
<td>100</td>
<td>0.013 cm</td>
</tr>
<tr>
<td>$y$ slope at collimator</td>
<td>100</td>
<td>0.08 mrad</td>
</tr>
</tbody>
</table>

- $\Xi^-$: Solid lines
- $\Xi^+$: Dashed lines
\(\Xi^-\) and \(\Xi^+\) \(x\) Slopes and Positions not Weighted

- Distributions almost identical \(\Rightarrow\) cut out regions where they are not.
- \(\Xi^-\): Solid lines
- \(\Xi^+\): Dashed lines
Extracting the $CP$ Asymmetry

- Determine weighted proton and weighted antiproton $\cos \theta$ distributions.

\[
\frac{dN_-}{d \cos \theta_-} = A_- \frac{N_-}{2} (1 + \alpha \bar{\alpha} \cos \theta_-) \quad \text{and} \quad \frac{dN_+}{d \cos \theta_+} = A_+ \frac{N_+}{2} (1 + \bar{\alpha} \alpha \cos \theta_+)
\]

- Take the ratio of $\cos \theta$ distributions and fit to:

\[
R(\theta, \delta) = C \frac{1 + \alpha \bar{\alpha} \cos \theta}{1 + (\alpha \bar{\alpha} - \delta) \cos \theta}
\]

to extract asymmetry $\delta$:

\[
\delta = \alpha \bar{\alpha} - \bar{\alpha} \alpha
\]

\[
A_{\Xi \Lambda} = \frac{\delta}{\alpha \bar{\alpha} - \bar{\alpha} \alpha} \approx \frac{\delta}{2\alpha \bar{\alpha}}
\]

- Note: acceptances cancel out!
Monte Carlo Tests

Important! Monte Carlo only used to:

- Verify code and algorithm.
- Study a few systematics.

**Final result has no Monte Carlo dependence!**

Problem: How do you generate ~1 billion MC events? Solution:

- Take $\Xi$, $\vec{p}$, $x$ and $y$ from real data at exit of collimator $\Rightarrow$ CHMC (Cascade Hybrid Monte Carlo).
- Run on Fermilab farms.

![Diagram of Monte Carlo process]

- Take $\Xi$ momentum, and XY position at Collimator exit.
- Store in intermediate files.
- Simulate 5 CHMC events for each real event.
Monte Carlo Results

With an input $\delta = 0$:

$$
\delta = (-1.35 \pm 1.41) \times 10^{-4}
$$

$$
A_{\Xi\Lambda} = (2.31 \pm 2.41) \times 10^{-4}
$$

$$
\chi^2/\text{ndf} = 0.79
$$

Proton $\cos \theta$ distributions, weighted and unweighted.

Difference between input and measured asymmetry $\delta$ as a function of input $\delta$. 
The raw proton and anti-proton cos(θ) distributions

- From the farm analysis.
- No acceptance corrections have been made.
- The two momenta distributions have not been normalized to each other.
Proton, $\Lambda$-pion, $\Xi$-pion Momenta Before/After Weighting

- Solid lines
+ dashed lines

- before weighting
$\Delta$ after weighting

Events/(5.5 GeV/c) vs. Proton z momentum (GeV/c)

Events/(1.95 GeV/c) vs. $\Lambda$ pion z momentum (GeV/c)

Events/(2.75 GeV/c) vs. $\Xi$ pion z momentum (GeV/c)

Ratio vs. Proton z momentum (GeV/c)
Ratio vs. $\Lambda$ pion z momentum (GeV/c)
Ratio vs. $\Xi$ pion z momentum (GeV/c)
\( \Lambda \) and \( \Xi \) Decay Vertices Before/After Weighting

- Solid lines
- Dashed lines

\( \Xi \) z vertex (cm) vs. Events/(32.25 cm)

\( \Lambda \) z vertex (cm) vs. Events/(32.25 cm)

Ratio

\( \circ \) before weighting
\( \Delta \) after weighting

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

- Data broken up into 18 sets.
- No acceptance corrections.
- No efficiency corrections.

Proton cos $\theta$ ratio from Analysis Set 1

Weighted average of all 18 data sets:

$$\delta = (-0.9 \pm 3.0) \times 10^{-4}$$

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

$\chi^2/\text{ndf} = 1.4$
The $CP$ Asymmetry $A_{\Xi\Lambda}$ from HMC Method

- Use real $\Lambda$ decay vertex for Monte Carlo (HMC) events.
- Generate isotropic $\Lambda$ decay HMC events and then weight by
  
  $$W(\alpha_\Lambda \alpha_\Xi) = \frac{1 + \alpha_\Lambda \alpha_\Xi \cos \theta_{\text{HMC}}}{1 + \alpha_\Lambda \alpha_\Xi \cos \theta_{\text{real}}}$$

- Vary $\alpha_\Lambda \alpha_\Xi$ until best fit between data and MC is obtained.

Monte Carlo verification of HMC

Input: $\alpha_\Lambda \alpha_\Xi = -0.2927$

Output: $\alpha_\Lambda \alpha_\Xi = -0.2953$, $\chi^2 = 15/19$ dof.
- Momentum $p - x$ of $\pi_\Lambda$ weighted with previously established value of $\alpha_\Lambda\alpha_\Xi$. 
HMC Measurement of $\alpha_\Lambda \alpha_\Xi$ vs Run

- Prescaled selection of entire 1997 and 199 data set:
  - $15 \times 10^6 \Xi^-$
  - $30 \times 10^6 \Xi^+$

Average $\alpha_\Lambda \alpha_\Xi = -0.2880 \pm 0.0004 \text{ (stat.)}$  \hspace{1cm} $\chi^2 = 26/19 \text{ dof}$
Systematics

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

There are several classes of biases.

1. Acceptance differences:
   - Differences in the $\Xi^-$ and $\Xi^+$ momentum and position at the exit of the collimator.
   - Efficiency differences: hodoscope, trigger, and calorimeter.
   - Different reconstruction efficiencies due to different interaction cross sections with the material in the spectrometer between the $\pi^-$ and $\pi^+$ and between the $p$ and $\bar{p}$.

2. Momentum differences.
   - Differences in the spectrometer magnetic fields.
   - Effect of Earth’s magnetic field.

3. Different $\Xi^-$ and $\Xi^+$ polarization.
   - This means that the $\Lambda$ is no longer found in a simple helicity state with the polarization magnitude given by $\alpha_\Xi$, but rather by:
     \[
     \vec{P}_\Lambda = \frac{(\alpha + \vec{P}_\Xi \cdot \hat{p}_\Lambda)\hat{p}_\Lambda + \beta(\vec{P}_\Xi \times \hat{p}_\Lambda) + \gamma(\hat{p}_\Lambda \times (\vec{P}_\Xi \times \hat{p}_\Lambda))}{(1 + \alpha \vec{P}_\Xi \cdot \hat{p}_\Lambda)}
     \]

4. Different backgrounds in the two data samples.
Helicity Frame Analysis Naturally Minimizes Biases

- The helicity frame axes change from event to event since we always define the polar axis to be the direction of the $\Lambda$ momentum in the $\Xi$ 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.

Important! Overall acceptance differences do not cause any biases.
Example: Power of Helicity Frame Analysis

\[ \Xi^- (-2.5 \text{ mrad}) \text{ vs } \Xi^- (+2.5 \text{ mrad}) \]

- \( \Xi^-, -2.5 \text{ mrad} \)
- \( \Xi^-, +2.5 \text{ mrad} \)

- No statistically significant effect at the several times \( 10^{-3} \) level, with no attempt of correction!
Effect of Targetting Angle on Fixed Axis Analysis

The fixed axis analysis frame.

- Effect on the fixed-axis $\cos \theta_p$ distribution is huge!
## Weighted Analysis Bias Error Summary

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Method</th>
<th>$\delta A_{\Xi A} (10^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$ position at collimator exit cut</td>
<td>Data</td>
<td>0.8</td>
</tr>
<tr>
<td>$x$ slope at collimator exit cut</td>
<td>Data</td>
<td>1.4</td>
</tr>
<tr>
<td>Analysis magnet field</td>
<td>Data</td>
<td>1.2</td>
</tr>
<tr>
<td>PWC inefficiency</td>
<td>CHMC</td>
<td>negligible</td>
</tr>
<tr>
<td>Hodoscope inefficiency</td>
<td>Data</td>
<td>0.3</td>
</tr>
<tr>
<td>Calorimeter inefficiency</td>
<td>CHMC</td>
<td>2.5</td>
</tr>
<tr>
<td>Background</td>
<td>Data</td>
<td>2.2</td>
</tr>
<tr>
<td>Bin size</td>
<td>Data</td>
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</tr>
<tr>
<td>CHMC error</td>
<td>CHMC</td>
<td>2.0</td>
</tr>
<tr>
<td>Particle interaction differences</td>
<td>MC</td>
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</tr>
<tr>
<td>Error on $\alpha\alpha_{PDG}$</td>
<td>Data</td>
<td>negligible</td>
</tr>
<tr>
<td>Polarization</td>
<td>MC</td>
<td>negligible</td>
</tr>
<tr>
<td>Earth’s magnetic field</td>
<td>CHMC</td>
<td>negligible</td>
</tr>
<tr>
<td>Total systematic error</td>
<td></td>
<td>4.5</td>
</tr>
</tbody>
</table>
• **Background fraction:**
  \[ \Xi^-: 0.43\% \text{ (lines)} \]
  \[ \Xi^+: 0.41\% \text{ (circles)} \]

• **Regions:**
  • **Signal:**
    \[ 1.3164 \text{ GeV/c}^2 - 1.3276 \text{ GeV/c}^2. \]
  • **Low mass:**
    \[ 1.29 \text{ GeV/c}^2 - 1.31 \text{ GeV/c}^2. \]
  • **High mass:**
    \[ 1.334 \text{ GeV/c}^2 - 1.354 \text{ GeV/c}^2. \]

• **Low mass:**
  \[ \delta = (-2.2\pm0.5)\times10^{-2} \]
  **High mass:**
  \[ \delta = (-3.8\pm0.7)\times10^{-2} \]

• **Weighted background asymmetry:**
  \[ A_{\Xi\Lambda}(\text{back}) = (2.2\pm0.5)\times10^{-4} \]
Asymmetry $\delta$ vs Momentum and Beam Intensity

- Low: 120 GeV/c – 158 GeV/c
- Middle: 158 GeV/c – 174 GeV/c
- High: 174 GeV/c – 225 GeV/c
Preliminary Results from CP Violation Search

Weighting Technique:
- ~10% total data sample
- selected from end of 1999 run
- 118.6 million $\Xi^-$
- 41.9 million $\Xi^+$
- no acceptance or efficiency corrections

$$A_{\Xi\Lambda} = [1.5\pm5.1\text{(sta)}\pm4.5\text{(sys)}]\times10^{-4}$$

HMC Technique:
- ~5% of the total data sample
- prescaled selection of 1997 and 1999
- 15 million $\Xi^-$
- 30 million $\Xi^+$

$$A_{\Xi\Lambda} = [7\pm12\text{(sta)}\pm6.2\text{(sys)}]\times10^{-4}$$

- 20× improvement on previous result.
Measuring the $\Lambda-\pi$ Strong Phase Shift

- This can be done by looking at the $\Lambda$ decay distribution for polarized $\Xi^-$ decays.
- For polarized $\Xi^-$ decays the $\Lambda$ is no longer found in a helicity state with magnitude $\alpha_\Xi$, but has polarization:

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

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

unpolarized

polarized

where:

$$\alpha = \frac{2 \text{Re}(S^*P)}{|S|^2 + |P|^2}$$

$$\beta = \frac{2 \text{Im}(S^*P)}{|S|^2 + |P|^2}$$

$$\gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

- Neglecting insignificant CP violation effects:

$$\frac{\beta_\Xi}{\alpha_\Xi} = \tan(\delta_P - \delta_S) \approx \delta_P - \delta_S$$
$p + Cu \rightarrow \Xi^- \uparrow +X$

- HyperCP’s polarized data sample is data rich, but polarization poor.
  - 142 million polarized $\Xi^-$ events
  - Mean polarization 3.6% @ $\langle p_T \rangle = 0.46 \text{ GeV}/c$, $\langle x_F \rangle = 0.2$.
  - Max. targeting angle ($\pm2.5 \text{ mrad}$), and hence polarization, limited by beamline elements.
The $\Xi^-$ Polarization

- Polarization extracted from the asymmetry in the $\Lambda$ decay using a Hybrid Monte Carlo method.
- Bias cancelled by subtracting $+2.5$ mrad from $-2.5$ mrad asymmetry.
- Mean polarization: $\sim 3.6\%$
  @ $\langle p_t \rangle = 0.46$ GeV/c
  $\langle x_F \rangle = 0.2$.
- Small polarization makes extracting $\beta$ particularly difficult.
Precession Angle Consistent with Previous Measurements

- $\mu_\Xi = (-0.65555 \pm 0.0056) \mu_N$ Consistent with PDG value.
- Small field integral precludes competitive measurement of $\mu_\Xi$. 

![Graph showing precession angle versus integral $Bdl$](image-url)
Preliminary Measurement of the $\Lambda$-$\pi$ Phase Shift

$\beta_\Xi = -0.061 \pm 0.010^{+0.022}_{-0.019}$ \hspace{1cm} $\gamma_\Xi = 0.890 \pm 0.010^{+0.011}_{-0.007}$

- Using the known value of $\alpha_\Xi (-0.456 \pm 0.008)$, the strong phase shift is:

$$\delta_P - \delta_S = \tan^{-1}\left(\frac{\beta_\Xi}{\alpha_\Xi}\right) = (4.6 \pm 1.3^{+2.4}_{-2.8})^\circ$$

- This is about the same magnitude as the $p-\pi$ phase shift

$\Rightarrow CP$ equally likely to be seen in $\Xi \rightarrow \Lambda \pi$ decays.
Search for Parity Violation in $\Omega^- \rightarrow \Lambda K^-$ Decays

$\Omega^- \rightarrow \Lambda K^-$ \hspace{1em} $\Lambda \rightarrow p\pi^-$

- Although spin-3/2, $\Omega^- \rightarrow \Lambda K^-$ decay goes much like the other hyperon two-body decays:

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

- Here:

$$\alpha_\Omega = \frac{2 \text{Re}(P^*D)}{|P|^2 + |D|^2}$$

- A non-zero $\alpha_\Omega$ indicates parity violation.

- All other hyperons have non-zero $\alpha$ parameters; only the $\Omega^-$ has resisted efforts to find an asymmetrical decay distribution.

- HyperCP is searching for an asymmetry using a Hybrid Monte Carlo analysis in the Lambda Helicity Frame.

- Large data sample, little background.
Extracting Proton $\cos \theta$ Slope

- HMC analysis using $\Lambda$ helicity frame
- 1999 data
- Raw proton $\cos \theta$ fit:
  $$S_m = (1.32 \pm 0.11) \times 10^{-2}$$

Proton $\cos \theta$ slope before weighting.
Preliminary Results

1999: $\alpha_\Omega = [2.01 \pm 0.17 \text{(stat.)}] \times 10^{-2}$
1997: $\alpha_\Omega = [1.84 \pm 0.46 \text{(stat.)}] \times 10^{-2}$

$\alpha_\lambda \alpha_\Omega$

$\Omega^- \text{ RUN-II}$

$\bar{\Omega}^+ \text{ RUN-II}$

Can search for $CP$ violation in $\Omega^- / \bar{\Omega}^+$ decays.
Search for Lepton Number Violation

Lepton number violating decay could imply existence of Majorana type neutrino.

Not constrained by limits on neutrinoless double $\beta$ decay.

$$\frac{B(\Xi^- \rightarrow p\mu^-\mu^-)}{B(\Xi^- \rightarrow \Lambda\pi^-)} < 1.06 \times 10^{-7} \ @ \ 90\% \ CL$$

PDG limit : $< 4 \times 10^{-4} \ @ \ 90\% \ CL$ (Littenberg and Shrock)

Preliminary result.
Search for FCNC in Hyperon Decays

\[ \Sigma^+ \to p \mu^+ \mu^- \]

- No observation to date of FCNC in Baryon sector.
- \( B(\Sigma^+ \to pe^+e^-) < 7 \times 10^{-6} \) (PDG)
- Theory: \( \Sigma^+ \to p\mu^+\mu^-/pe^+e^- < 1/100 \).
  \[
  \frac{B(\Sigma^+ \to p\mu^+\mu^-)}{B(\Sigma^+ \to \text{all})} \approx 3 \times 10^{-8}
  \]
- Very Preliminary!

\[ \Sigma^+ \to p \mu^+ \mu^- (+: 1997 \text{ run}) \]

\[ \Sigma^+ \to p \mu^+ \mu^- (+: 1999 \text{ run}) \]
Measurement of the Branching Ratio

\[ K^{\pm} \rightarrow \pi^{\pm} \mu^{+} \mu^{-} \]

- FCNC decay.

- Test of Chiral Perturbation theory.

- \( K^{+} \rightarrow \pi^{+} l^{+} l^{-} \) also gives an estimate of the indirect CP-violating amplitude in \( K_{L} \rightarrow \pi^{0} e^{+} e^{-} \).

- In the Standard Model this FCNC decay is dominated by long-distance one-photon exchange:

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

\[ R = \frac{(K^{+} \rightarrow \pi^{+} \mu^{+} \mu^{-})}{(K^{+} \rightarrow \pi^{+} e^{+} e^{-})} > 0.23 \]
Experimental Problems

- BR($K^+ \rightarrow \pi^+ e^+ e^-$) well measured:
  
  \[
  (2.6 \pm 0.5) \times 10^{-7} \quad \text{(CERN)}
  \]
  
  \[
  (2.75 \pm 0.23 \pm 0.13) \times 10^{-7} \quad \text{(BNL-777)}
  \]
  
  \[
  (2.94 \pm 0.05 \pm 0.13 \pm 0.05) \times 10^{-7} \quad \text{(BNL-865)}
  \]
  
  \[
  (2.88 \pm 0.13) \times 10^{-7} \quad \text{(PDG)}
  \]

- BR($K^+ \rightarrow \pi^+ \mu^+ \mu^-$) not so well measured!
  
  \[
  (5.0 \pm 0.4 \pm 0.7 \pm 0.6) \times 10^{-8} \quad \text{BNL-787}
  \]
  
  \[
  (9.22 \pm 0.60 \pm 0.49) \times 10^{-8} \quad \text{BNL-865}
  \]

\[ \Rightarrow 3.3\sigma \text{ discrepancy!} \]

- The BNL-E787 result on $R$ is too low:

  \[
  R = 0.17 \pm 0.03 \quad \text{BNL-787}
  \]
  
  \[
  R = 0.32 \pm 0.03 \quad \text{BNL-865}
  \]
Measuring the Number of $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ Events

- Signal is clean with minimum of cuts.
- Large peak to the left of the signal is from $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ decays reconstructed with the $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ hypothesis.
- First observation of $K^- \rightarrow \pi^- \mu^+ \mu^-$!
Counting the Number of $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ 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:
  \[ N(K^+ \rightarrow \pi^+ \pi^+ \pi^-) = (4.446 \pm 0.010) \times 10^5 \]
  \[ N(K^- \rightarrow \pi^- \pi^+ \pi^-) = (2.318 \pm 0.008) \times 10^5 \]
HyperCP $K^\pm \rightarrow \pi^\pm \mu^+\mu^-$ Results

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

- Combined result:
  
  \[
  B(K^\pm \rightarrow \pi^\pm \mu^+\mu^-) = (9.8 \pm 1.0 \pm 0.5) \times 10^{-8}
  \]

- 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

  \[
  R = (K^+ \rightarrow \pi^+ \mu^+\mu^-)/(K^+ \rightarrow \pi^+e^+e^-).
  \]

- 3× more events with 1999 data.
Search for $\Delta S = 2$ Hyperon Decays

- SM branching ratios $< 10^{-12}$
  $\Rightarrow$ window for new physics

- Limits from K decays do not preclude an observable effect.

  “...it is possible for new $\Delta S = 2$ interactions to induce hyperon decays at an observable level while evading the bounds from $K^0\!-\!\bar{K}^0$ mixing.”


- Preliminary results:

<table>
<thead>
<tr>
<th>Mode</th>
<th>HyperCP (90% CL)</th>
<th>PDG limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega^- \rightarrow \Lambda\pi^-$</td>
<td>$&lt; 2.7 \times 10^{-6}$</td>
<td>$&lt; 1.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Xi^0 \rightarrow p\pi^-$</td>
<td>$&lt; 7.8 \times 10^{-6}$</td>
<td>$&lt; 3.6 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
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 find no evidence of CP violation in $\Xi^\pm$ and $\Lambda$ decays, with two independent analyses of the data:

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

- We will be able to push our limit 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.

- 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.