Status Report from the HyperCP Experiment at Fermilab

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HyperCP Physics Goals

- Perform a sensitive search for CP violation by comparing the decay process $\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^-$ with its anti-process $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+, \overline{\Lambda} \to \overline{p}\pi^+$. A positive result would be:
  - Evidence of CP violation outside of the decay of the K_L
  - Evidence of direct CP violation
- Search for CP violation in $K^\pm \to 3\pi$ decays.
- Search for rare and forbidden hyperon and charged kaon decays.
- Measure various hyperon parameters, including: polarization, production cross sections and decay parameters.

Advantages of Using Hyperon Decays to Measure CP Violation

- An unconventional way to measure CP violation
- Hyperons can be produced in large quantities

$$p + Cu \to \Xi^{\pm} + X$$

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

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

- The spectrometer can be fairly simple - important for minimizing systematic effects.

Non-Leptonic Hyperon Decay

The decay distribution of a spin-$\frac{1}{2}$ daughter baryon from a hyperon decay, in the rest frame of the parent, spin averaged over final states is:

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_p \vec{P}_p \cdot \hat{p}_d)$$

where $\vec{P}_p$ is the parent hyperon polarization, and $\hat{p}_d$ is the daughter baryon momentum unit vector.

In addition, the polarization of the daughter baryon is related to the polarization of the parent by:

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

where the Lee-Yang variables α, β, γ are defined in terms of the S and P-wave amplitudes by:

$$\alpha = \frac{2Re(S * P)}{|S|^2 + |P|^2}, \quad \beta = \frac{2Im(S * P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

Note $\vec{P}_d = \alpha \hat{p}_d$ if the parent is unpolarized. Some asymmetry observables have been defined which are sensitive to CP violation:

$$A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}, \quad B = \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}}, \quad \Delta = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$$

What do we expect? Theoretical Predictions

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

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

where:

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

Some predictions of Δ, A, and B for $\Lambda \to p\pi$ and charged $\Xi \to \Lambda\pi$ decays.

$\Lambda \to p\pi$

	Δ_Λ	A_Λ	B_Λ
CKM	$< 10^{-6}$	(-5 to -1) $\times 10^{-5}$	(0.6 to 3)$\times 10^{-4}$
Weinberg	-8×10^{-6}	-2.5×10^{-5}	1.6×10^{-3}
Left-Right	0	(-0.1 to 6)$\times 10^{-4}$	7×10^{-4}

Charged $\Xi \to \Lambda\pi$

	Δ_Ξ	A_Ξ	B_Ξ
CKM	0	(-10 to -1) $\times 10^{-5}$	(10 to 1) $\times 10^{-3}$
Weinberg	0	-3.2×10^{-4}	3.8×10^{-3}
Left-Right	0	(-2.5 to 6) $\times 10^{-5}$	-3.1×10^{-4}

- The CP asymmetry manifests itself through the interference between the $S-$ and $P-$ wave amplitudes:

$$A \equiv \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}$$

$$A_\Lambda \approx -tan(\delta_1^P - \delta_1^S) sin(\phi_1^P - \phi_1^S)$$

$$A_\Xi \approx -tan(\delta_3^P - \delta_3^S) sin(\phi_1^P - \phi_1^S)$$

where δ and ϕ are the strong and weak phases, and the subscripts 1 and 3 refer to the $\Delta I = 1/2$ and $\Delta I = 3/2$ isospin transitions.

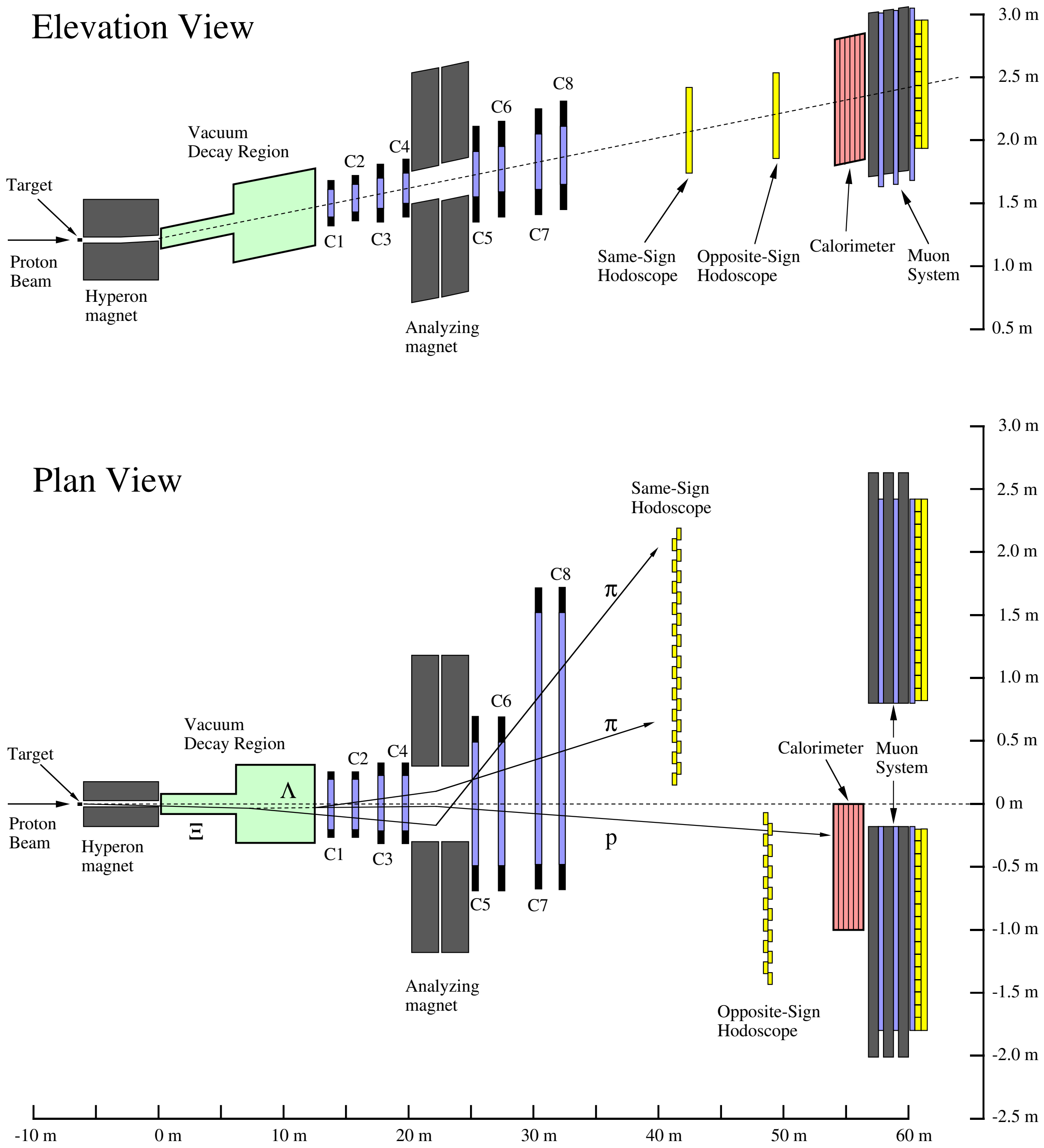
- In almost all calculations the sign of A_Λ and A_Ξ are the same.

What is the Experimental Situation?

- There are no experimental limits on A_Ξ.
- These are the current limits on A_Λ:

Mode	Limit on A_Λ	Experiment
$pp \to \Lambda X, \overline{p}p \to \overline{\Lambda} X$	0.02 ± 0.14	R608
$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	0.01 ± 0.10	DM2
$p\overline{p} \to \Lambda\overline{\Lambda}$	0.013 ± 0.022	PS185

The HyperCP Spectrometer



- 800 GeV/c primary proton beam hits copper target
- 170 GeV/c secondaries exit the hyperon magnet
  - Negative mode secondary beam contains Ξ^-
  - Positive mode secondary beam contains $\overline{\Xi}^+$

Summary of the 1997 HyperCP Run

- Between April and September, 1997, collected:

$$\approx 75 \times 10^9 \text{ triggers}$$

of which,

$$\approx 39 \times 10^9 \text{ are } \Xi \text{ triggers}$$

on $\approx 10,000$ Exabyte 5 Gb tapes

- This should yield roughly

$$1.2 \times 10^9 \text{ reconstructed } \Xi^- \text{ decays}$$

and

$$0.3 \times 10^9 \text{ reconstructed } \overline{\Xi}^+ \text{ decays}$$

- This results in an overall sensitivity of

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

Status of Analysis

- Since the end of the run:
  - Studied, optimized and decided on official reconstruction code
  - Brought up farm processing code
  - Determined various run-dependent parameters such as alignment constants, magnetic field maps, efficiencies, etc.
- Preliminary event reconstruction has been done on $\approx 100\%$ of the data on Fermilab farms

Systematics

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

There are three classes of biases.

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

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

   - This results in the Λ and $\overline{\Lambda}$ inhabiting different regions of phase space.
   - Nonzero Ξ polarization can in principle be corrected for.
3. Different backgrounds under the Λ and $\overline{\Lambda}$ and the Ξ^- and $\overline{\Xi}^+$ mass peaks.

Define slope asymmetry: $\delta g = \frac{g-\overline{g}}{g+\overline{g}}$

Theoretical Predictions

	$\lvert\delta g\rvert$
H.-Y. Cheng (1991)	$< 1 \times 10^{-5}$
D'Ambrosio *et. al.* (1991)	$\leq 1 \times 10^{-5}$
Isidori *et. al.* (1992)	$\approx 1 \times 10^{-6}$
E.P. Shabalin (1993)	$\leq (5 \pm 2) \times 10^{-5} \lvert sin\delta \rvert$
A.A. Bel'kov *et. al.* (1993)	$\approx 0.5 \times \lvert\epsilon'/\epsilon\rvert$
D'Ambrosio *et. al.* (1998)	$\approx 2 \times 10^{-6}$
E.P. Shabalin (1998)	$\approx 2 \times 10^{-4}$

- Previous experimental result from dedicated search at BNL AGS in 1970:

$$\delta g = (-0.70 \pm 0.52) \times 10^{-2}$$

  based on 1.6×10^6 $K \to 3\pi$ decays for each charge.

- HyperCP expects to have 109×10^6 K^+ events and 48×10^6 K^- events from 1997 data sample for a statistical sensitivity in δg of about 6.8×10^{-4}

- Experimentally, measure number of events in the X and Y bins of the Dalitz plot and form asymmetry

$$A(X,Y) = \frac{N^+(X,Y) - N^-(X,Y)}{N^+(X,Y) + N^-(X,Y)} = \frac{\epsilon^+(X,Y)(1+gY) - \epsilon^-(X,Y)(1+\overline{g}Y)}{\epsilon^+(X,Y)(1+gY) + \epsilon^-(X,Y)(1+\overline{g}Y)}$$

  where $N^{+(-)}(X,Y)$=number of positive (negative) events in X and Y bin, and $\epsilon^{\pm}(X,Y)$ = acceptance

Other Physics Topics

- Lepton number non conservation in kaon and hyperon decays:
  - $\Xi^- \to p\mu^-\mu^-$ Expect sensitivity 4 to 5 orders of magnitude better than PDG limit
  - $\Sigma^- \to p\mu^-\mu^-$
  - $K^+ \to \pi^-\mu^+\mu^+$
- Flavor changing neutral currents in hyperon and charged kaon decays:
  - $\Sigma^+ \to p\mu^+\mu^-$
  - $K^\pm \to \pi^\pm\mu^+\mu^-$ Signal observed for K^+ and K^- modes. Branching ratio for K^+ mode consistent with PDG value, K^- mode previously unobserved.
- Decay parameter α_Ω for Ω decay, $\Omega \to \Lambda K, \Lambda \to p\pi$. We measure $\alpha_\Omega\alpha_\Lambda$ from the slope of the angular distribution of the proton in the Λ helicity frame. $\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda\alpha_\Omega cos\theta)$. We expect a statistical sensitivity of about an order of magnitude better than PDG average, from our sample of several million omegas.

1999 HyperCP Run

HyperCP began the 1999 run in early June and will run until the end of the Fermilab fixed target run, $\approx$ Nov. 1999. Upgrades include:

- Substantial improvements to data acquisition system:
  - Data compression reduces raw event size by 35%
  - Dead-time reduction from $\approx 3\mu$sec to $\approx 1\mu$ sec
  - Increased DAQ throughput
- Minor improvments to spectrometer.

1997 run statistics:

Average primary beam intensity:	5.1×10^9 p/sec
Average secondary beam rate:	14 MHz
Average event size:	550 bytes
Average inhibited trigger rate:	62 kHz
Total triggers written to tape:	6.2×10^{10}

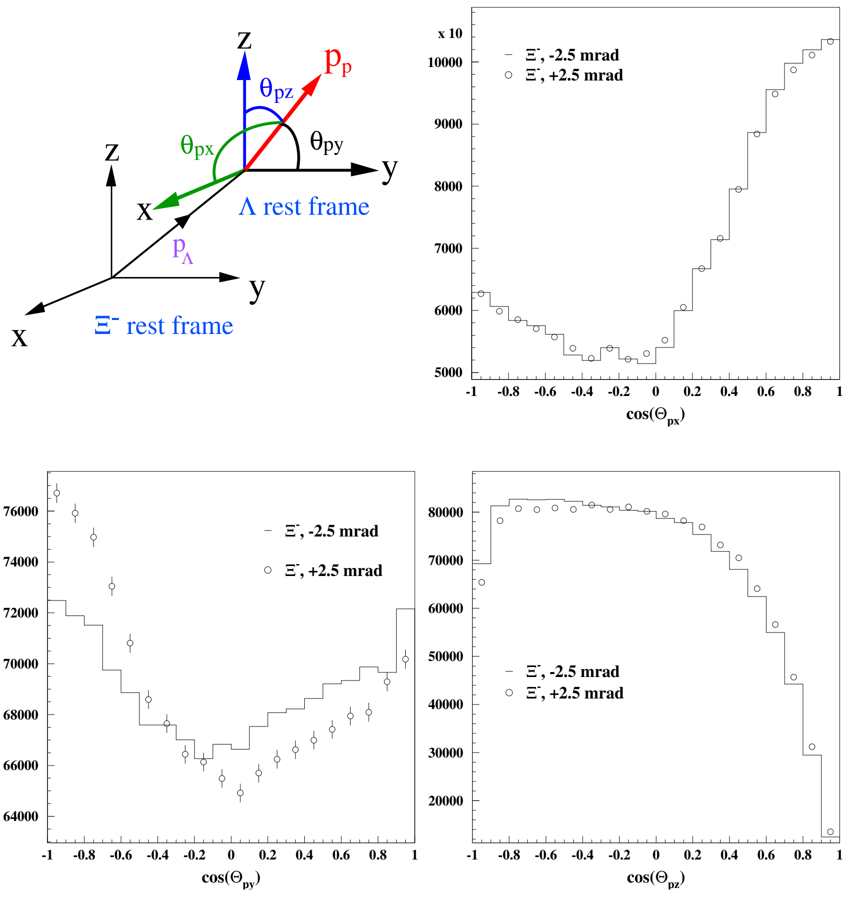
1999 projections (based on a 16 week run):

Average primary beam intensity:	7.5×10^9 p/sec
Average secondary beam rate:	20 MHz
Average event size:	420 bytes
Average inhibited trigger rate:	100 kHz
Total triggers written to tape:	24.2×10^{10}

Each month of running will increase our data sample by an amount equal to that acquired in the 1997 run. A five month run will give us a sensitivity of 8.7×10^{-5}.

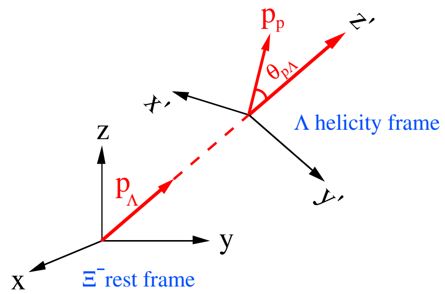
Conclusions and Outlook

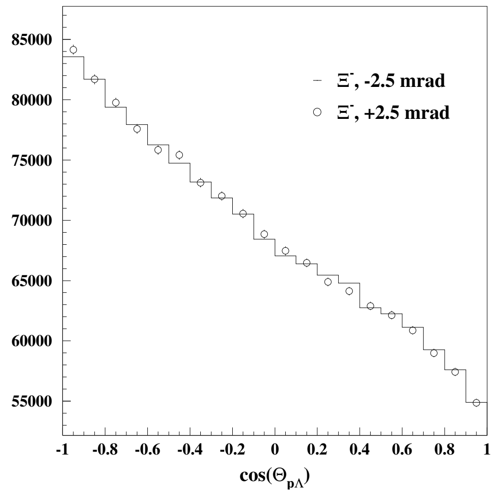
- HyperCP had a very successful first run, and we expect to achieve a sensitivity in $A_{\Xi\Lambda}$ of 2×10^{-4}, two orders of magnitude better than the present limit and where some theories predict an effect.
- Farm processing for initial reconstruction of our data was recently completed and analysis is in progress on CP violation result as well as on several other topics.
- HyperCP has begun its second run with an upgraded DAQ. Each month of running will increase our data sample by an amount equal to that aquired in the 1997 run. A five month run will give us a sensitivity of 8.7×10^{-5} in $A_{\Xi\Lambda}$.



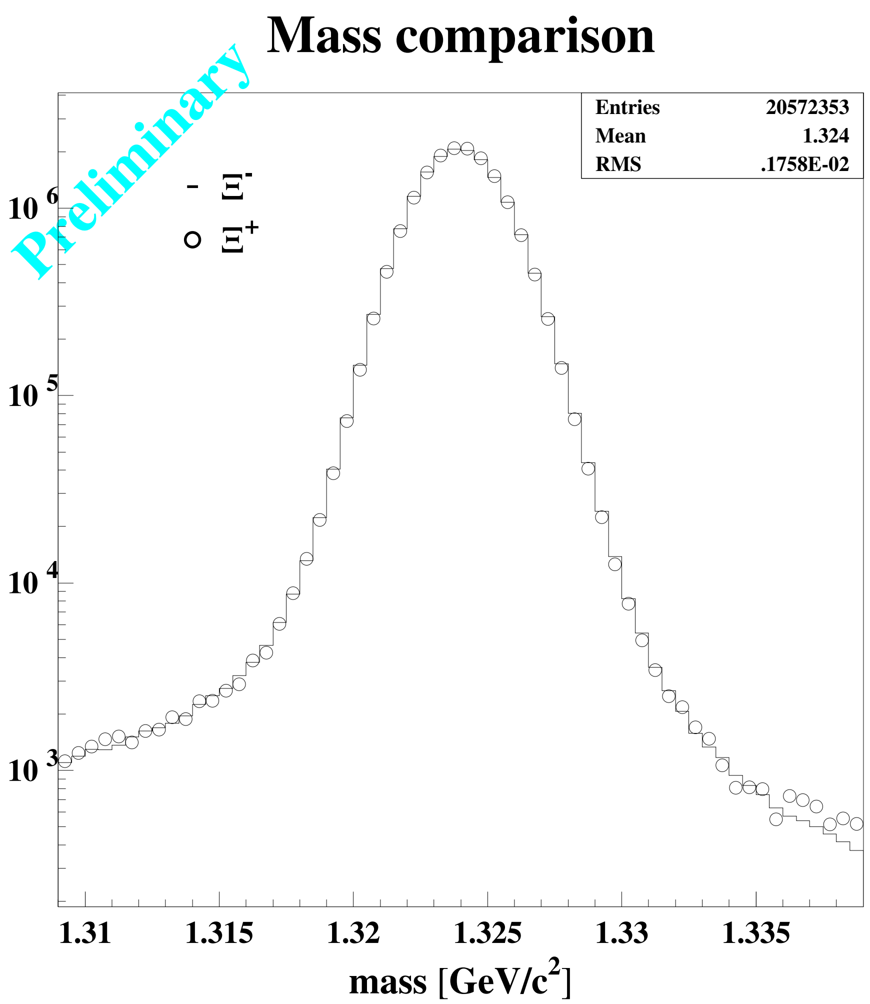
- **The effect of the small polarization is clearly seen in the $cos(\theta_{py})$ distribution in the Λ rest frame**

Ξ^- (-2.5 mrad) vs Ξ^- (+2.5 mrad)

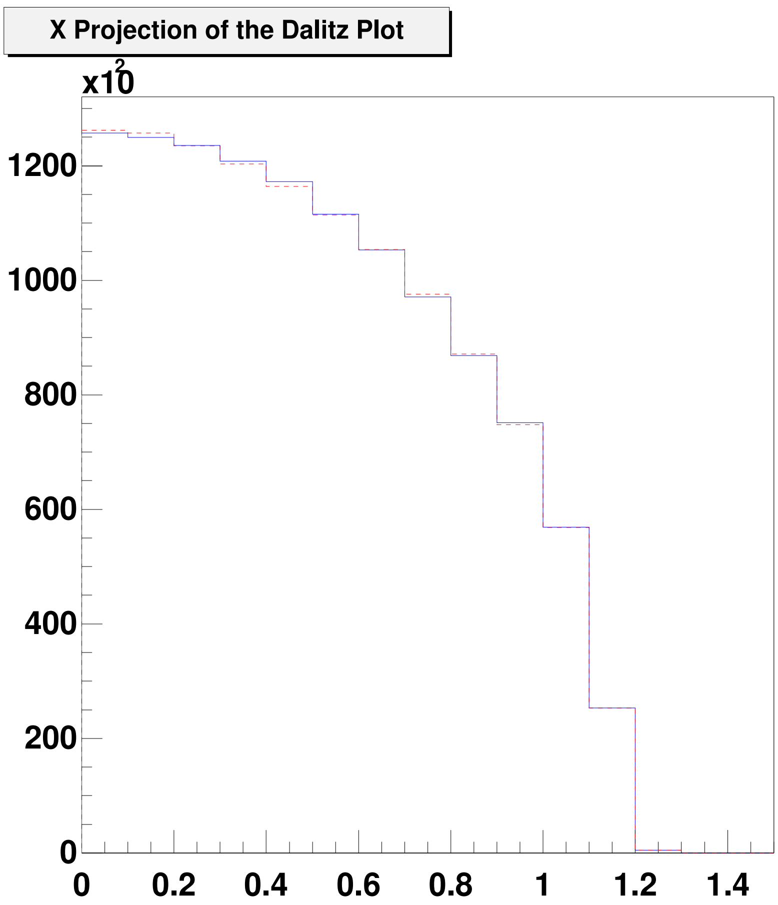




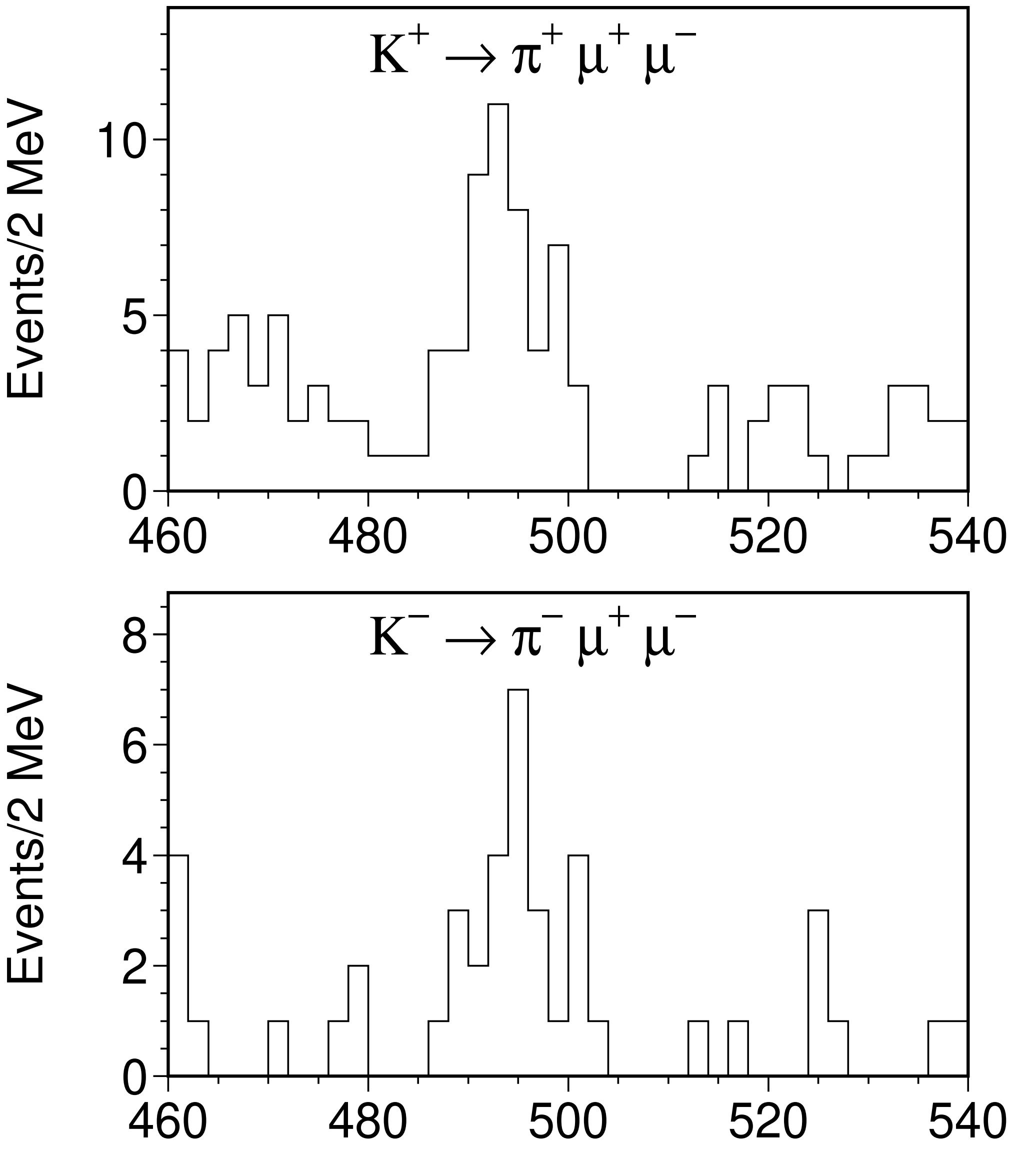
- **In the Λ helicity frame the effect of the small polarization on the $cos(\theta_{p\Lambda})$ distribution disappears**
- **Monte-Carlo studies show that a 1% polarization only modifies the slope of the $cos(\theta_{p\Lambda})$ at the 2×10^{-4} level**



Mass comparison
Preliminary
Entries 20572353
Mean 1.324
RMS .1758E-02
10 6
10 5
10 4
10 3
1.31
1.315
1.32
1.325
1.33
1.335
mass [GeV/c2]



- The asymmetry in the X projection of the Dalitz plot is expected to be zero.
- Any observed asymmetry would indicate an acceptance difference between the positive and negative data.


$K^+ \to \pi^+ \mu^+ \mu^-$
Events/2 MeV
10
5
0
460
480
500
520
540
$K^- \to \pi^- \mu^+ \mu^-$
Events/2 MeV
8
6
4
2
0
460
480
500
520
540
Invariant Mass (MeV)