Precision Measurements with the Hyper\textit{CP}
Spectrometer at Fermilab

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HyperCP Physics Goals

Primary Goal:

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

Secondary Goals:

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

<table>
<thead>
<tr>
<th>Trigger</th>
<th>1997</th>
<th>1999</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascade</td>
<td>$39 \times 10^9$</td>
<td>$81 \times 10^9$</td>
<td>$120 \times 10^9$</td>
</tr>
<tr>
<td>All</td>
<td>$58 \times 10^9$</td>
<td>$173 \times 10^9$</td>
<td>$231 \times 10^9$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Channeled beam polarity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi \rightarrow \Lambda \pi$</td>
<td>$458 \times 10^6$</td>
<td>$2032 \times 10^6$</td>
</tr>
<tr>
<td>$K \rightarrow \pi\pi\pi$</td>
<td>$391 \times 10^6$</td>
<td>$164 \times 10^6$</td>
</tr>
<tr>
<td>$\Omega \rightarrow \Lambda K$</td>
<td>$4.9 \times 10^6$</td>
<td>$14.1 \times 10^6$</td>
</tr>
</tbody>
</table>

- We expect a statistical precision of:

$$\delta A_{\Xi\Lambda} \approx 2 \times 10^{-4}$$
The Primary Event Reconstruction is Finished!

- Data volume compared to other, much larger experiments:

<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>

- 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

**Invariant mass of** $p\pi\pi$ [GeV/c$^2$]

- $\Xi^-$, 2.07 billion
- $\Xi^+$, 0.46 billion
- $\sigma_{\Xi} = 1.6$ MeV/c$^2$

**Invariant mass of** $\pi\pi\pi$ [GeV/c$^2$]

- $K^+$, 394 million
- $K^-$, 164 million
- $\sigma_K = 2.0$ MeV/c$^2$

**Invariant mass of** $Kp\pi$ [GeV/c$^2$]

- $\Omega^-$, 14.6 million
- $\bar{\Omega}^+$, 5.0 million
- $\sigma_\Omega = 1.5$ MeV/c$^2$

**Invariant mass of** $\pi\pi$ [GeV/c$^2$]

- $K^0$, (+)2.04 billion
- $K^0$, (-)0.72 billion
- $\sigma_{K^0} = 2.9$ MeV/c$^2$
Rare Decay Physics: the Measurement of the Branching Ratio of $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$

- Importance of Rare Decays
  - Test the Standard Model: where it predicts a small effect, look for a bigger effect.
  - Test of Chiral Perturbation theory.
  - $K^+ \rightarrow \pi^+ l^+ l^-$ 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

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

$$(5.0 \pm 0.4 \pm 0.7 \pm 0.6) \times 10^{-8} \quad \text{BNL-787}$$

$$(9.22 \pm 0.60 \pm 0.49) \times 10^{-8} \quad \text{BNL-865}$$

$\Rightarrow 3.3\sigma$ discrepancy!

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

$$R = 0.17 \pm 0.03 \quad \text{BNL-787}$$

$$R = 0.32 \pm 0.03 \quad \text{BNL-865}$$

(where the well-measured $K^+ \to \pi^+ e^+ e^-$ branching ratio has been used)
Measuring the $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ Branching Ratio

- Use $K^\pm \rightarrow \pi^\pm \pi^\mp \pi^\mp$ for normalization.

- Simply a counting experiment with a few acceptances and efficiencies thrown in:

$$B(K^\pm_{\pi \mu \mu}) = \frac{1}{200} \frac{N^{obs}_{K^\pm_{\pi \mu \mu}} A_{K^\pm_{\pi3}} \epsilon_{K^\pm_{\pi3}} B(K^\pm_{\pi3})}{N^{obs}_{K^\pm_{\pi3}} A_{K^\pm_{\pi \mu \mu}} \epsilon_{K^\pm_{\pi \mu \mu}} \epsilon_{\mu + \mu^-} \epsilon_{rel}'}$$

where:

$N^{obs}$ = number of observed events  
$A_i$ = geometrical acceptances  
$\epsilon_i$ = event selection efficiencies  
$\epsilon_{trig}^{rel}$ = relative trigger efficiencies  
$B(K^\pm_{\pi3}) = B(K^\pm \rightarrow \pi^\pm \pi^\mp \pi^\mp) = (5.59 \pm 0.05)\%$

- 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: ±5 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 $z_{\text{vertex}}$

$$d_{\text{stc}} < 2 \text{ mm}.$$  

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 $K^\pm \rightarrow \pi^\pm \mu^+ \mu^-$ 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 $K^- \rightarrow \pi^- \mu^+ \mu^-$!
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

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_B/B$ (%)</th>
<th>$\sigma_B/B(K_{\pi\mu\mu}^\pm)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam targeting</td>
<td>1.1 (0.9)</td>
<td>1.0</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0.5 (0.4)</td>
<td>0.5</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>3.1 (3.1)</td>
<td>3.1</td>
</tr>
<tr>
<td>Muon identification</td>
<td>0.3 (0.3)</td>
<td>0.3</td>
</tr>
<tr>
<td>Background Estimation ($K_{\pi3}^\pm$)</td>
<td>0.2 (0.3)</td>
<td>0.2</td>
</tr>
<tr>
<td>Background Estimation ($K_{\pi\mu\mu}^\pm$)</td>
<td>2.4 (6.4)</td>
<td>3.6</td>
</tr>
<tr>
<td>Data and MC disagreement</td>
<td>0.4 (0.4)</td>
<td>0.4</td>
</tr>
<tr>
<td>Dalitz parameter</td>
<td>0.3 (0.3)</td>
<td>0.3</td>
</tr>
<tr>
<td>Slope parameter ($\delta$)</td>
<td>0.2 (0.3)</td>
<td>0.2</td>
</tr>
<tr>
<td>$B(K^+ \rightarrow \pi^+\pi^+\pi^-)$</td>
<td>0.9 (0.9)</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>4.2 (7.3)</strong></td>
<td><strong>5.0</strong></td>
</tr>
</tbody>
</table>

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

1. Uncertainty in the relative trigger efficiency.
2. Background to the $K^\pm \rightarrow \pi^+\mu^+\mu^-$ peak.
**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 \( R = (K^+ \rightarrow \pi^+ \mu^+ \mu^-)/(K^+ \rightarrow \pi^+ e^+ e^-) \).

- 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 $\text{BR}(K^{\pm} \to \pi^{\pm} \mu^{+} \mu^{-})$

- BNL-E787
- BNL-E865
- HyperCP (Pos)
- HyperCP (Neg)
- HyperCP (Comb)

Branching Ratio ($10^{-8}$)
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.

\[
\text{“To extract useful information and constraints on new physics, results from hyperon decays, K-decays, and B-decays will have to be pooled and confronted with models on a case by case basis.”}
\]

S. Pakvasa
How to Search for CP Violation in Λ Decays?

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

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:

\[ \alpha_\Lambda \xrightarrow{CP} \overline{\alpha}_\Lambda = -\alpha_\Lambda \]

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 $\bar{\Lambda}$’s of precisely know polarization can be produced through the decay of unpolarized $\Xi^-$ and $\Xi^+$ hyperons:

$$\Xi^- \rightarrow \Lambda \pi^-$$  \hspace{1cm}  $$\Xi^+ \rightarrow \bar{\Lambda} \pi^+$$

If the $\Xi$ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the $\Lambda$ is found in a helicity state:

$$\vec{P}_\Lambda = \alpha_\Xi \hat{P}_\Lambda$$  \hspace{1cm}  $$\vec{P}_{\bar{\Lambda}} = \bar{\alpha}_\Xi \hat{P}_{\bar{\Lambda}}$$

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

$$\alpha_\Xi \alpha_\Lambda = \bar{\alpha}_{\Xi} \bar{\alpha}_{\Lambda}$$
We are sensitive to \( CP \) violation in \( \Xi \) and \( \Lambda \) decays

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

where:

\[
A_{\Xi} = \frac{\alpha_{\Xi} + \alpha_{\Xi\Xi}}{\alpha_{\Xi} - \alpha_{\Xi\Xi}} \quad \text{and} \quad A_{\Lambda} = \frac{\alpha_{\Lambda} + \alpha_{\Xi\Xi}}{\alpha_{\Lambda} - \alpha_{\Xi\Xi}}
\]

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.
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} \rightarrow \Lambda X, \bar{p}P \rightarrow \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^- \rightarrow J/\psi \rightarrow \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} \rightarrow \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 \textit{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 \rightarrow \Xi \pi \rightarrow \Lambda \pi \rightarrow \rho \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.

• \textit{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.”


- 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 $A_\Lambda$ of $O(10^{-3})$. 

![Diagram showing excluded regions for SUSY models](image-url)
If $CP$ is not violated then the $\Xi^-$ and $\Xi^+$ decays appear identical

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

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

$$\Xi^+ \rightarrow \bar{\Lambda} \pi^+ \rightarrow \bar{p} \pi^+ \pi^+$$

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

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 \( \Lambda \) 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.
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 Targeting on Asymmetry

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

- 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 $\bar{p}A$, 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 $\bar{p}$ cos $\theta$ distributions differently.

- This has been studied by taking real $\Xi^-$ 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 $\Xi \rightarrow \Lambda \pi$, $\Lambda \rightarrow p \pi$ event, discard proton and pion, generate 10 new unpolarized $\Lambda$ 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 and reconstructed.

East Coast (UVa):
Weighting Method

- Direct comparison of the proton and antiproton cos($\theta$) distributions.
- Force the $\Xi$ and $\Xi^+$ 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 $\alpha_\Lambda \alpha_{\Xi^+}$. 

\[ \Xi \rightarrow \Lambda \pi \rightarrow p \pi \]
A Preliminary $CP$ Violation Study

• Four sets of 1997 runs widely separated in time were used.

• $5.9 \times 10^6 \ \Xi^+ \text{ events : } 1.2\%$

• $37.2 \times 10^6 \ \Xi^- \text{ events : } 1.9\%$

• The positive and negative data sets were normalized to each other in five variables:

  \[
  \begin{cases}
    \Xi \times \text{target origin} \\
    \Xi \times \text{collimator exit position} \\
    \Xi \times \text{momentum}
  \end{cases}
  \]

  \[
  \begin{cases}
    \Xi \times \text{target origin} \\
    \Xi \times \text{collimator exit position} \\
    \Xi \times \text{momentum}
  \end{cases}
  \]

• The effect of the normalization scheme on any real asymmetry was tested with a Hybrid Monte Carlo:

  • $20 \times 10^6 \ \Xi^+ \text{ MC events}$

  • $150 \times 10^6 \ \Xi^- \text{ MC events}$

  • MC Input:  $\rightarrow A_{\Xi \Lambda} = -17.1 \times 10^{-3}$

  • Analysis Output:  $\rightarrow A_{\Xi \Lambda} = (16.9 \pm 0.4) \times 10^{-3}$

• Biases from interactions, backgrounds, and the normalization process were studied and found to be consistent with zero with a precision of:

  $\delta A_{\Xi \Lambda} < 1.6 \times 10^{-3}$
EFFECTS OF THE EQUALIZATION

- Graphs showing dN/dZ, dN/dp, dN/dX, and dN/dcos θ for π(Ξ) distributions before and after equalization.

- Data points and error bars indicated for each distribution.
Helicity Frame $\cos(\theta)$ From Set I

- **RAW**: $\Delta \alpha_A \alpha_\Xi = (4.7 \pm 1.7) \times 10^{-3}$
- **WEIGHTED**: $\Delta \alpha_A \alpha_\Xi = (-0.8 \pm 1.7) \times 10^{-3}$
This preliminary *HyperCP* study, based on an analysis of 1.7% of the 1997 data gives:

\[
A_{ΞΛ} = (-1.6 \pm 1.3 \pm 1.6) \times 10^{-3}
\]

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 $K^- \rightarrow \pi^- \mu^+ \mu^-$ 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 $\Xi$ and $\Lambda$ 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!
Vertex Fit Parameters from $K^- \to \pi^-\pi^+\pi^-$ Events
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.

\[
A_\Lambda \approx - \tan (\delta_1^P - \delta_1^S) \sin (\phi_1^P - \phi_1^S),
\]
\[
A_\Xi \approx - \tan (\delta_2^P - \delta_2^S) \sin (\phi_1^P - \phi_1^S).
\]

- Asymmetry greatly reduced by the small strong phase shifts.
  - The $p\pi$ phase shifts have been measured to a precision of about one degree:
    \[
    \Lambda \left\{ \begin{array}{c}
    \delta_1^P = -1.1 \pm 1.0^\circ \\
    \delta_1^S = 6.0 \pm 1.0^\circ
    \end{array} \right. 
    \]
    - The $\Lambda\pi$ phase shifts can’t be measured, and theoretical predictions disagree.
    \[
    \Xi^- \left\{ \begin{array}{c}
    \delta_2^P = -2.7^\circ \\
    \delta_2^S = -18.7^\circ
    \end{array} \right\} 1965 = -1^\circ = 0^\circ \text{ recent } \chi PT
    \]

- By measuring $\beta_\Xi$ HyperCP will be able to measure the strong phase shifts in $\Xi$ decay to a precision of about one degree through the relationship:

\[
\frac{\beta}{\alpha} = - \tan (\delta_S - \delta_P)
\]
Comparison of $\epsilon'/\epsilon$ and $A_\Xi$, $A_\Lambda$

$\epsilon'/\epsilon$

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

\[
\begin{align*}
K^0 & \rightarrow \pi^+\pi^- \\
\text{Diagram:} & \\
\end{align*}
\]

- 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.

\[
\begin{align*}
\Lambda & \rightarrow p\pi^- \\
\text{Diagram:} & \\
\end{align*}
\]

- 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 $\epsilon'/\epsilon$, in that it probes potential sources of CP violation at a level that has not been probed by the kaon experiments.”

Measuring the $\Xi^-$ 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:

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

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:

$$\frac{\beta_{\Xi}}{\alpha_{\Xi}} = \tan(\delta_2^P - \delta_2^S) \approx \delta_2^P - \delta_2^S$$

- We have 135 million polarized $\Xi^-$ ($\Xi^+$) events with an average polarization of about 7%. Hence our estimated error in the phase shift is:

$$\delta(\delta_2^P - \delta_2^S) = \pm 0.5^\circ$$
A 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:**

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

- **Note!** If parent unpolarized daughter baryon found in helicity state:

$$\vec{P}_d = \alpha_p \hat{d}$$