Hyper*CP* at Fermilab–A Status Report

The primary purpose of the Hyper*CP* experiment at Fermilab is to test *CP* in hyperon decays by comparing the alpha parameters for Ξ^- and $\overline{\Xi}^+$ decays in the decay sequence: $\Xi^- \rightarrow \pi + \Lambda^0, \quad \Lambda^0 \rightarrow \pi^- + p.$

In addition we can test *CP* in charged kaon decays by comparing the slopes of the Dalitz plot for K^+ and K^- decays. We are also looking at rare decay modes of charged kaons and hyperons, particularly those involving muons.

In two runs in 1997 and 1999, we collected approx. 500 million charged kaon decays, 2.5 billion Ξ^- and $\overline{\Xi}^+$ decays, and 19 million Ω^- and $\overline{\Omega}^+$ decays.

The status of these analyses will be summarized.

HyperCP (E871) Collaboration

A. Chan, Y.C. Chen, C. Ho, P.K. Teng
Academia Sinica, Taiwan

W.S. Choong, Y. Fu, G. Gidal, P. Gu, T.Jones,
K.B. Luk, B. Turko, P. Zyla
Lawrence Berkeley National Laboratory and University of California

C. James, J. Volk
Fermilab

J. Felix, G. Moreno, M. Sosa
University of Guanajuato, Mexico

R. Burnstein, A. Chakravorty, D. Kaplan, W. Luebke,
L. Lederman, H. Rubin, D. Rajaram, N. Solomey,
Y. Torun, C. White, S. White
Illinois Institute of Technology

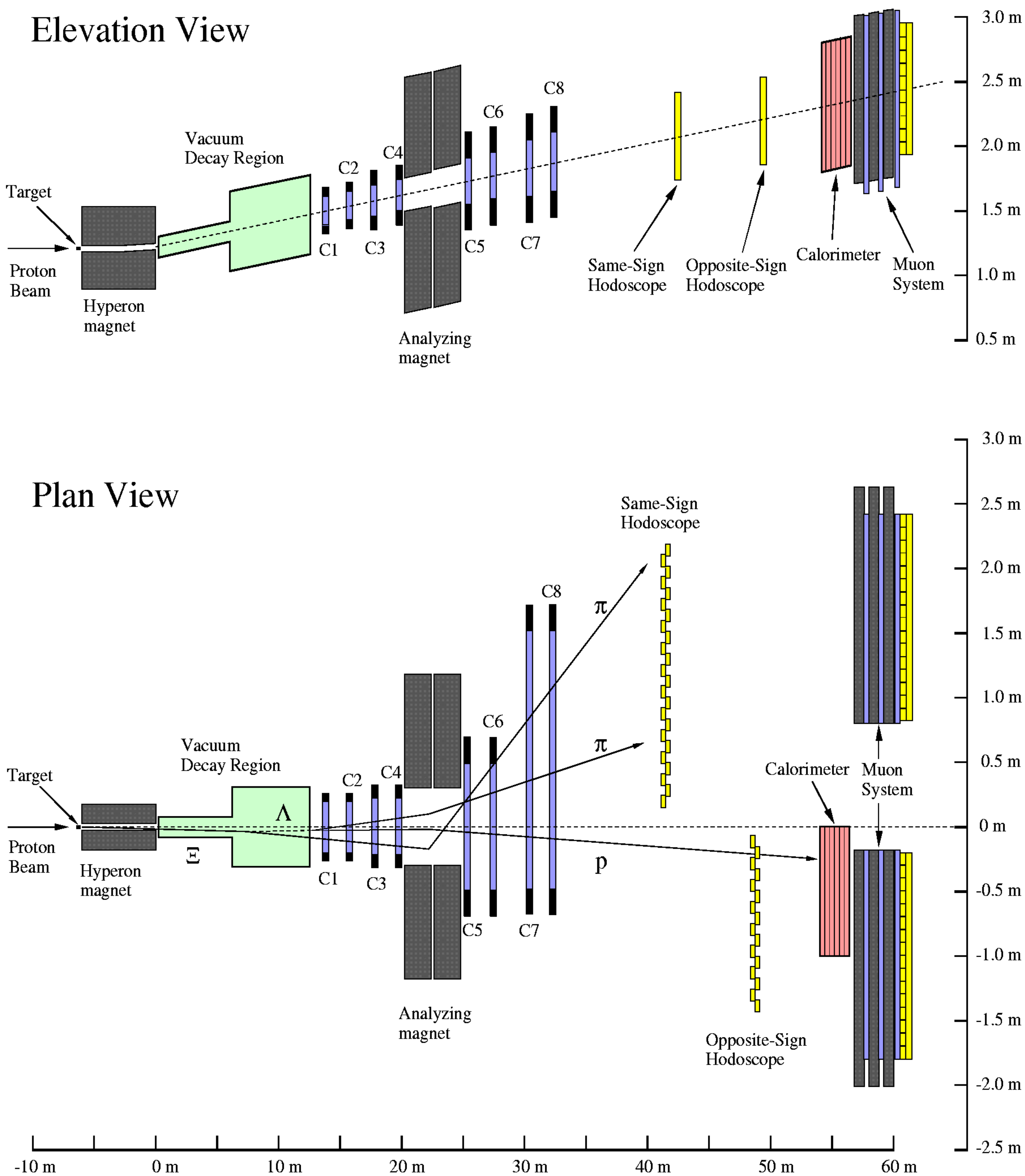
N. Leros, J. P. Perroud
Universite de Lausanne

H.R. Gustafson, M. Longo, F. Lopez, H.K. Park
University of Michigan

K. Clark, M. Jenkins
University of South Alabama

C. Dukes, C. Durandet, R. Godang, T. Holmstrom,
M. Huang, L.C. Lu, K. Nelson
University of Virginia

Hyper*CP* Spectrometer



Data Sample from the 1997 and 1999 Runs

	1997 Run	1999 Run
Number of Tapes	9,376	18,838
Data Volume	38 TB	71 TB

* These include 250 x 10^6 polarized Ξ^- and 50 x 10^6 polarized anti-Ξ^+ taken at non-zero production angles.

Projected number of reconstructed events:

Ξ^-	**2 x 10**	K^-	**0.16 x 10^9**	Ω^-	**14 x 10^6**
$\bar{\Xi}^+$	**0.5 x 10^9**	K^+	**0.39 x 10^9**	Ω^+	**4.9 x 10^6**

Statistical precision expected in Ξ decay CP test: $\delta A_{\Xi\Lambda} = 1.4 \times 10^{-4}$

Physics Topics

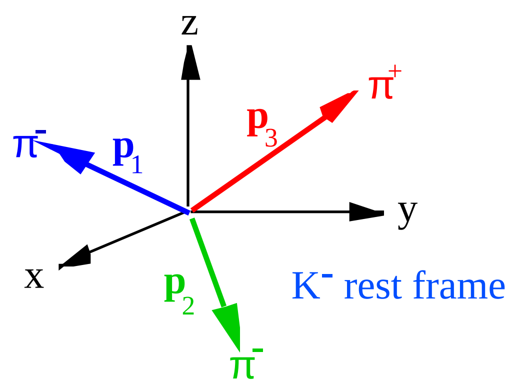
- **Searching for direct CP-violation by comparing the decay process:**
  - $\Xi^- \to \Lambda\,\pi^-$, $\Lambda \to p\,\pi^-$ **with** $\overline{\Xi}^+ \to \overline{\Lambda}\,\pi^+$, $\overline{\Lambda} \to \overline{p}\,\pi^+$
  - $K^- \to 3\pi$ **with** $K^+ \to 3\pi$
- **Flavor changing neutral currents:**
  - $K^\pm \to \pi^\pm\mu^+\mu^-$, $\Sigma^+ \to p\mu^+\mu^-$
- **Lepton number violation:**
  - $K^\pm \to \pi^\mp\mu^\pm\mu^\pm$, $\Xi^- \to p\mu^-\mu^-$, $\Sigma^- \to p\mu^-\mu^-$
- ΔS**=2 Decays:**
  - $\Xi^- \to p\pi^-\pi^-$, $\Omega^- \to \Lambda\pi^-$, $\Omega^- \to pK^-\pi-$
- **Hyperon decay properties and production:**
  - $\Xi^-(\overline{\Xi}^+)$ **and** $\Omega^-(\overline{\Omega^+})$ **polarization**
  - β **decay parameter in** $\Xi^-(\overline{\Xi}^+)$ **decays**
  - α **decay parameter in** $\Omega^-(\overline{\Omega^+})$ **decays**
  - **production cross section**
- **CPT Test: mass and lifetime of** $\Xi^-(\overline{\Xi}^+)$, $\Lambda(\overline{\Lambda})$, **and** $\Omega^-(\overline{\Omega^+})$

CP Violation in $K^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}$

$\rightarrow$ Decay amplitudes depends only on two independent kinematical variables:

$$X = \frac{s_2 - s_1}{m_\pi^2}$$

$$Y = \frac{s_3 - s_0}{m_\pi^2}$$



where

$$s_i = (\mathbf{p}_K - \mathbf{p}_i)^2 = (m_K - m_i)^2 - 2m_K T_i\,, i = 1, 2, 3$$

$$s_0 = \frac{1}{3}\sum_i s_i = \frac{1}{3}(m_K^2 + m_1^2 + m_2^2 + m_3^2)$$

The differential decay rate is proportional to the invariant matrix element that can be parametrized as:

$$|M^2| \quad 1 + gY + \ldots$$

If $g_{K^-} \neq g_{K^+}$, then CP symmetry is broken.

CP-violating Observables

Slope asymmetry

$$\delta g = \frac{g - \bar{g}}{g + \bar{g}}$$

$$\delta g = \frac{Im[(a_{11} + a_{13})^*(b_{11} + b_{13})]sin(\delta_{1S} - \delta_{1M}) + Im[(a_{11} + a_{13})^* b_{23}]sin(\delta_{1S} - \delta_2)}{Re[(a_{11} + a_{13})^*(b_{11} + b_{13})]cos(\delta_{1S} - \delta_{1M}) + Re[(a_{11} + a_{13})^* b_{23}]cos(\delta_{1S} - \delta_2)}$$

- The dominant CP-violating effect is due to the interference between two $|\Delta I = 1/2|$ amplitudes (a_{11} and b_{11}).
- No cancellation between gluonic and electroweak penguin diagrams at large top mass.

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)	$\sim 1 \times 10^{-6}$
E.P. Shabalin (1993)	$\leq (5 \pm 2) \times 10^{-5} \lvert sin\delta\rvert$
A.A. Bel'kov *et al.* (1993)	$\sim 0.5 \times \lvert\epsilon'/\epsilon\rvert$
D'Ambrosio *et al.* (1998)	$\sim 2 \times 10^{-6}$
E.P. Shabalin (1998)	$\sim 2 \times 10^{-4}$

Summary of Systematic Errors

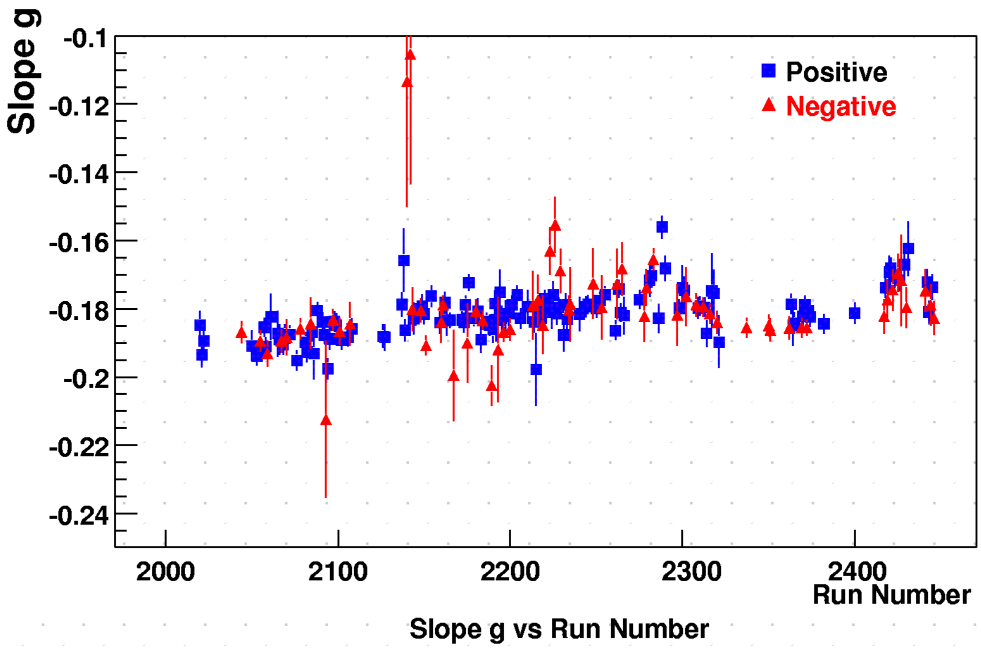
Systematic Source	$\frac{\Delta g}{2g_{PDG}}$ Error (units of 10^{-3})	Comment
Secondary Beam	1.6	Could be corrected
Cal Fiducial	0.5	
Interaction	0.2	
Hodo Eff.	1.3	Could be corrected
Wire Eff.	0.7	Could be corrected
Targeting	0.5 ± 1.0	
Magnetic Field	1.7 ± 1.0	Earth's field could be corrected
MC statistics	1.9	Need to generate MORE MC
Total error	3.7	

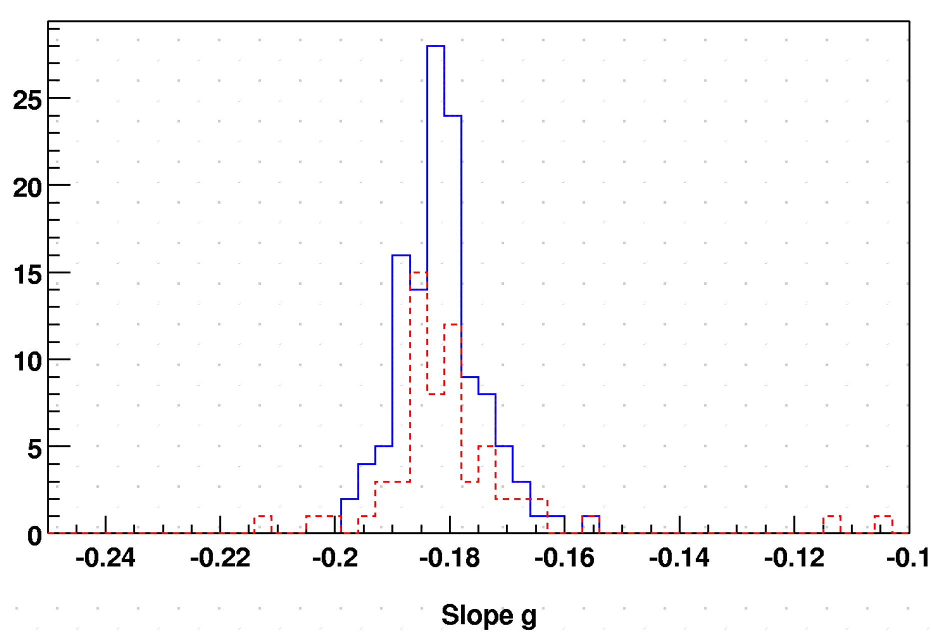
Note:

1. Some of these numbers could change when more MC events are analyzed. Numbers are dominated by MC statistics. It is not clear whether correction is needed.
2. Would require detailed MC simulation and more MC events. Much time and effort need to be invested.

$K \to 3\pi$ CP Test

Preliminary Study Based on ≈54 x 10^6 $K^\pm$ Events (10% of total sample)





NONLEPTONIC HYPERON DECAYS

- **In the ΔS = 1 decay of spin-$\frac{1}{2}$ strange baryon, angular momentum conservation allows only two final states for the spin-$\frac{1}{2}$ baryon and pion**

Parity violating S-wave
Parity conserving P-wave

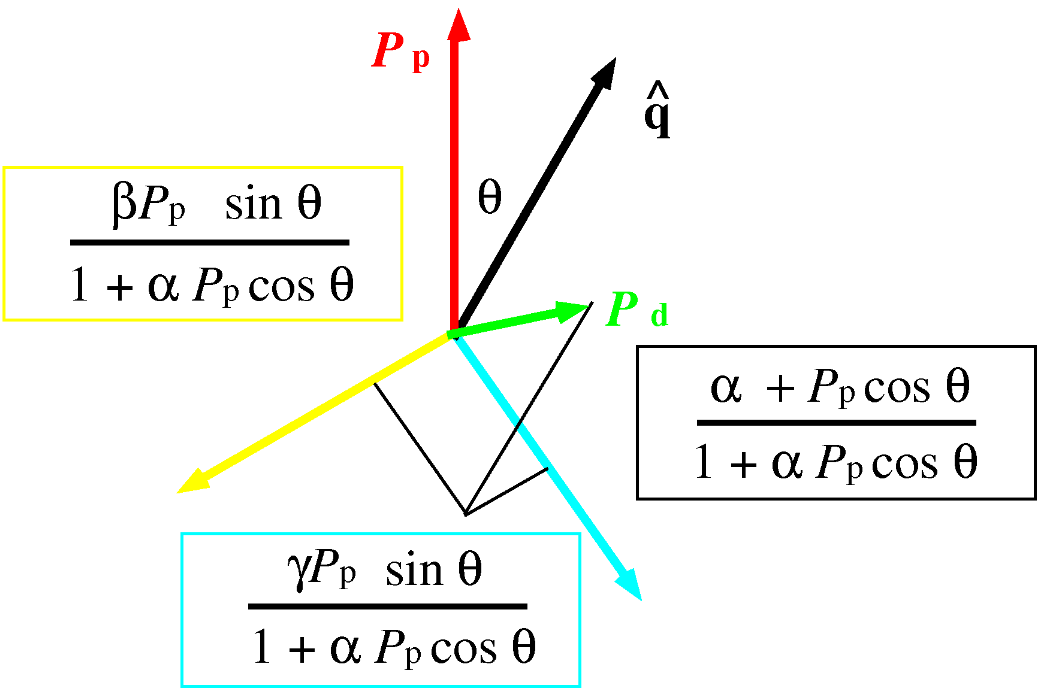
- **Decay parameters**

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

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

- **The angular distribution of the final state baryon in the rest frame of the parent baryon with polarization $\mathcal{P}$ depends on α**

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha\vec{\mathcal{P}} \cdot \hat{q}) = \frac{1}{4\pi}(1 + \alpha\mathcal{P}\cos\theta)$$



$$\vec{\mathcal{P}}_d = \frac{(\alpha + \vec{\mathcal{P}}_p \cdot \hat{q})\hat{q} + \beta\vec{\mathcal{P}}_p \times \hat{q} + \gamma\hat{q} \times (\vec{\mathcal{P}}_p \times \hat{q})}{(1 + \alpha\vec{\mathcal{P}}_p \cdot \hat{q})}$$

- **Thus β gives the component of polarization perpendicular to the plane formed by $\vec{\mathcal{P}}_p$ and $\hat{q}$**

- **For an unpolarized parent baryon α is the magnitude of the longitudinal polarization of the decay baryon**

$$\vec{\mathcal{P}}_d = \alpha\hat{q}$$

- **If CP is conserved**

$$\bar{\Gamma} = \Gamma \qquad \bar{\alpha} = -\alpha \qquad \bar{\beta} = -\beta$$

- **Some CP violation observables**

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

- **Search for direct CP violation in Λ decays**
  Need to produce Λ, $\bar{\Lambda}$ with known polarizations

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

- **Search for direct CP violation in Ξ and Λ decays**

Experiment	Decay Mode	$A_\Xi + A_\Lambda$
E756 at Fermilab	$\Xi \to \Lambda\pi, \Lambda \to p\pi$	0.012 ± 0.014

Hyper$\mathcal{CP}$ APPROACH

- **Produce unpolarized Ξ's to obtain Λ's with longitudinal polarization α_Ξ from Ξ decays**

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

identified via decays

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

- **In Λ rest frame**

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{\mathcal{P}}_\Lambda \cdot \hat{q}_p) = \frac{1}{4\pi}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_p)$$

- **Measure asymmetry**

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

with 1×10^{-4} precision

THEORETICAL PREDICTIONS

- **Superweak model predicts**

No ΔS=1 CP violation

- **For $\Lambda \to p\,\pi$ decay**

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

- **For $\Xi \to \Lambda\,\pi$ decay**

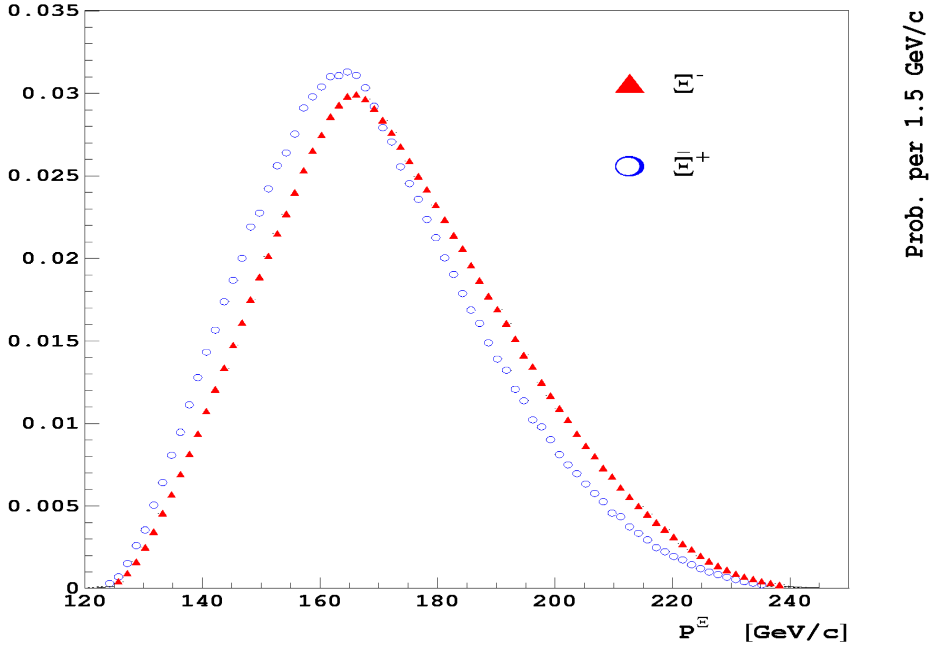
	Δ_Ξ	A_Ξ	B_Ξ
CKM	**0**	$(-10, -0.5) \times 10^{-5}$	$(10, 1) \times 10^{-3}$
Weinberg	**0**	-3.2×10^{-4}	3.8×10^{-3}
Left-Right	**0**	$(-2.5, 6) \times 10^{-5}$	-3.1×10^{-4}

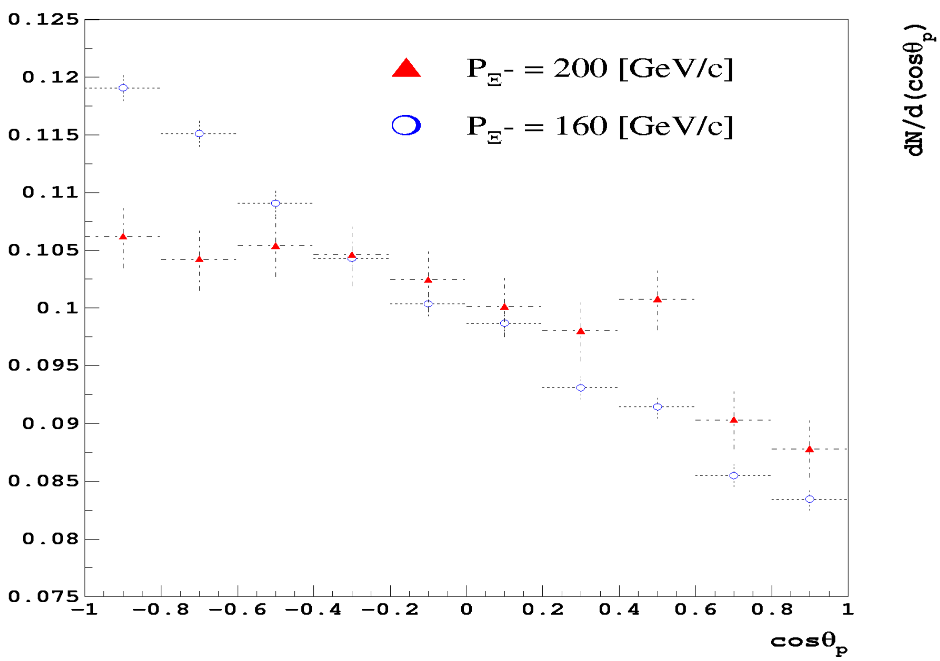
SYSTEMATICS

If not corrected for will cause false asymmetries between Ξ^- and $\overline{\Xi}^+$ decays

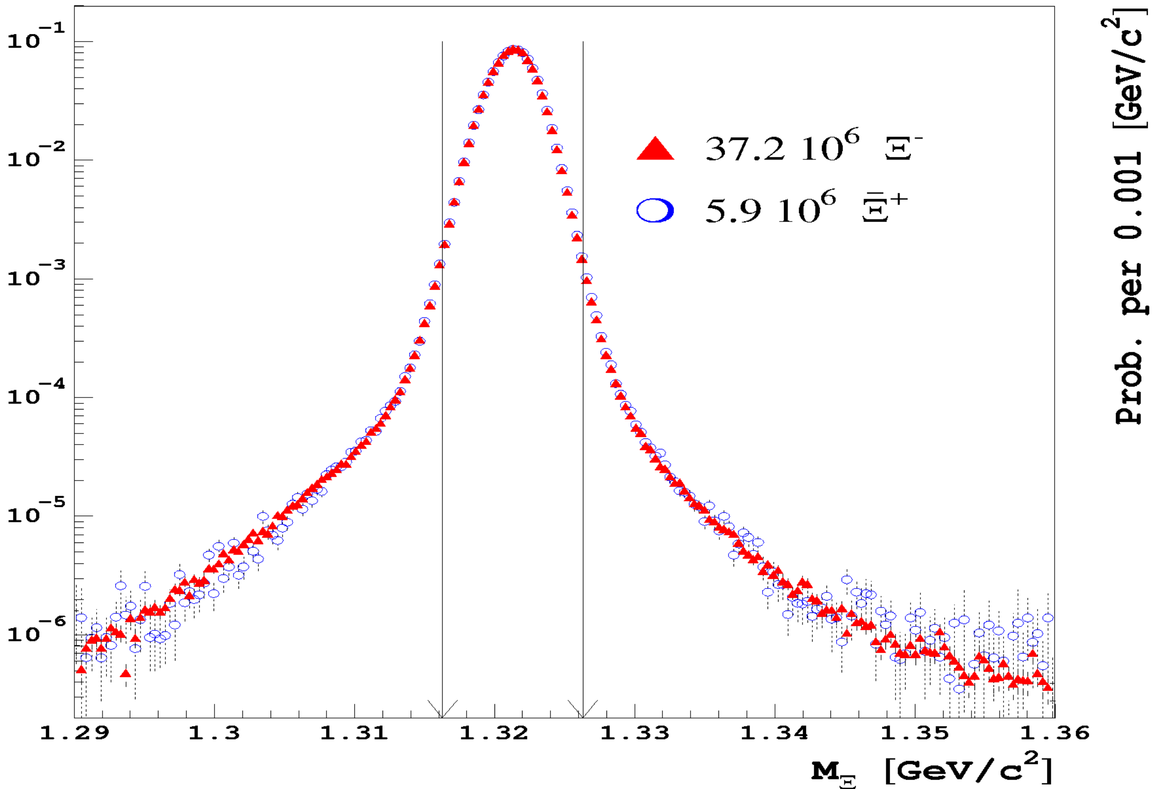
- **Acceptance differences**
  - * **targeting differences**
  - * **magnetic field differences**
  - * **chamber efficiency differences**
  - * **temporal changes**
  - * **different backgrounds for Λ, Ξ^- versus $\overline{\Lambda}$, $\overline{\Xi}^+$**
- **Nonzero Ξ^-, $\overline{\Xi}^+$ polarizations**
- **Different interaction cross sections of π^- and π^+ and of p and $\overline{p}$**

DIFFERENCES IN PRODUCTION BETWEEN Ξ^- AND $\overline{\Xi}^+$





Differences in Background after "Matching"



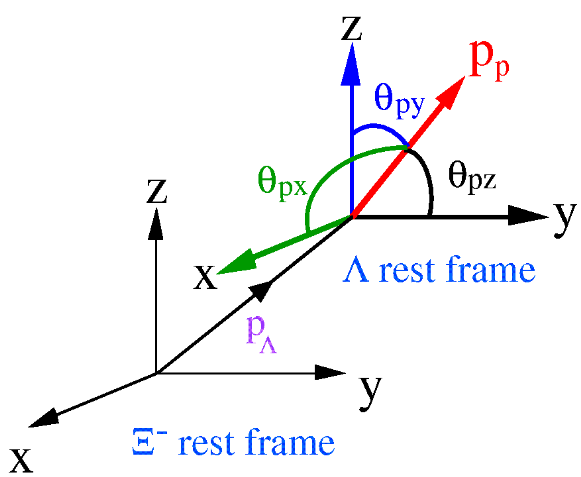
- Measured differences in the slope of cos θ_p in the sidebands after the matching process–

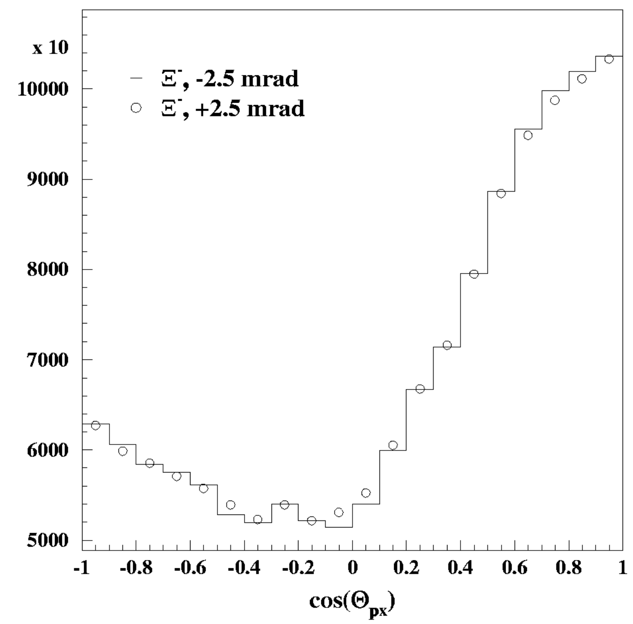
  Left sideband: $\Delta\alpha = (\ 0.5\ \pm 1.0) \times 10^{-2}$
  Right sideband: $\Delta\alpha = (-0.9 \pm 1.1) \times 10^{-2}$

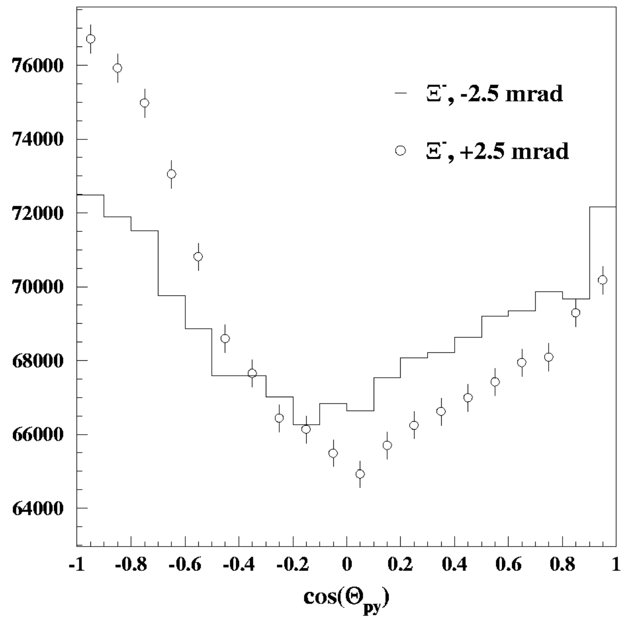
- (Background/Signal) is about 3×10^{-3}
  Contribution to uncertainty in α is $\leq 1.2 \times 10^{-4}$

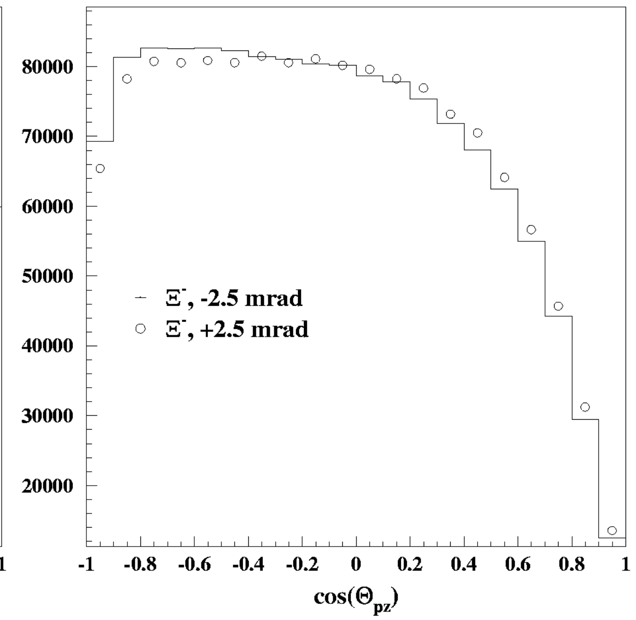
The data taken with polarized Ξ's provide important checks for systematic biases.

(Polarization is along the y-direction.)

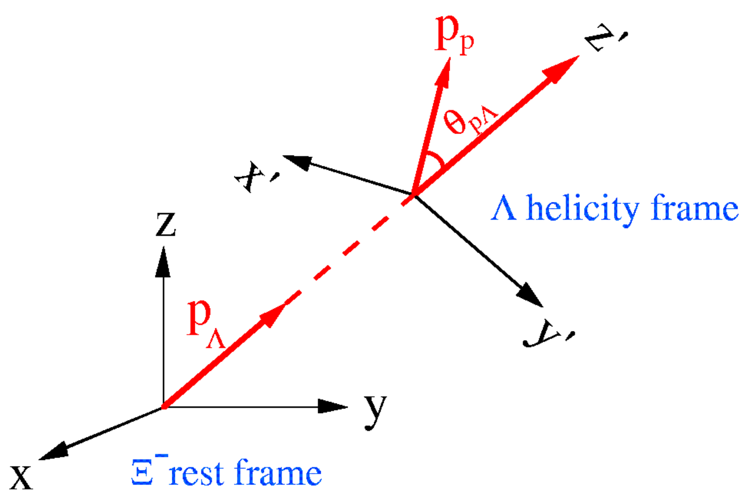


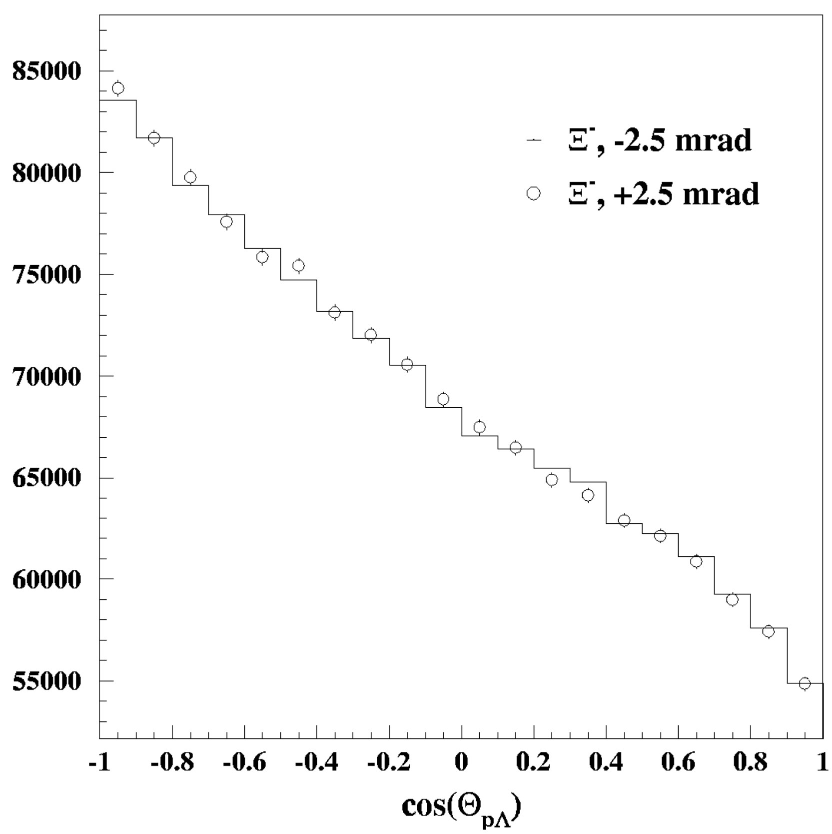






Geometric biases for the CP test are greatly reduced because the events are analyzed in the Λ helicity frame which changes for each event.



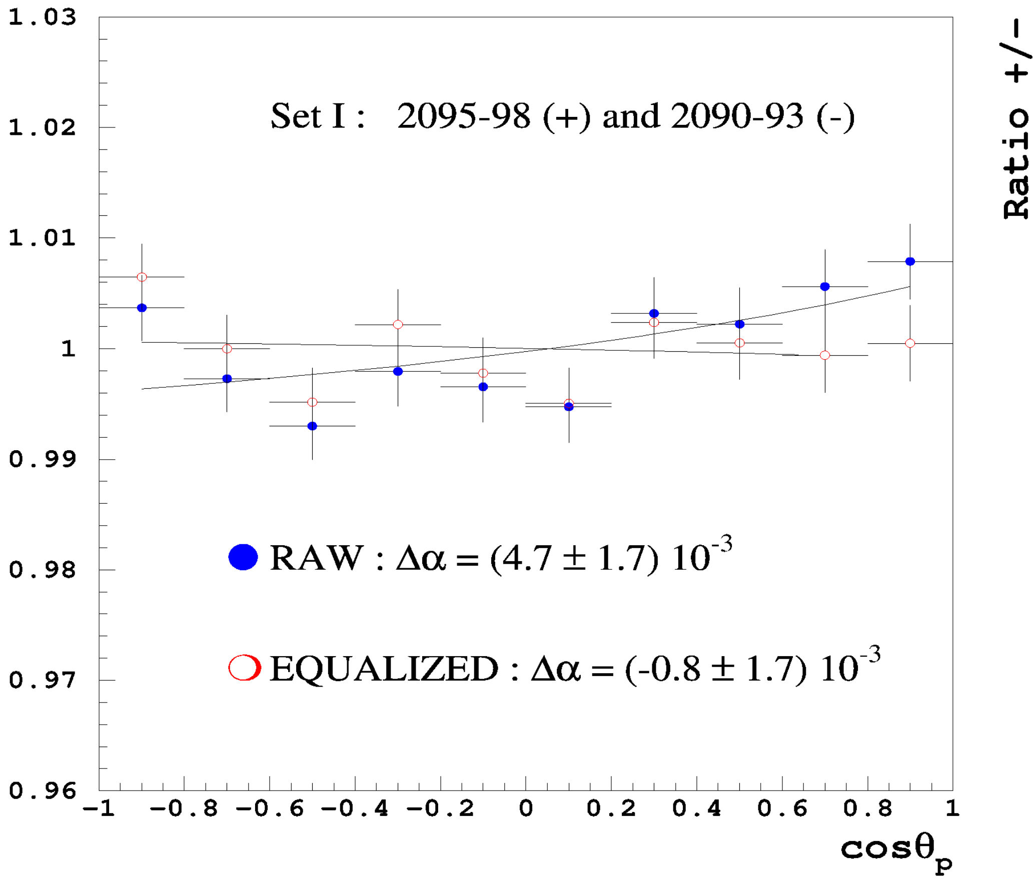


PRELIMINARY RESULTS

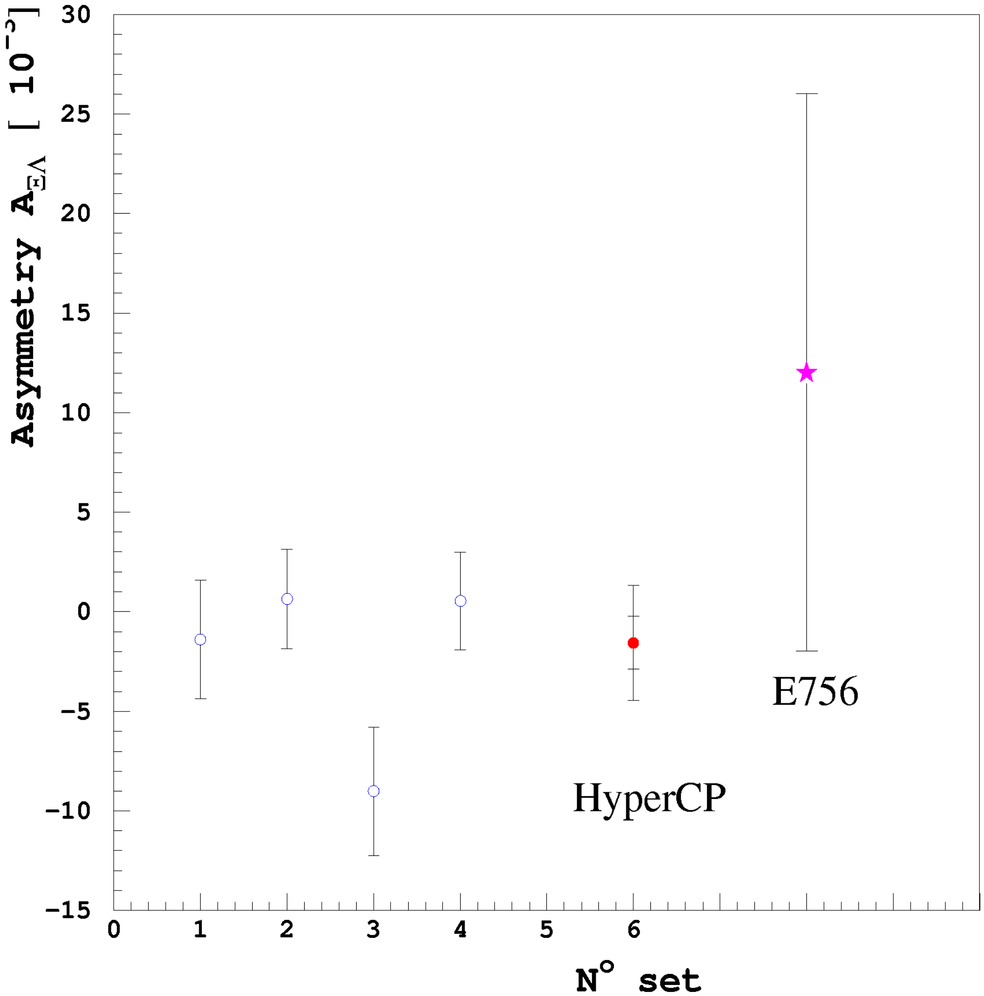
The data sets and the total number of events remaining after all cuts :

Set	$\overline{\Xi}^+$	Ξ^-	Nb. events of $\overline{\Xi}^+$	Nb. events of Ξ^-
I	2095 + 2098	2090 + 2093	1˙086˙878	11˙466˙695
II	2263 + 2264	2262 + 2265	1˙527˙962	14˙609˙278
III	2363 + 2365	2362	961˙351	7˙199˙146
IV	2371 + 2373 + 2374	2369	2˙288˙576	3˙895˙153

- **TOTAL :** $5.9 \times 10^6\ \overline{\Xi}^+$ **and** $37.2 \times 10^6\ \Xi^-$
  1.2 % ($\overline{\Xi}^+$) and 1.9 % (Ξ^-) of the data



Results of Ξ CP Test Study
(≈1.7% of total sample)



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

DiMuon Decays

Measurements of $B(K^{\pm} \to \pi^{\pm} \mu^{+} \mu^{-})$

- **To estimate the number of $K^+ \to \pi^+\mu^+\mu^-$ and $K^- \to \pi^-\mu^+\mu^-$, we used unbinned maximum likelihood fits:**

$$\mathcal{L} = e^{-(N_S+N_B)} \prod_{i=1}^{N} (N_S f_s(x_i) + N_B f_b(x_i))$$

N_S and N_B are number of signal and background.

x_i is an invarinat mass of event i.

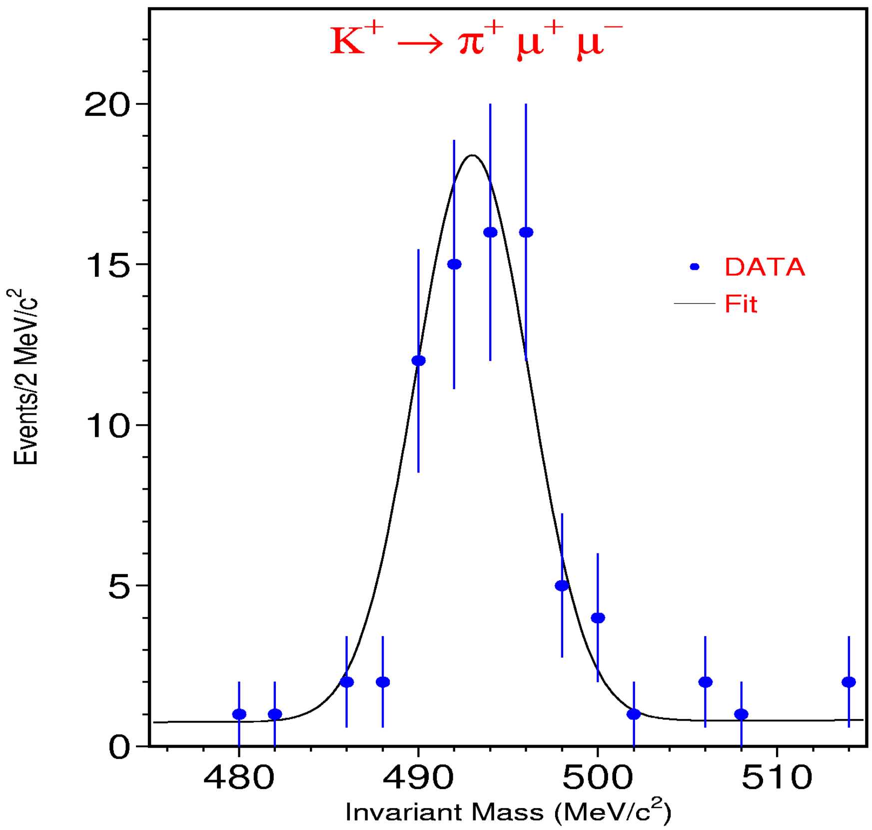
$$f_s(x_i) = \frac{1}{p(1)\sqrt{2\pi}} e^{-\frac{(p(2)-x_i)^2}{2p(1)^2}}$$

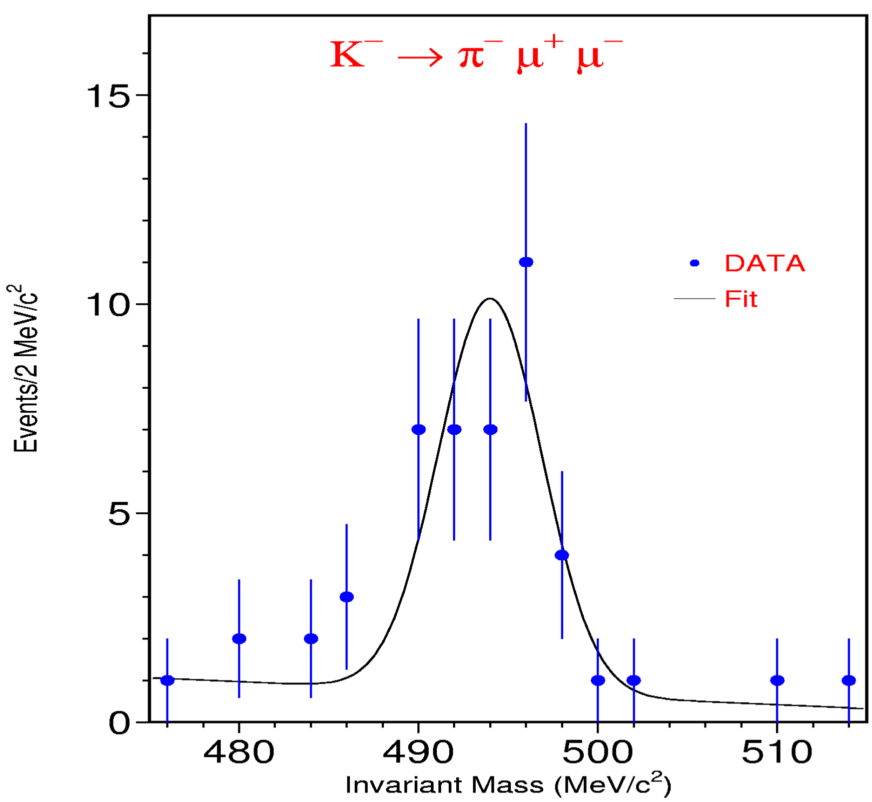
$$f_b(x) = c(p(3) + p(4)x_i)$$

- **From the fit, the number of signal events are obtained as follows:**

  No. of $K^+ \to \pi^+\mu^+\mu^-$: $70.28^{+9.45}_{-8.83}$

  No. of $K^- \to \pi^-\mu^+\mu^-$: $34.09^{+7.16}_{-6.39}$


$K^+ \rightarrow \pi^+ \mu^+ \mu^-$
DATA
Fit
Events/2 MeV/c^2
Invariant Mass (MeV/c^2)
0
5
10
15
20
480
490
500
510


$K^- \rightarrow \pi^- \mu^+ \mu^-$
DATA
Fit
Events/2 MeV/c^2
Invariant Mass (MeV/c^2)
0
5
10
15
480
490
500
510

Preliminary Results

$$B(K^+ \to \pi^+\mu^+\mu^-) = (9.1^{+1.2}_{-1.2} \pm 0.5) \times 10^{-8}$$

$$B(K^- \to \pi^-\mu^+\mu^-) = (8.5^{+1.8}_{-1.6} \pm 0.6) \times 10^{-8}$$

Combined Result: $(8.9 \pm 1.0 \pm 0.5) \times 10^{-8}$

CP asymmetry in $K^+ \to \pi^+\mu^+\mu^-$ and $K^- \to \pi^-\mu^+\mu^-$ decays:

$$\Delta_{K^+\to\pi^+\mu^+\mu^-} = \frac{B(K^+\to\pi^+\mu^+\mu^-) - B(K^-\to\pi^-\mu^+\mu^-)}{B(K^+\to\pi^+\mu^+\mu^-) + B(K^-\to\pi^-\mu^+\mu^-)}$$

$$\Delta_{K^+\to\pi^+\mu^+\mu^-} = 0.03 \pm 0.12 \pm 0.05$$

Decays into like-sign dimuons – rough estimates of eventual upper limits

Decay Mode	No. of Obs.	A	ϵ_{cut}	No. of Normal.
$K^+ \to \pi^-\mu^+\mu^+$	4	0.32	0.56	$\sim 3.8 \times 10^9$
$\Sigma^- \to p\mu^-\mu^-$	1	0.03	0.63	$\sim 1.6 \times 10^{10}$
$\Xi^- \to p\mu^-\mu^-$	0	0.11	0.33	$\sim 6.5 \times 10^9$

$$B(K^+ \to \pi^-\mu^+\mu^+) < \quad \sim 6.7 \times 10^{-8}$$

$$B(\Sigma^- \to p\mu^-\mu^-) < \quad \sim 1.1 \times 10^{-8}$$

$$B(\Xi^- \to p\mu^-\mu^-) < \quad \sim 1.0 \times 10^{-8}$$