Search for CP Violation in Hyperon Decays

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Heavy Quarks and Leptons 2002

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Nonleptonic Hyperon Decays

The parity violating decay of a spin-$\frac{1}{2}$ hyperon

$$Y_{1/2} \to B_{1/2} + \pi$$

proceeds through a mixture of S and P waves.

Three observables;

- Partial rate: $\Gamma \propto |S|^2 + |P|^2$ and
- Decay Parameters:

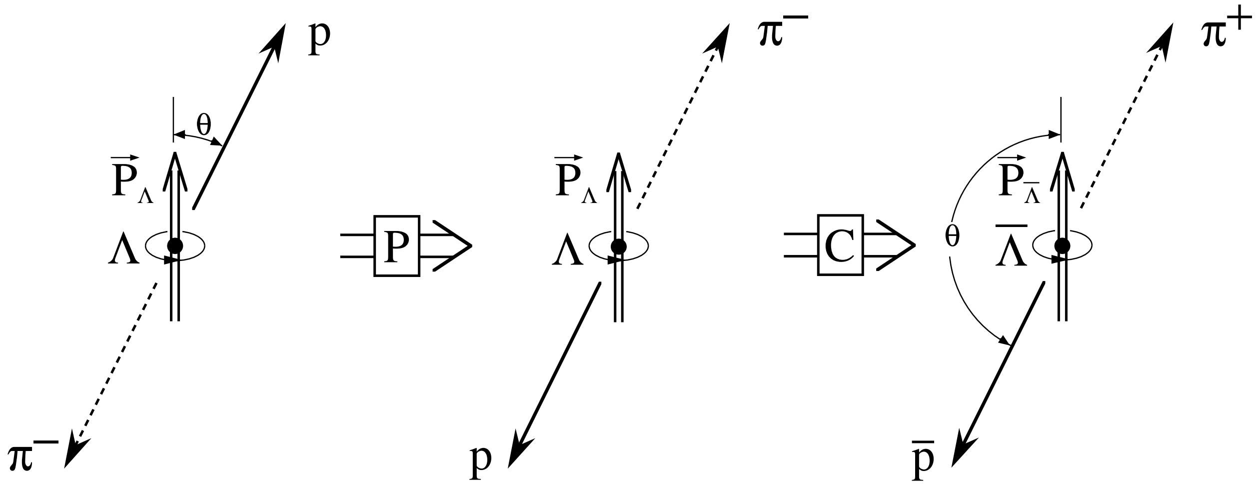
$$\alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2 + |P|^2} \qquad \beta = \frac{2\mathrm{Im}(S^*P)}{|S|^2 + |P|^2} \qquad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

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

A Signature for CP Violation in $\Lambda \to p\pi$

- Parity violation: $\frac{d\mathrm{N(p)}}{d\cos\theta} = \frac{\mathrm{N_0}}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta)$.

- Under CP transformation: $\alpha_\Lambda \quad \Longrightarrow \quad \alpha_{\overline{\Lambda}} = -\alpha_\Lambda$



CP is violated if the slope of the proton $\cos\theta$ distribution is not the exact negative of the slope of the antiproton distribution *for Λ and $\overline{\Lambda}$ having equal polarization.*

Searches for CP Violation in $\Lambda \to p\pi$

- Require known polarization, *e.g.* $\mathbf{P}_\Lambda = \mathbf{P}_{\overline{\Lambda}}$
- Define asymmetry $A_\Lambda = \dfrac{\alpha_\Lambda + \alpha_{\overline{\Lambda}}}{\alpha_\Lambda - \alpha_{\overline{\Lambda}}}$

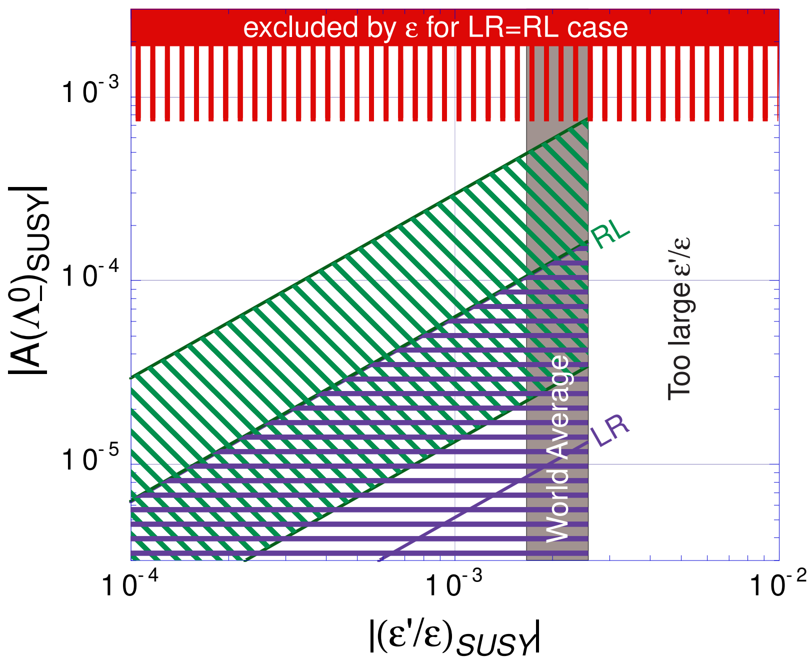
Method	Limit	Exp.	Date
$p\overline{p} \to \Lambda X$, $p\overline{p} \to \overline{\Lambda} X$	-0.02 ± 0.14	R608	1985
$e^+e^- \to \mathrm{J}/\psi \to \Lambda\overline{\Lambda}$	0.01 ± 0.10	DM2	1988
$p\overline{p} \to \Lambda\overline{\Lambda}$	0.010 ± 0.022	PS185	1998

None of these measurements constrain theory

Theoretical Predictions

- Hyperon *CP*V different from Kaon *CP*V.
- Simple form: $A \approx \tan(\delta_p - \delta_s)\sin(\phi_p - \phi_s)$

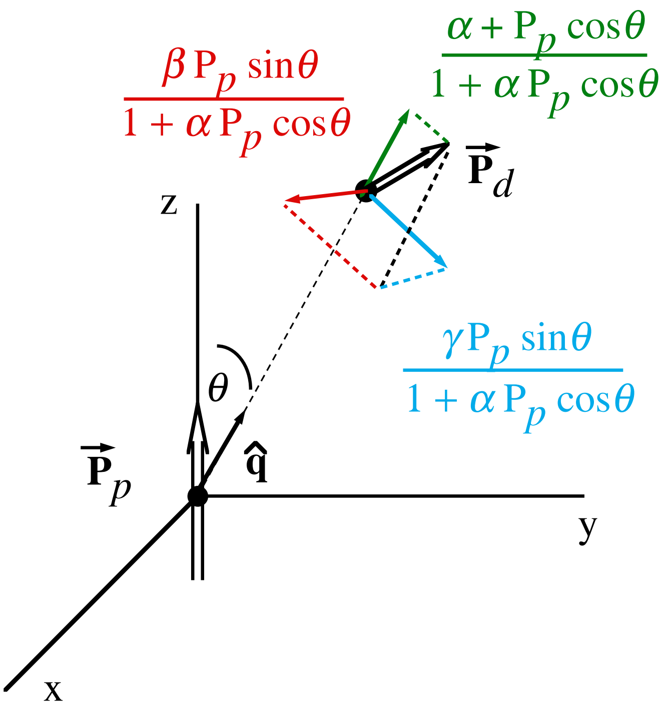
Model	A_Ξ $[10^{-4}]$	A_Λ $[10^{-4}]$
SM (CKM)	-0.04	-0.4
L-R-S (with mixing)	1	6
SUSY	–	10



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

Producing Λ's of Known Polarization

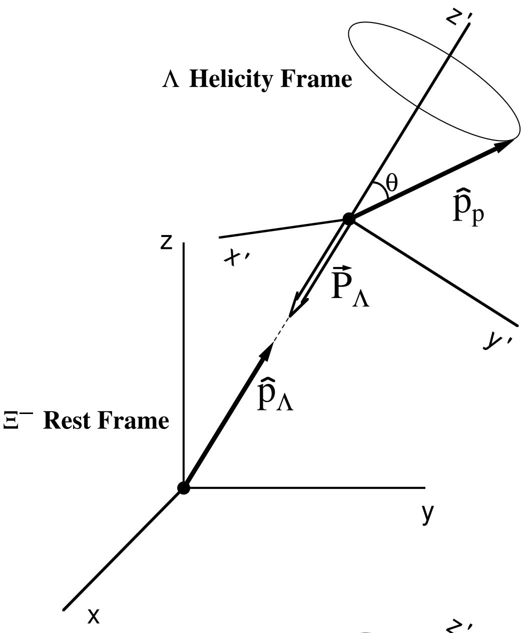
Λ's are polarized in $\Xi \to \Lambda\pi$ decay.



For *unpolarized* Ξ (*i.e.* produced w/ $P_T = 0$),

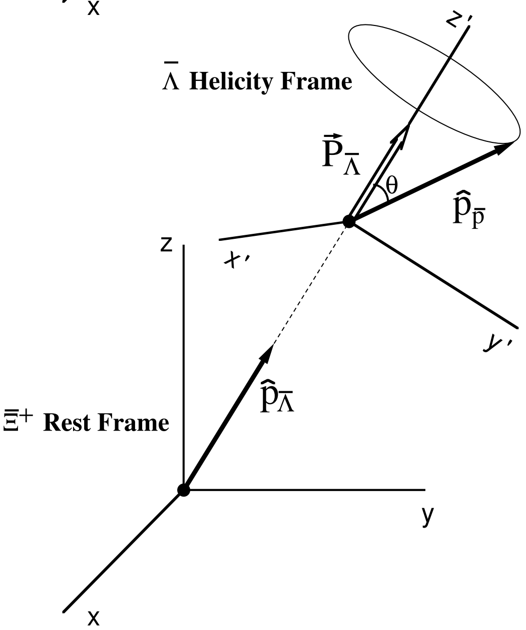
$$\boxed{\vec{\mathbf{P}}_\Lambda = \alpha_\Xi \hat{\mathbf{p}}_\Lambda \qquad \vec{\mathbf{P}}_{\overline{\Lambda}} = \alpha_{\overline{\Xi}} \hat{\mathbf{p}}_{\overline{\Lambda}}}$$

If CP conserved then unpolarized Ξ^- and $\overline{\Xi}^+$ decays appear identical



$$\boxed{\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-}$$

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

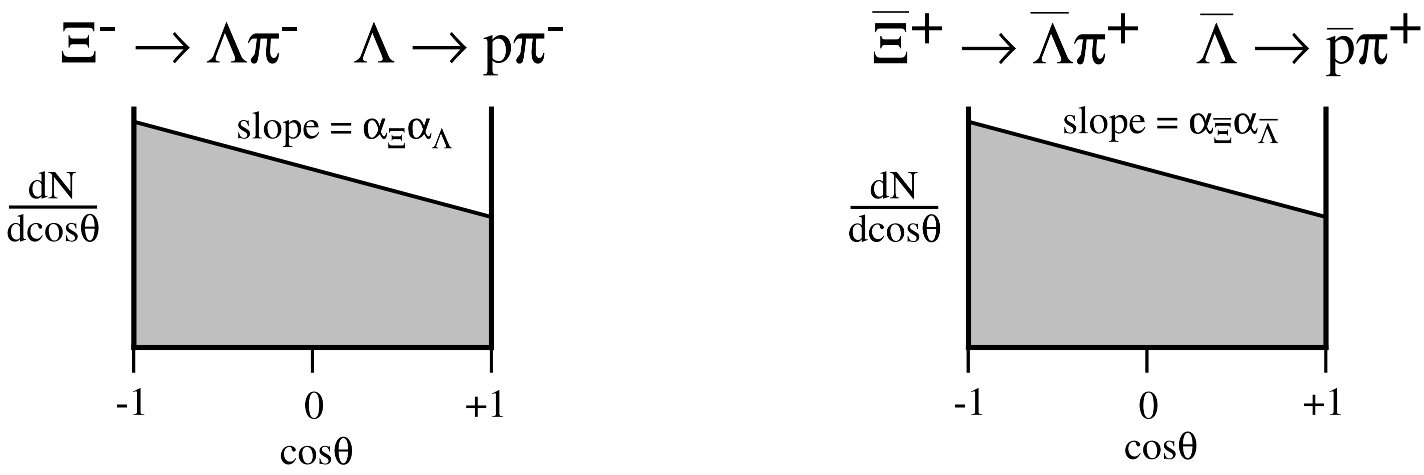


$$\boxed{\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \overline{p}\pi^+\pi^+}$$

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

CP Asymmetry in $\Xi \rightarrow \Lambda\pi \rightarrow p\pi\pi$

Experimentally measure the difference in slope of the p and $\overline{p}$ cos(θ) distributions.



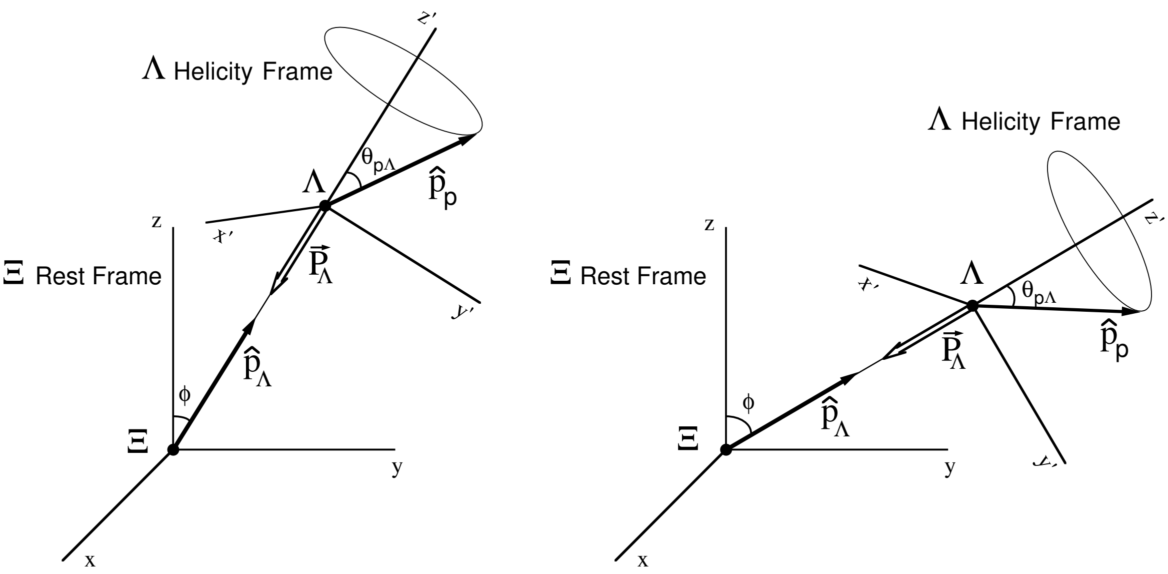
$$\boxed{A_{\Xi\Lambda} \equiv \frac{\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}}{\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}} \approx A_\Xi + A_\Lambda}$$

Previous measurements of $A_{\Xi\Lambda}$

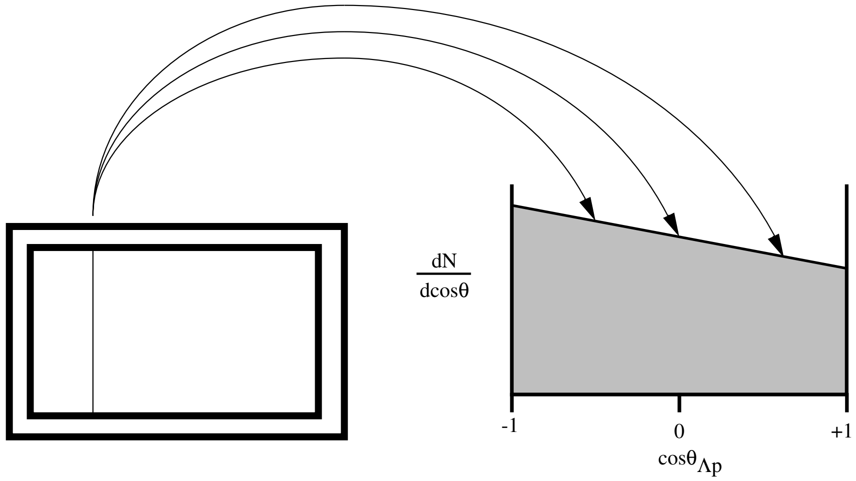
Method	Limit	Exp	Date
pN $\rightarrow \Xi\pi \rightarrow \Lambda\pi \rightarrow p\pi\pi$	0.012 ± 0.014	E756	2000

Helicity Frame Analysis Minimizes Biases

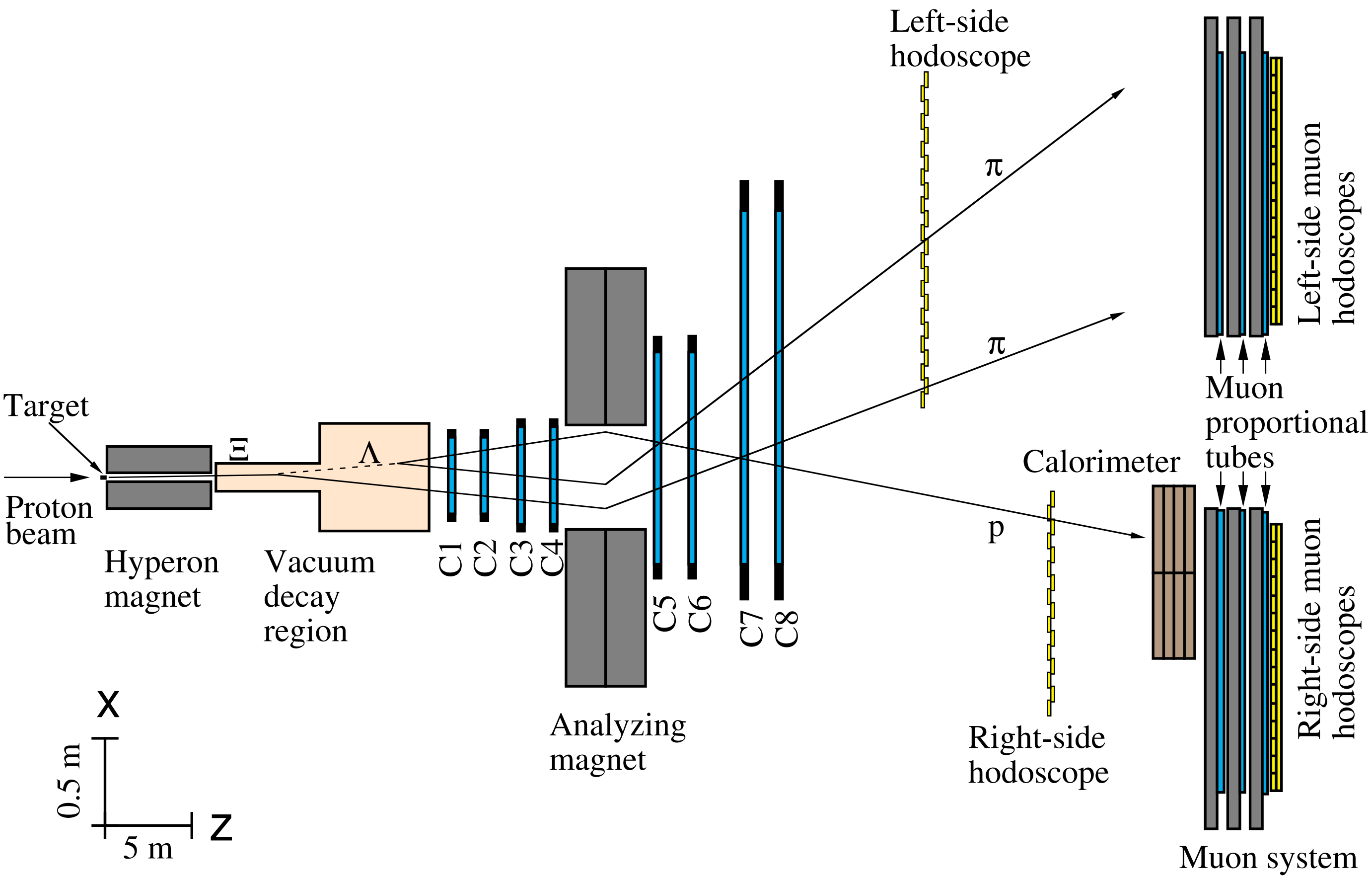
Helicity axis varies from event to event.



Localized inefficiencies diluted in cos(θ) distribution.



The HyperCP Spectrometer



- 8 fast, low-gain, narrow-pitch wire chambers.
- Very high-rate DAQ: up to 27 MB/s to tape.
- Low-bias trigger using hodoscopes and calorimeter.
- Muon system for rare hyperon and kaon decays.
- 8GHz protons $\Longrightarrow$ 10–15 MHz channeled beam.

HyperCP Yields

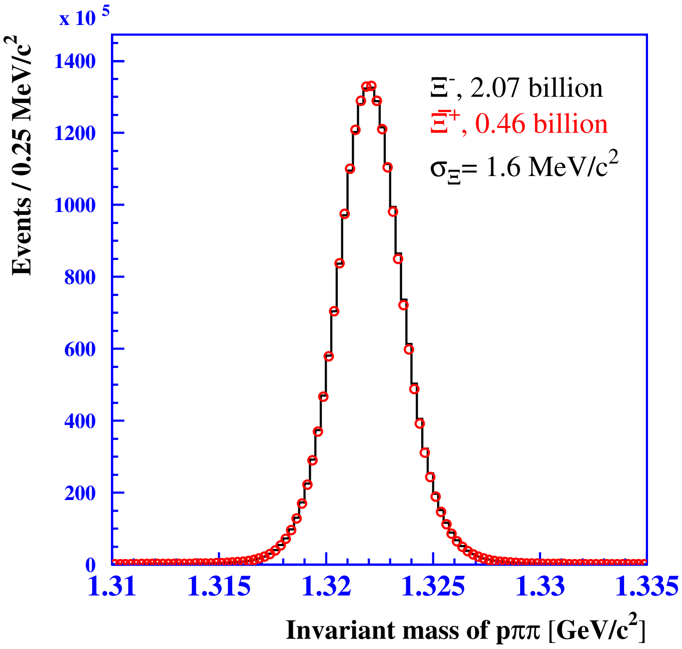
- 2.3×10^{11} events collected in 1997 and 1999 runs.

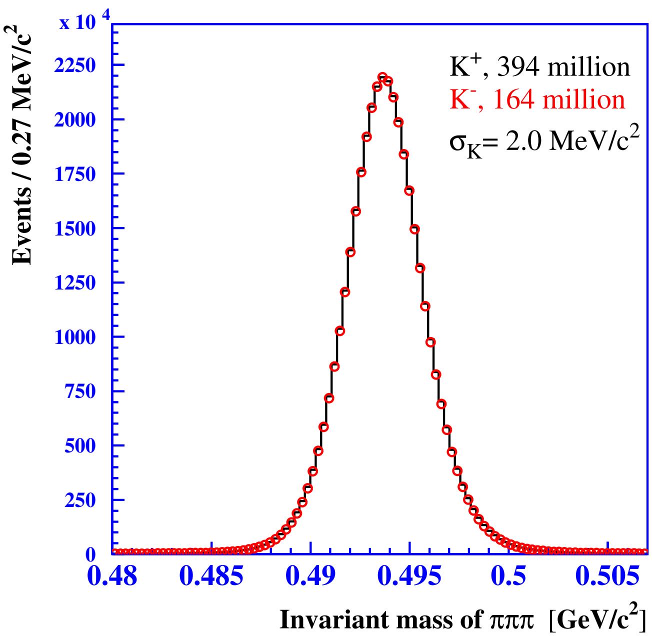
Number of Reconstructed Events		
Type	Channeled beam polarity +	Channeled beam polarity −
$\Xi \to \Lambda\pi$	0.46×10^9	2.0×10^9
$K \to \pi\pi\pi$	391×10^6	164×10^6
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6

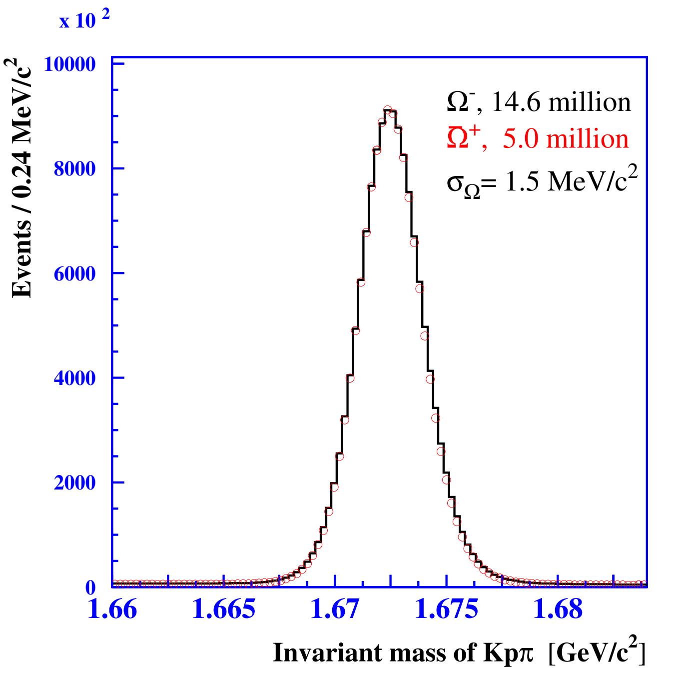
- Expect a statistical precison of:

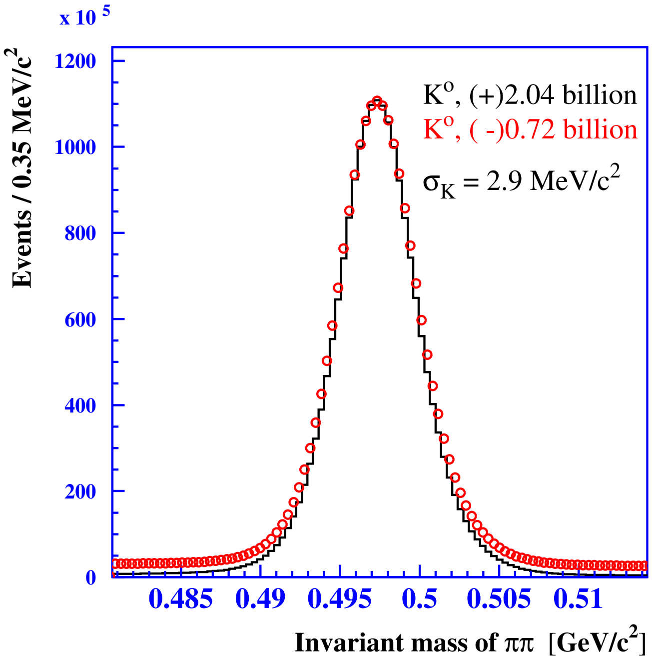
$$\boxed{\delta A_{\Xi\Lambda} \approx 2 \times 10^{-4}}$$

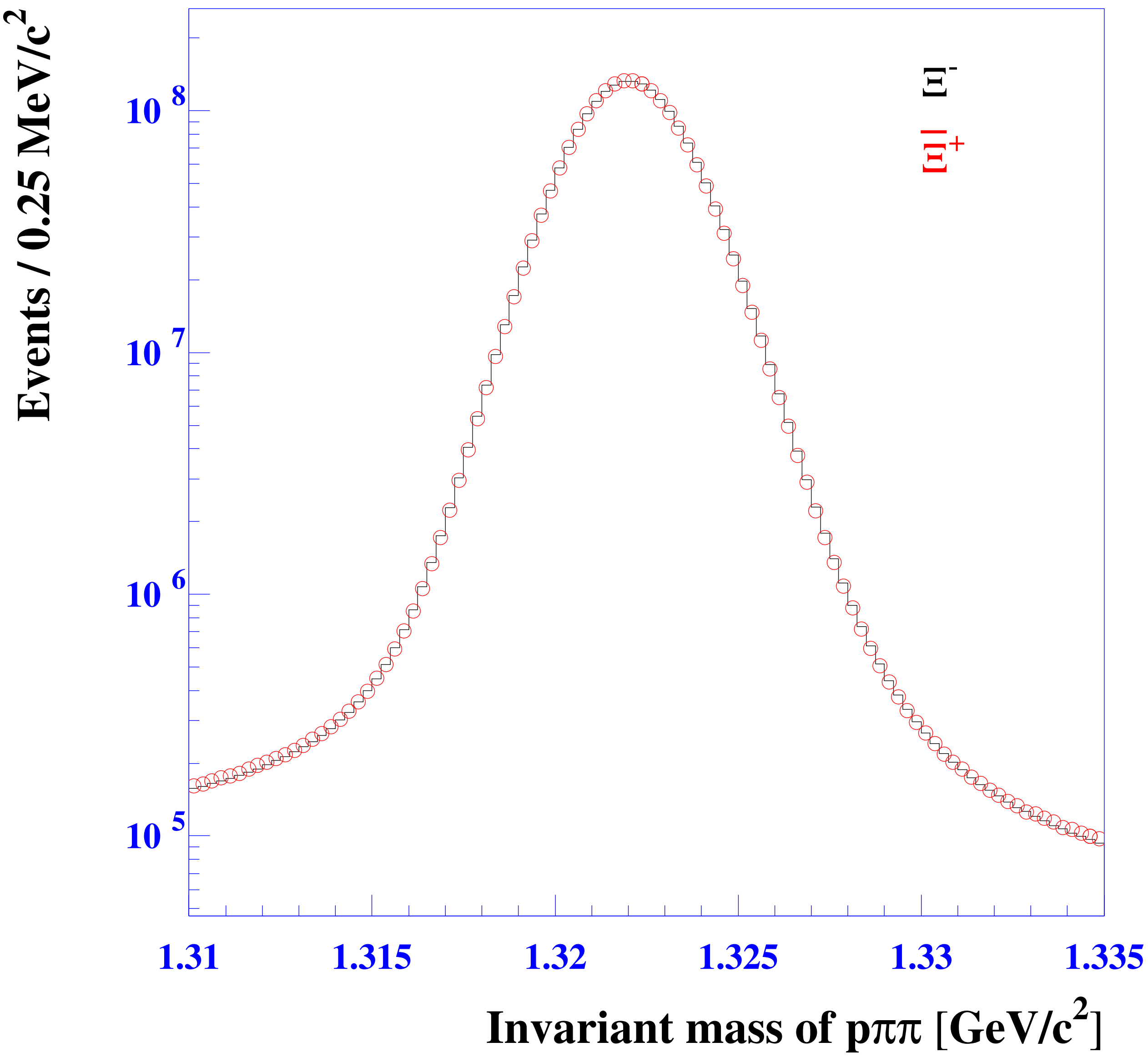
Masses from the Farm Processing





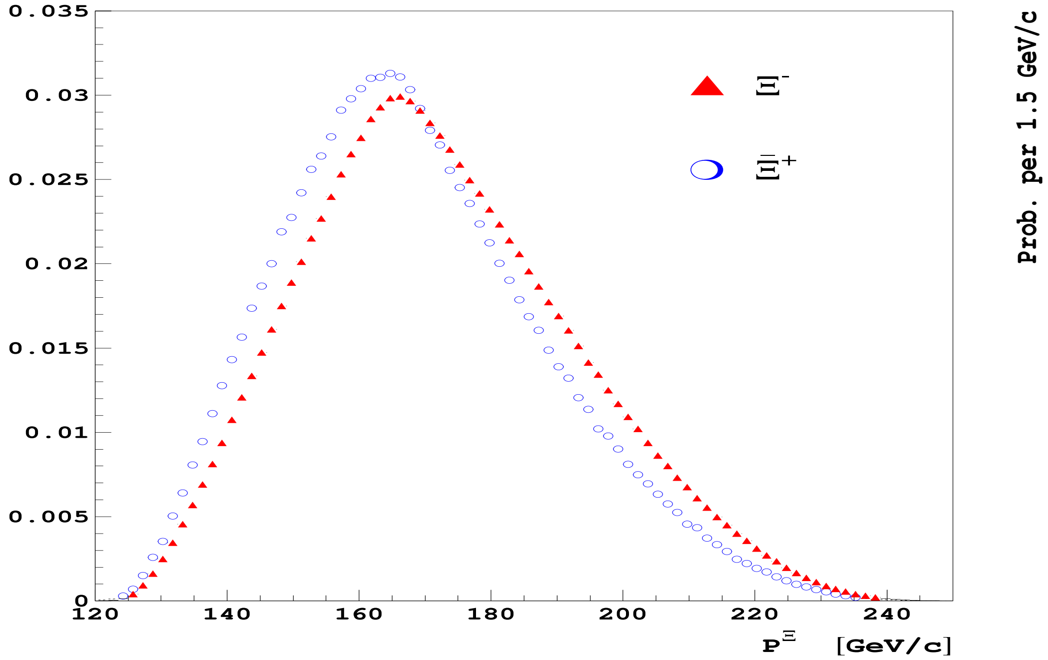


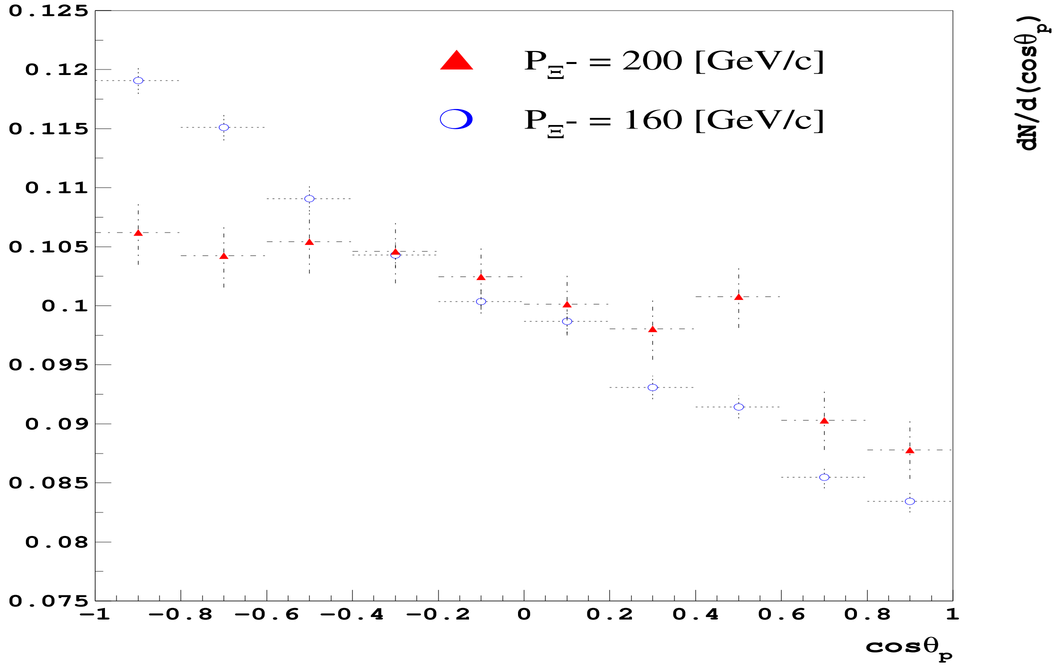




Events / 0.25 MeV/c^2
10^8
10^7
10^6
10^5
1.31
1.315
1.32
1.325
1.33
1.335
Invariant mass of p$\pi\pi$ [GeV/c^2]
Ξ^-
$\bar{\Xi}^+$

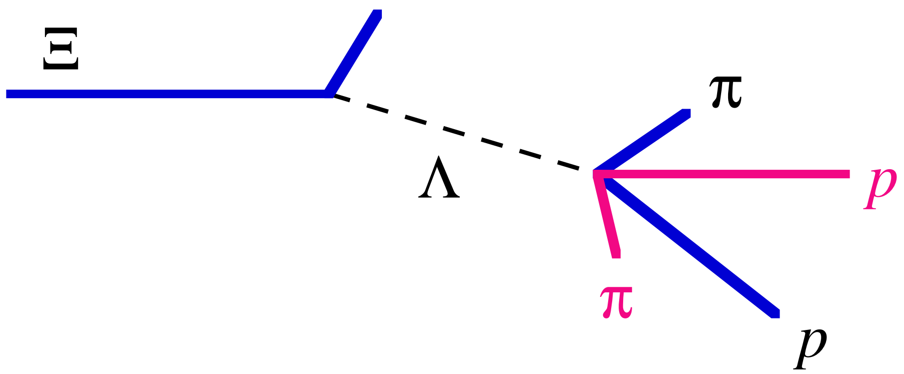
DIFFERENCES IN PRODUCTION BETWEEN Ξ^- AND $\overline{\Xi}^+$





Hybrid Monte Carlo (HMC) Method

Real $\Lambda \to p\pi$ vertex replaced by a Monte Carlo decay which is generated uniform in $\cos(\theta_{p\Lambda})$.

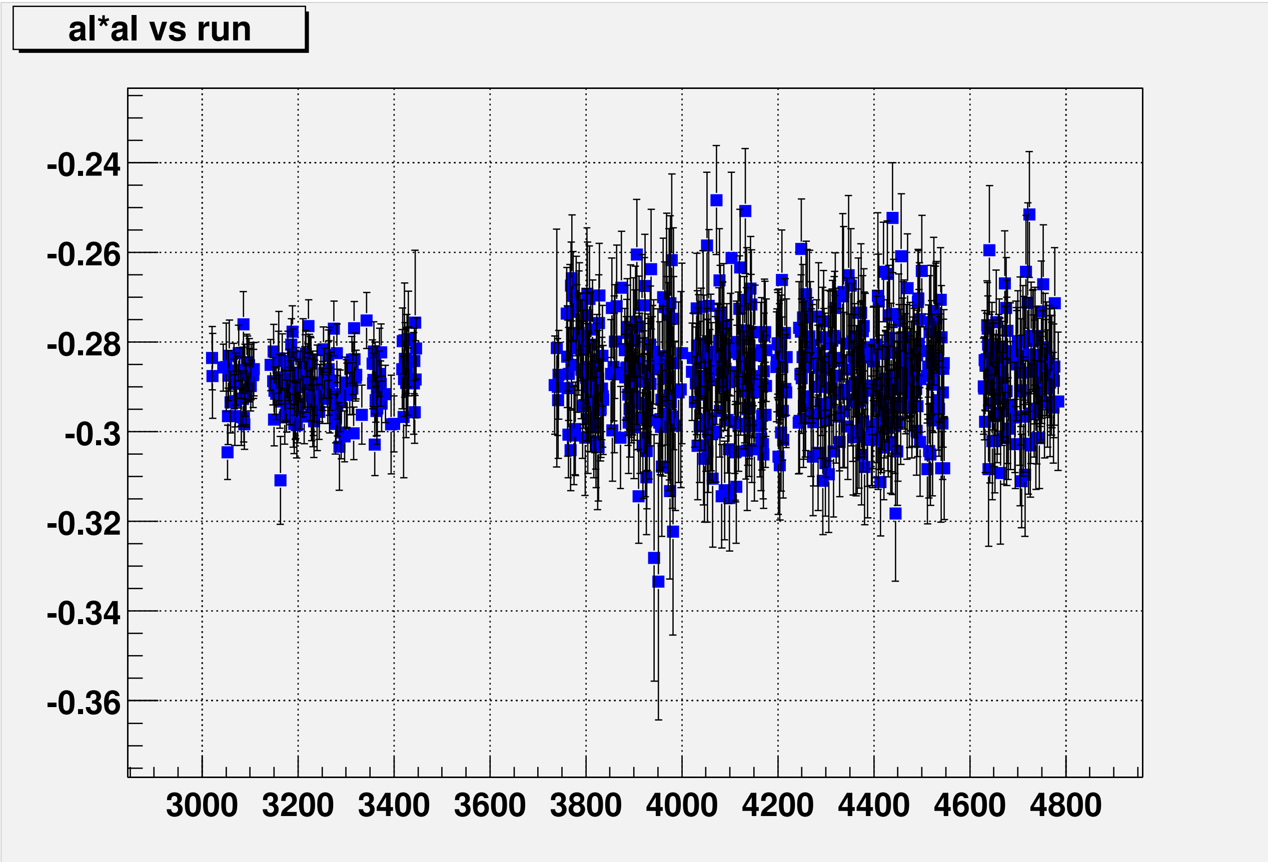


HMC events are subjected to the same effects as real events, *e.g.* detection efficiency, multiple scattering, reconstruction,,,

HMC events are weighted by $W(\alpha_\Xi \alpha_\Lambda)$ in which $\alpha_\Xi \alpha_\Lambda$ is varied to match the real $\cos(\theta_{p\Lambda})$ distribution.

Stability of $\alpha_\Xi \alpha_\Lambda$ vs run

Data: 15×10^6 Ξ^- and 30×10^6 Ξ^+ randomly selected during reconstruction



Average: $\alpha_\Xi \alpha_\Lambda = -0.2880 \pm 0.0004$

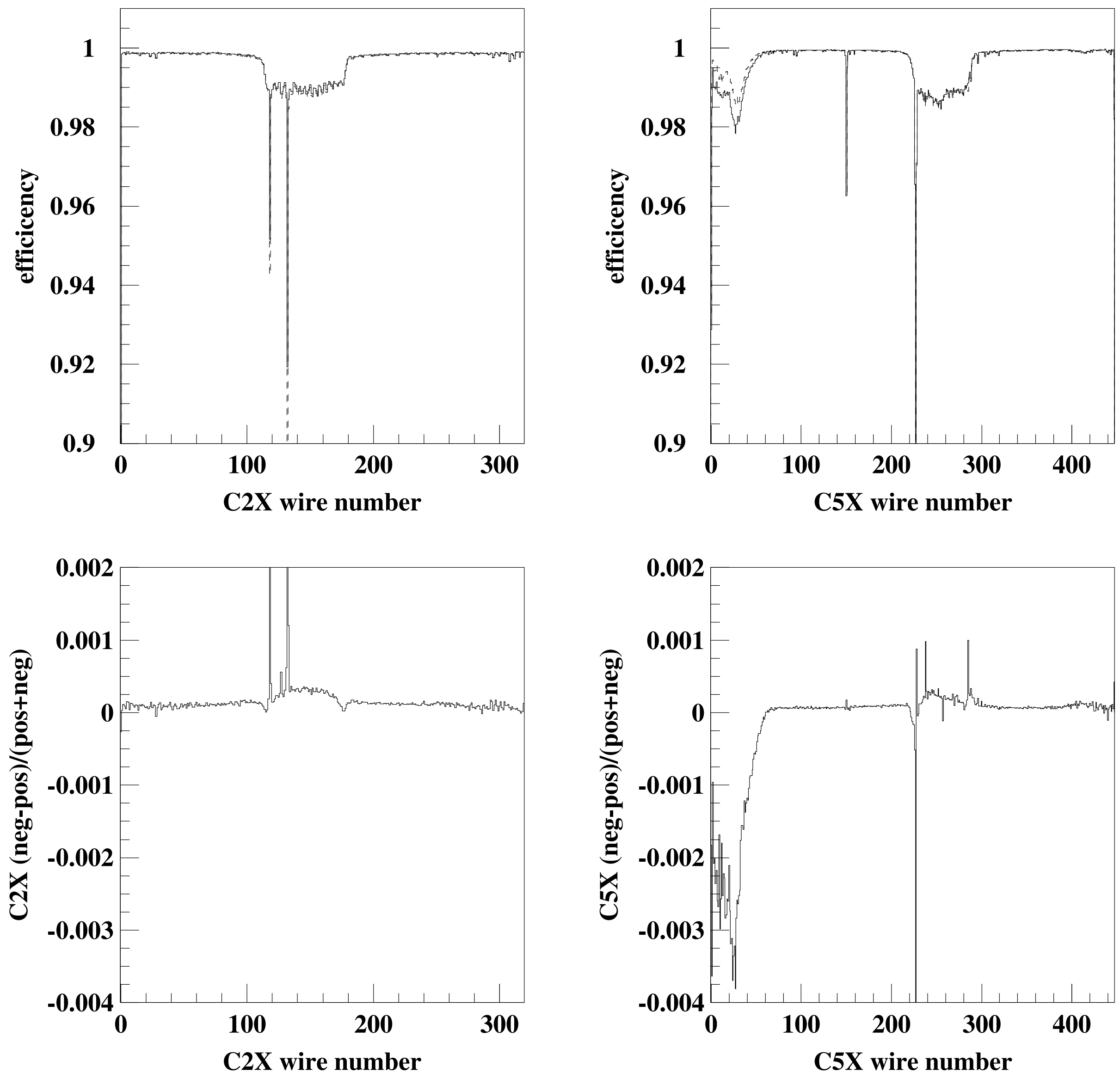
$(\mathrm{PDG}: -0.294 \pm 0.005)$

Potential Sources of Systematic Uncertainties

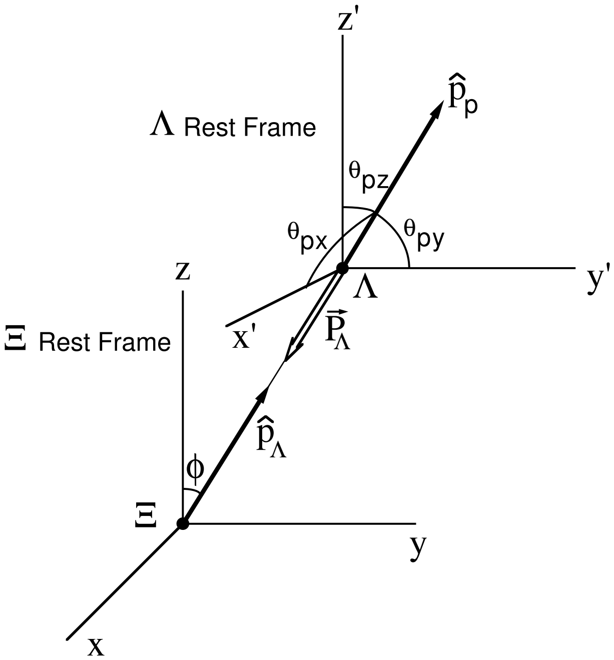
- Difference in $\Xi^-/\overline{\Xi}^+$ polarization
- Difference in channeled beam rate
- Asymmetry between Ξ^- and $\overline{\Xi}^+$ background
- Uncertainty in trigger inefficiency
- Uncertainty in MWPC inefficiency
- Uncertainty in B–field of analyzing magnet
- Differences between anti/particle interactions

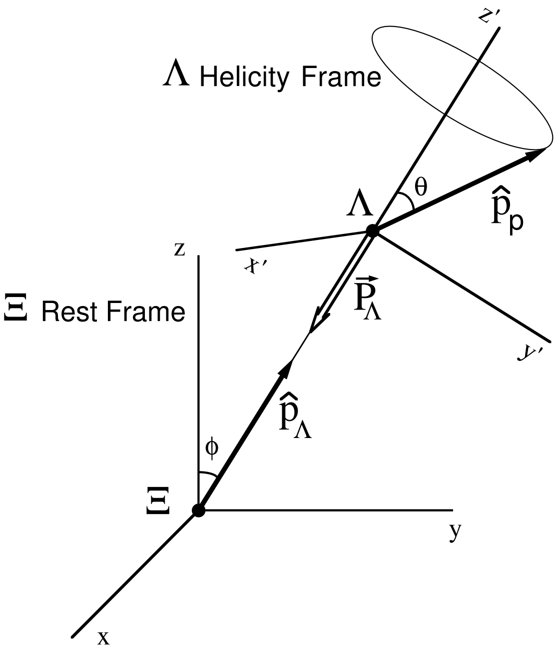
Effect of uncertainty in PWC efficiency:

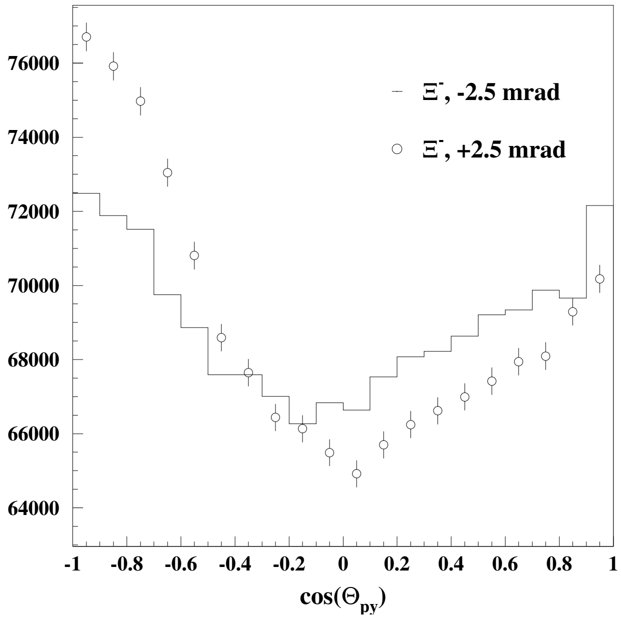
$$\delta A_{\Xi\Lambda} = 1.7 \times 10^{-4}$$

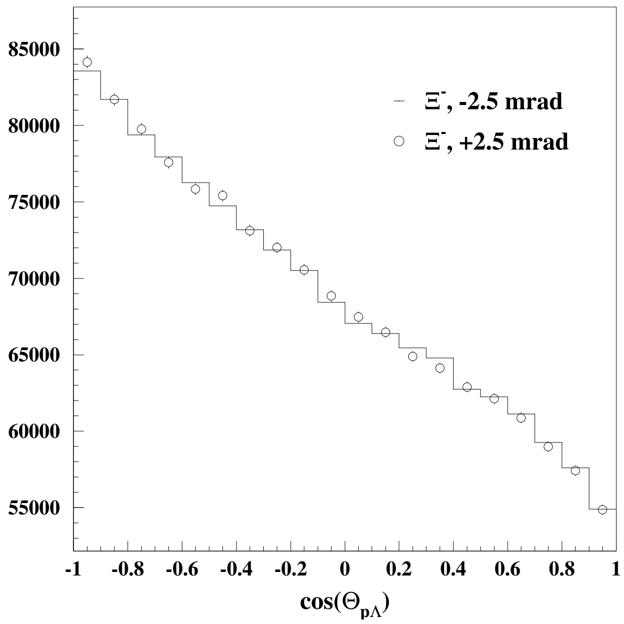


Effect of Polarization: Ξ at ± 2.5mrad









From larger data sample : $\delta A_{\Xi\Lambda} = 0.4 \times 10^{-4}$

Summary of Systematic Uncertainties

The uncertainties are established using **data**.
Limited by the sample size: 15M Ξ^- and 30M $\overline{\Xi}^+$.

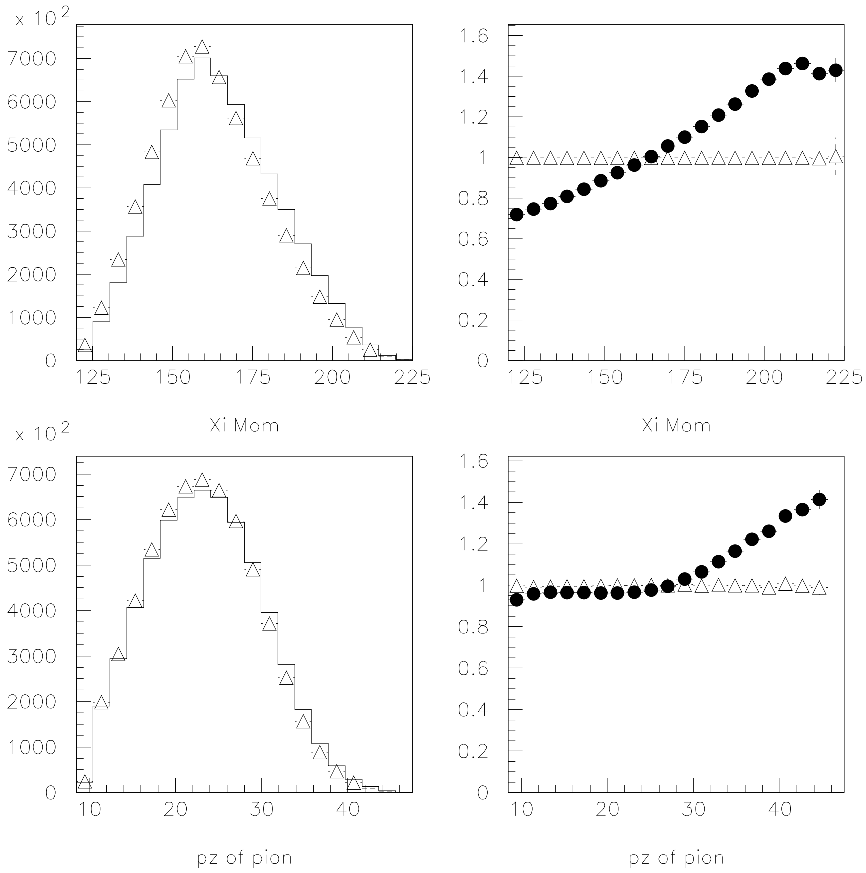
Source	$\delta A_{\Xi\Lambda}$ $[10^{-4}]$
Polarization	0.4
Rate dependence	3.4
Background	2.4
Hodoscope Eff.	1.7
Calorimeter Eff.	1.8
PWC Efficiency	2.7
B field	2.2
Interactions	0.5
TOTAL	6.2

Preliminary:

$$A_{\Xi\Lambda} = [-7 \pm 12\,(\text{stat.}) \pm 6.2\,(\text{sys.})] \times 10^{-4}$$

Alternative Weighting Method

$\overline{\Xi}^{+}$ and Ξ^{-} data sets are weighted to match 5–tuple describing Ξ position and momentum at collimator.

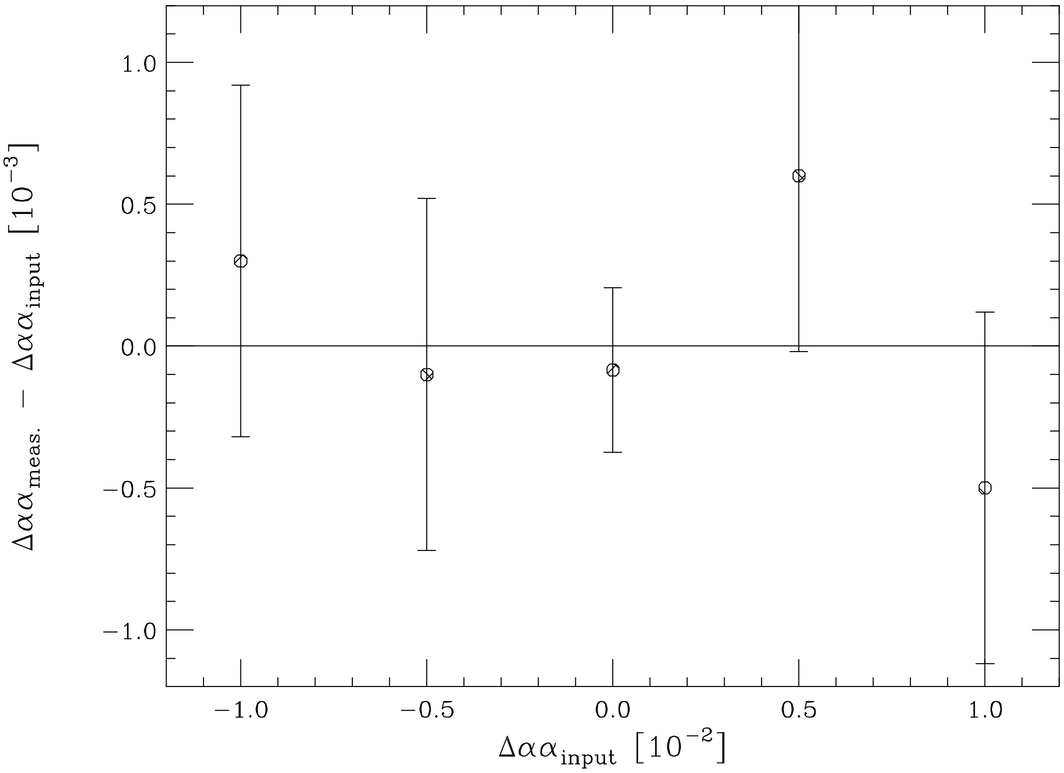


Data sample: $6 \times 10^{6}\, \Xi^{-}$ and $3 \times 10^{6}\, \overline{\Xi}^{+}$.

Effect of weighting on asymmetry tested with Monte Carlo Ξ decays overlayed on real data.

Before weighting: $\Delta\alpha\alpha_{\mathrm{meas.}} - \Delta\alpha\alpha_{input} > 10\sigma$.

Weighting removes bias caused by production but preserves signal.



Conclusions

- A preliminary limit on CP asymmetry in $\Xi - \Lambda$ decays from a small fraction of the data:

$$A_{\Xi\Lambda} = [-7 \pm 12\,(\mathrm{stat.}) \pm 6.2\,(\mathrm{sys.})] \times 10^{-4}$$

  – an order of magnitude better than the current limit.

- The projected statistical sensitivity from the full data sample is $\sim 2 \times 10^{-4}$, within range of some theoretical predictions. Current systematic uncertainties are expected to scale down with the sample statistics.

- The large samples of Ξ, Ω and K decays permit a variety of precision measurements and rare decay searches