Search for direct CP violation in hyperon decays

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FRONTIERS IN CONTEMPORARY PHYSICS - II
Vanderbilt University
March 6, 2001

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NONLEPTONIC HYPERON DECAYS

- **Parity violating, $\Delta S = 1$ decay of a spin-$\frac{1}{2}$ strange baryon into a spin-$\frac{1}{2}$ baryon and a pion, e.g.**

$$\Lambda \to \mathrm{p}\ \pi$$

is described by the decay amplitude

$$\mathcal{M}(\Lambda \to \mathrm{p}\ \pi) = S + P\,\vec{\sigma}\cdot\widehat{q}_p$$

S **is the amplitude of the S-wave final state**
P **is the amplitude of the P-wave final state**
$\widehat{q}_p$ **is the momentum unit vector of the proton**

- **In the rest frame of the Λ**
the angular distribution of the proton

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

where $\vec{\mathcal{P}}_\Lambda$ is the polarization of Λ
and the decay parameter α is defined as

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

CP IN HYPERON DECAYS

- **If CP is conserved**

$$\alpha_{\overline{\Lambda}} = -\alpha_\Lambda$$

- **One can form a CP violating asymmetry**

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

- **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	$pp \to \Lambda X, pp \to \bar{\Lambda} X$	-0.02 $\pm$ 0.14
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	0.01 $\pm$ 0.10
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	-0.013 $\pm$ 0.022

- **Search for direct CP violation in Ξ and Λ decay sequence**

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

Hyper$\mathcal{CP}$ APPROACH

- **Produce Ξ^- and $\overline{\Xi}^+$ baryons with 800 GeV protons at 0 mrad**

$$p + N \rightarrow \Xi^- + X \qquad\qquad p + N \rightarrow \overline{\Xi}^+ + X$$

- **With unpolarized Ξ^- and $\overline{\Xi}^+$, in their decay**

$$\Xi \rightarrow \Lambda\, \pi$$

daughter Λ acquires longitudinal polarization

$$\vec{\mathcal{P}}_\Lambda \;=\; \alpha_\Xi \cdot \hat{q}_\Lambda$$

- **In Λ rest frame the angular distribution of proton from $\Lambda \rightarrow p\pi$ is**

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

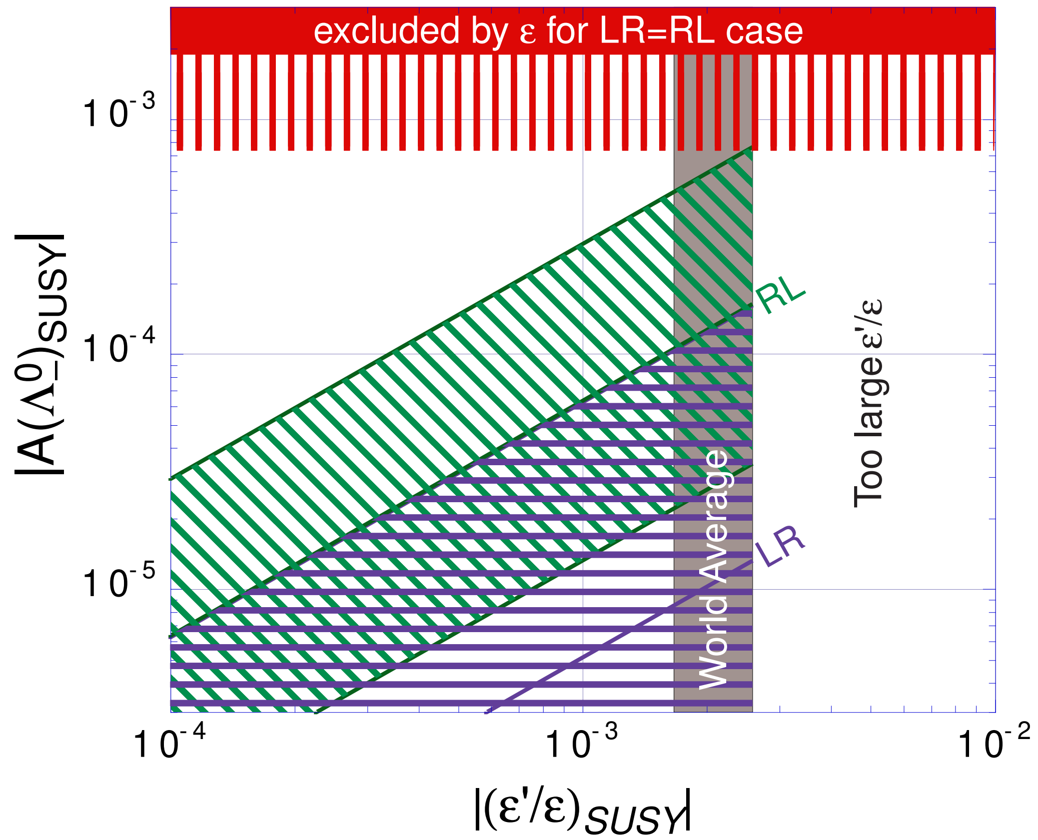
- **Measure asymmetry**

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

with 1×10^{-4} precision

THEORETICAL PREDICTIONS

	$\lvert A_\Lambda \rvert$ (10^{-4})	$\lvert A_\Xi \rvert$ (10^{-4})
Left-Right	$(0.1, 6)$	$(2, 6)$
CKM	$(0.1, 0.5)$	$(0.05, 1)$
SUSY	$(0.2, 8)$	-

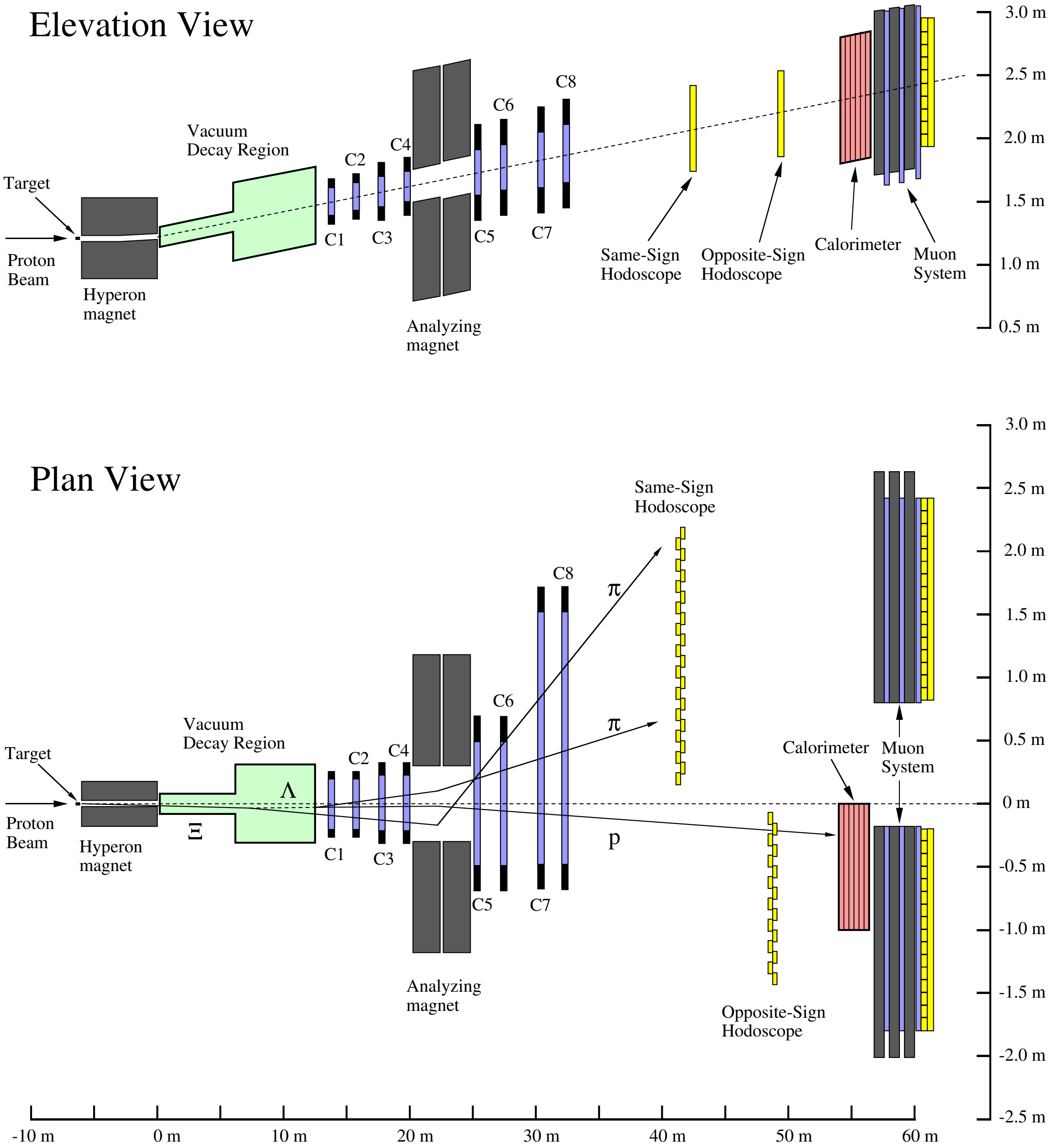


He *et al*, Phys. Rev. D61:071701, 2000

DIRECT ΔS=1 CP VIOLATION IN KAON AND HYPERON DECAYS

$\epsilon^{'}/\epsilon$	$\mathbf{A}_{\Lambda\Xi}$
Pure S-wave decay: probes only parity-violating amplitudes	**Probes interference between parity-violating and conserving amplitudes. Sensitive to new physics in parity-conserving channel**
Large cancellation between electroweak and strong penguin diagrams at large top mass	**No such cancellation**
Large uncertainty in hadronic matrix elements	**Somewhat smaller uncertainty that could be narrowed by measurement of $\Lambda\pi$ phase shifts $(\delta_S - \delta_P)$ at E=$\mathbf{M}_{\Xi}$**

The HyperCP Spectrometer



There were minor differences between 97 and 99 runs

STATISTICS
OF THE 1997 AND 1999 RUNS

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

Projected number of reconstructed events

Ξ^-	2×10^9
$\overline{\Xi}^+$	0.5×10^9
K^+	0.40×10^9
K^-	0.16×10^9
Ω^-	14×10^6
$\overline{\Omega}^+$	5.3×10^6

$\delta(A_{\Xi\Lambda}) \; = \; 1.4 \times 10^{-4}$ statistical precision

CURRENT STATUS

- Established consistent alignments of spectrometer for the 1997 and 1999 runs

- Finished processing 1999 data using Fermilab Farms. Started reprocessing the 1997 data

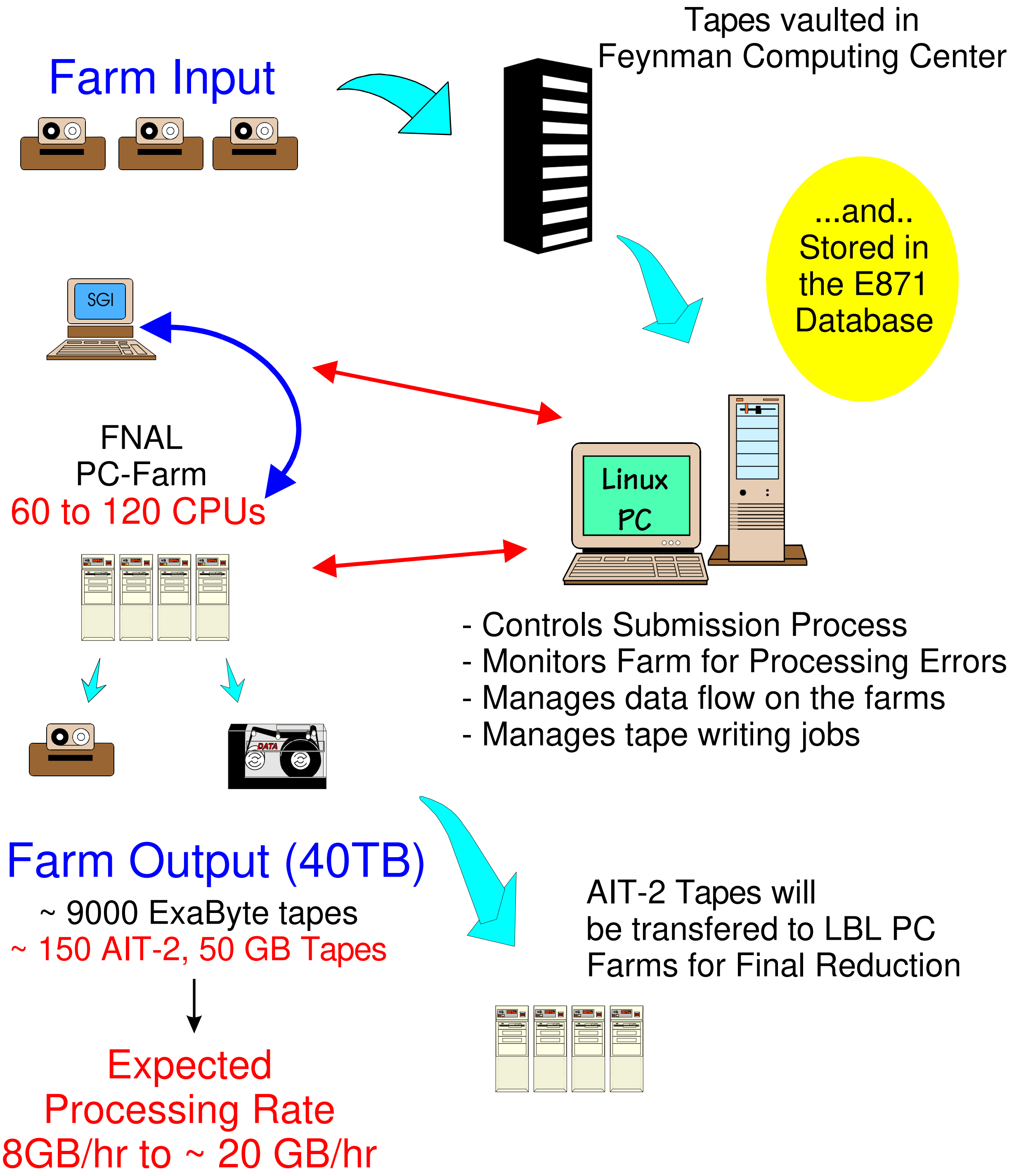
- Upgrading NERSC PDSF and developing software infrastructure for detailed analysis

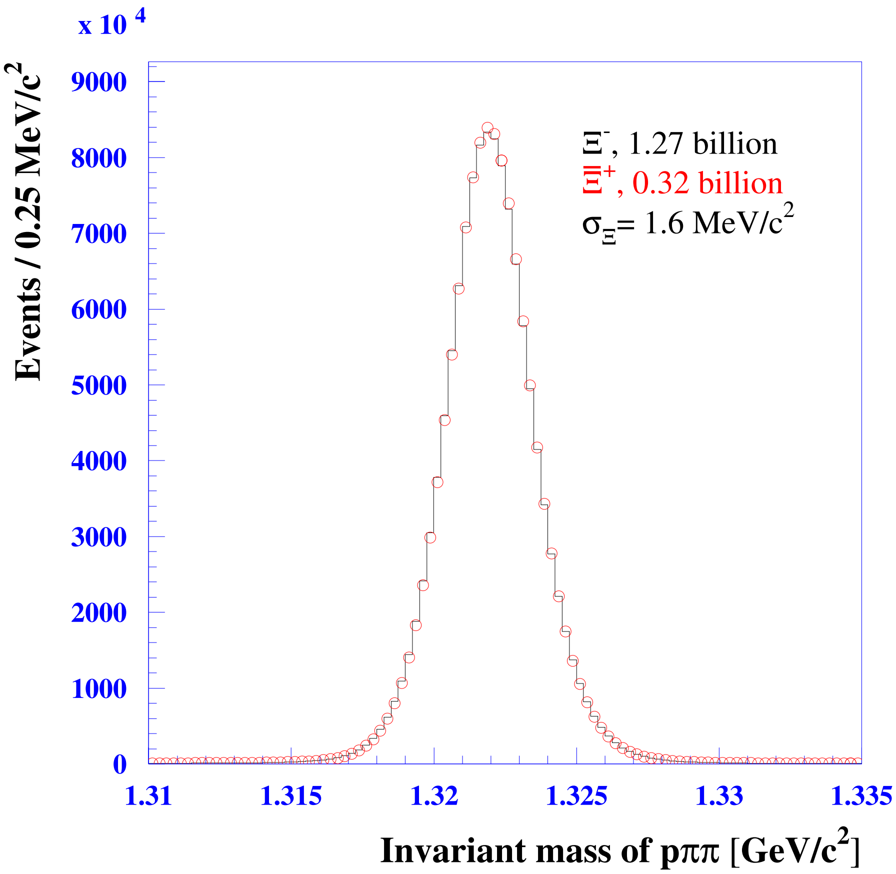
- Several analyses are in progress

  * CP violation in Ξ, Λ decays
  * CP violation in $K \to 3\pi$ decay
  * Measurement of the decay parameter α of $\Omega^- \to \Lambda K^-$
  * Measurement of the decay parameter β of $\Xi^- \to \Lambda\pi^-$
  * Measurement of production polarization of Ξ
  * Production polarization of Ω
  * Production cross section of Ξ
  * Searches for rare and forbidden decays

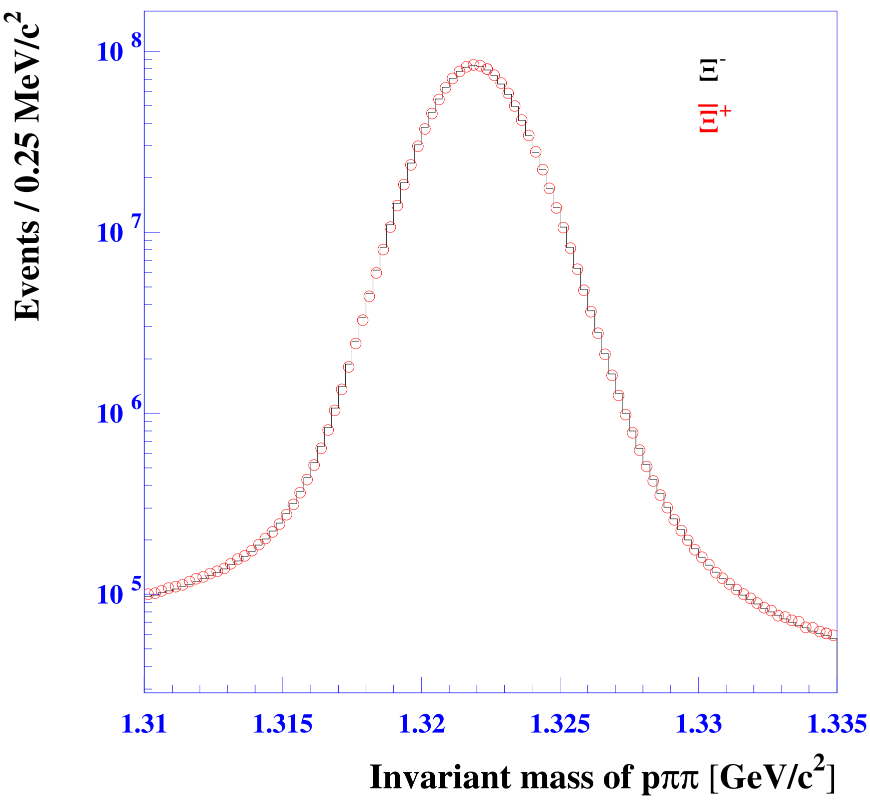
Processing the Data

1999 Data Flow

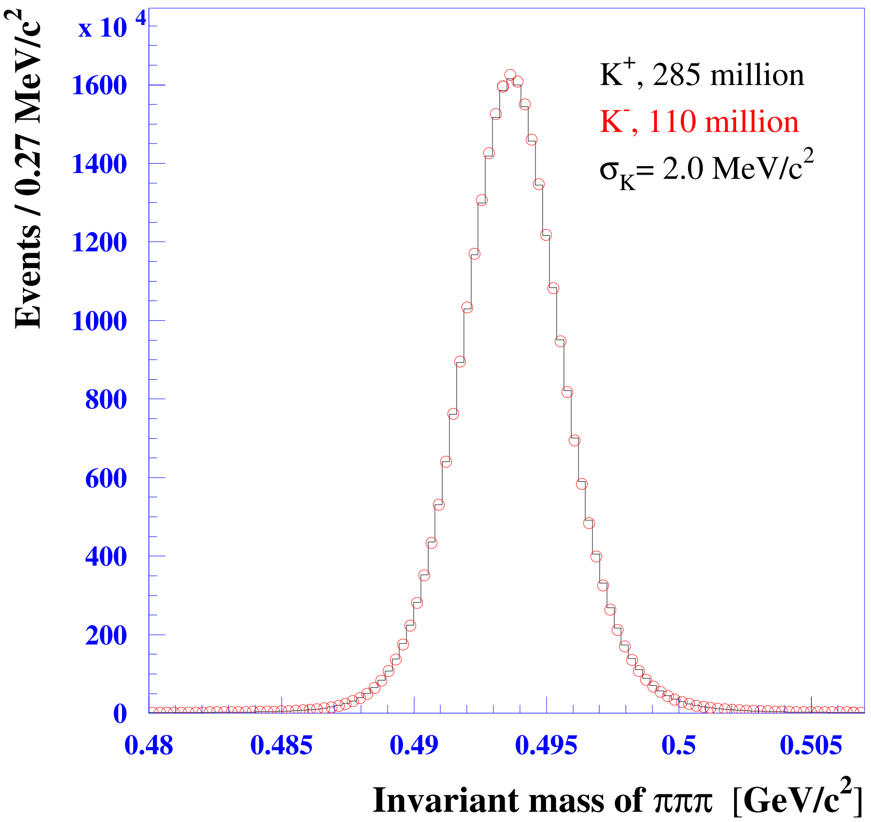




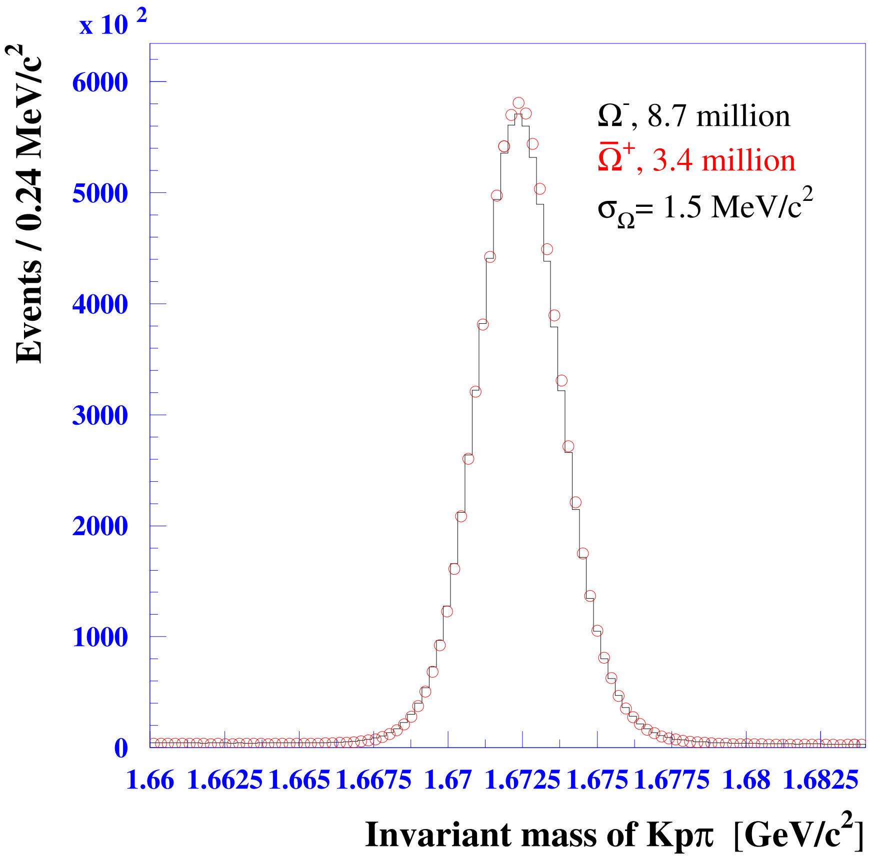
x 10^4
Events / 0.25 MeV/c^2
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Ξ-, 1.27 billion
Ξ̄+, 0.32 billion
σ_Ξ= 1.6 MeV/c^2
1.31
1.315
1.32
1.325
1.33
1.335
Invariant mass of pππ [GeV/c^2]



Events / 0.25 MeV/c^2
10^8
10^7
10^6
10^5
Ξ-
Ξ̄+
1.31
1.315
1.32
1.325
1.33
1.335
Invariant mass of pππ [GeV/c^2]



x 10 4
Events / 0.27 MeV/c2
K+, 285 million
K-, 110 million
σK= 2.0 MeV/c2
Invariant mass of πππ [GeV/c2]



x 10 2
Events / 0.24 MeV/c2
Ω-, 8.7 million
Ω̄+, 3.4 million
σΩ= 1.5 MeV/c2
Invariant mass of Kpπ [GeV/c2]

CP STUDY IN HYPERON DECAYS

- **The goal is to determine**

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

  by studying the difference between the angular distributions in the helicity frames of the Λ and $\overline{\Lambda}$.

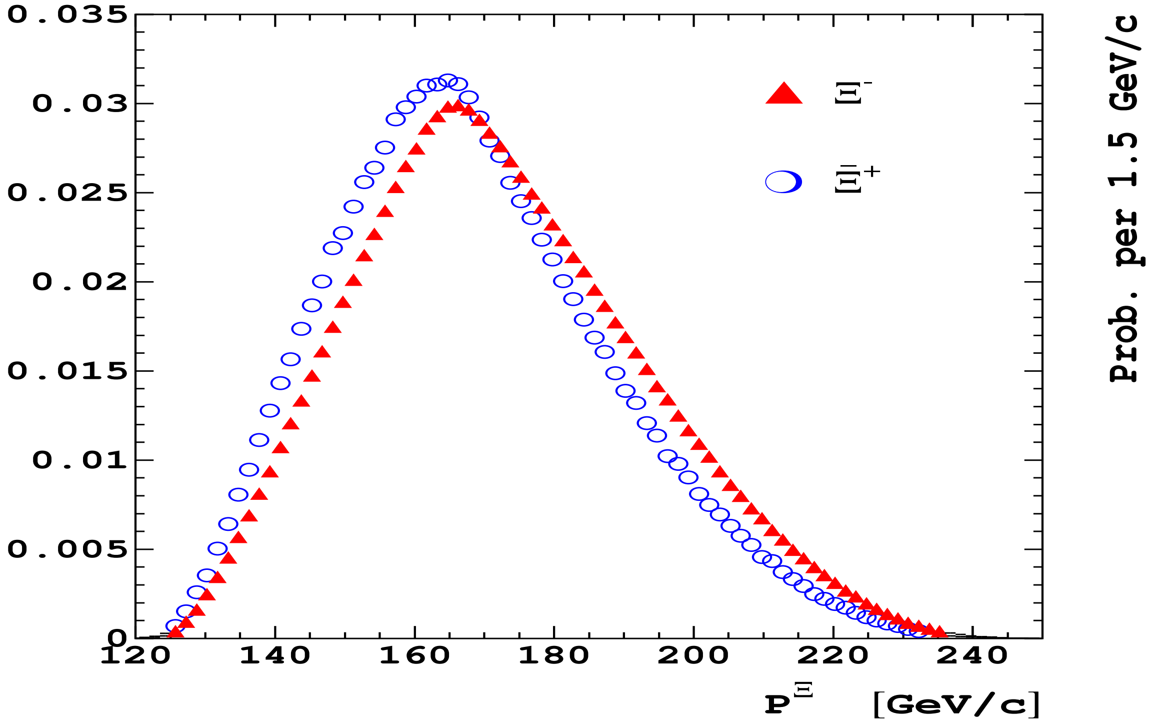
- **Currently analyzing a sample of 20 million hyperons and an equal number of anti-hyperon decays to reach a precision of**

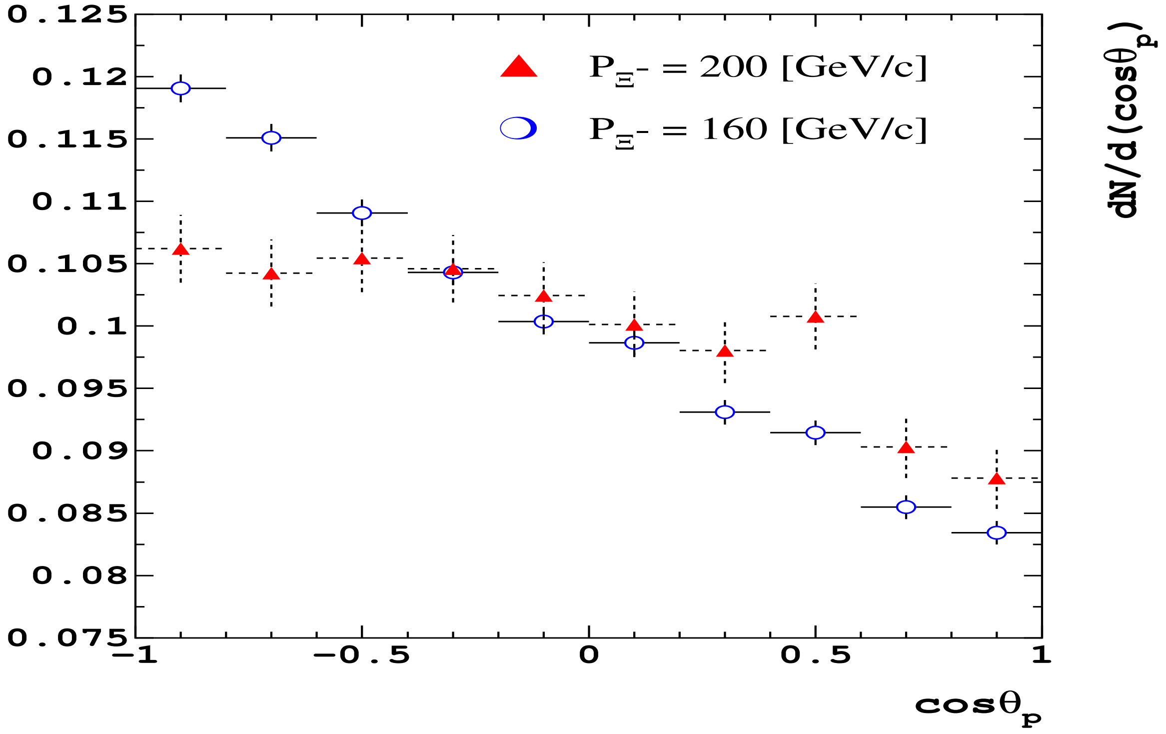
$$\delta A_{\Lambda\Xi} \approx 10^{-3}$$

- **With another upgrade of computing resources, improved data management, and better understanding of the systematics, analyze the entire data sample to achieve the final precision of**

$$\delta A_{\Lambda\Xi} \approx 1.4 \times 10^{-4}$$

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





ANALYSIS TECHNIQUES

- **Matching Method**
  Match a minimal set of kinematic and geometric variables to take out any production differences between the Ξ^- and the $\overline{\Xi}^+$. Without performing any further corrections, extract the difference in the slopes of the helicity distributions directly.

- **Hybrid Monte Carlo Method**
  Determine the value of $\alpha_\Xi \alpha_\Lambda$ for the Ξ^- and $\overline{\Xi}^+$ samples separately. Then calculate $A_{\Lambda\Xi}$.

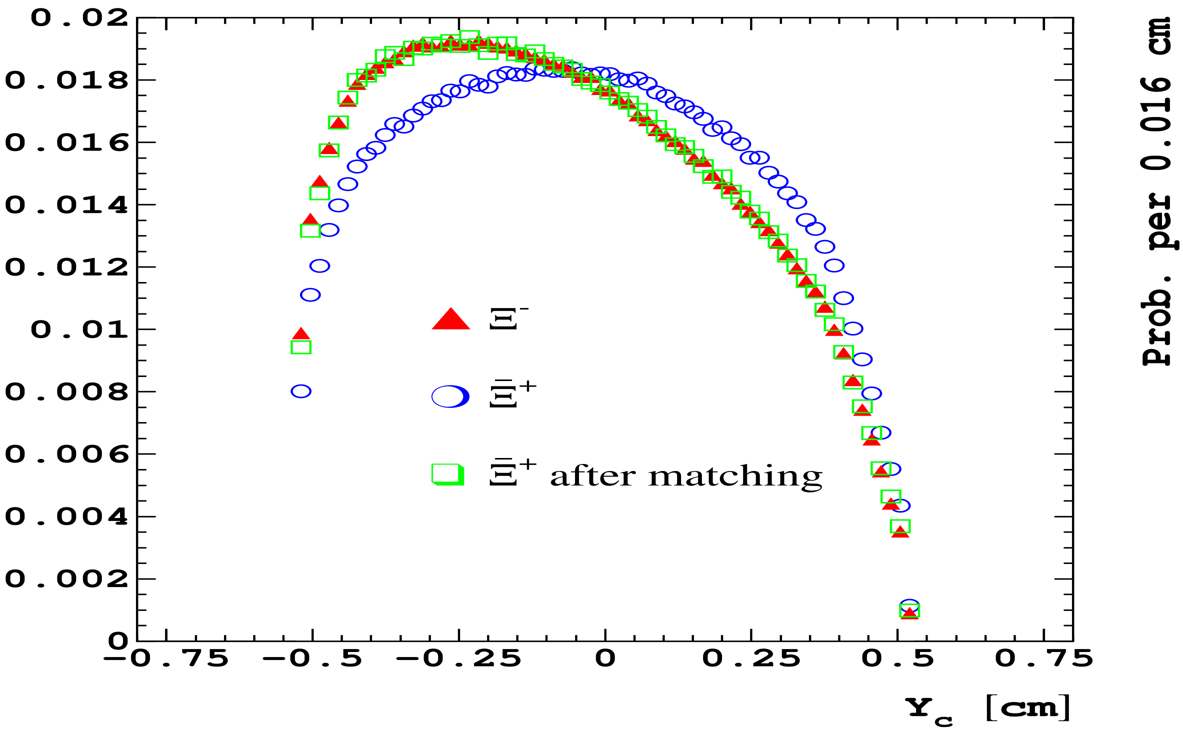
- Both methods should minimize the reliance on extremely detailed Monte Carlo simulation.

- These methods have been tried out in E756.

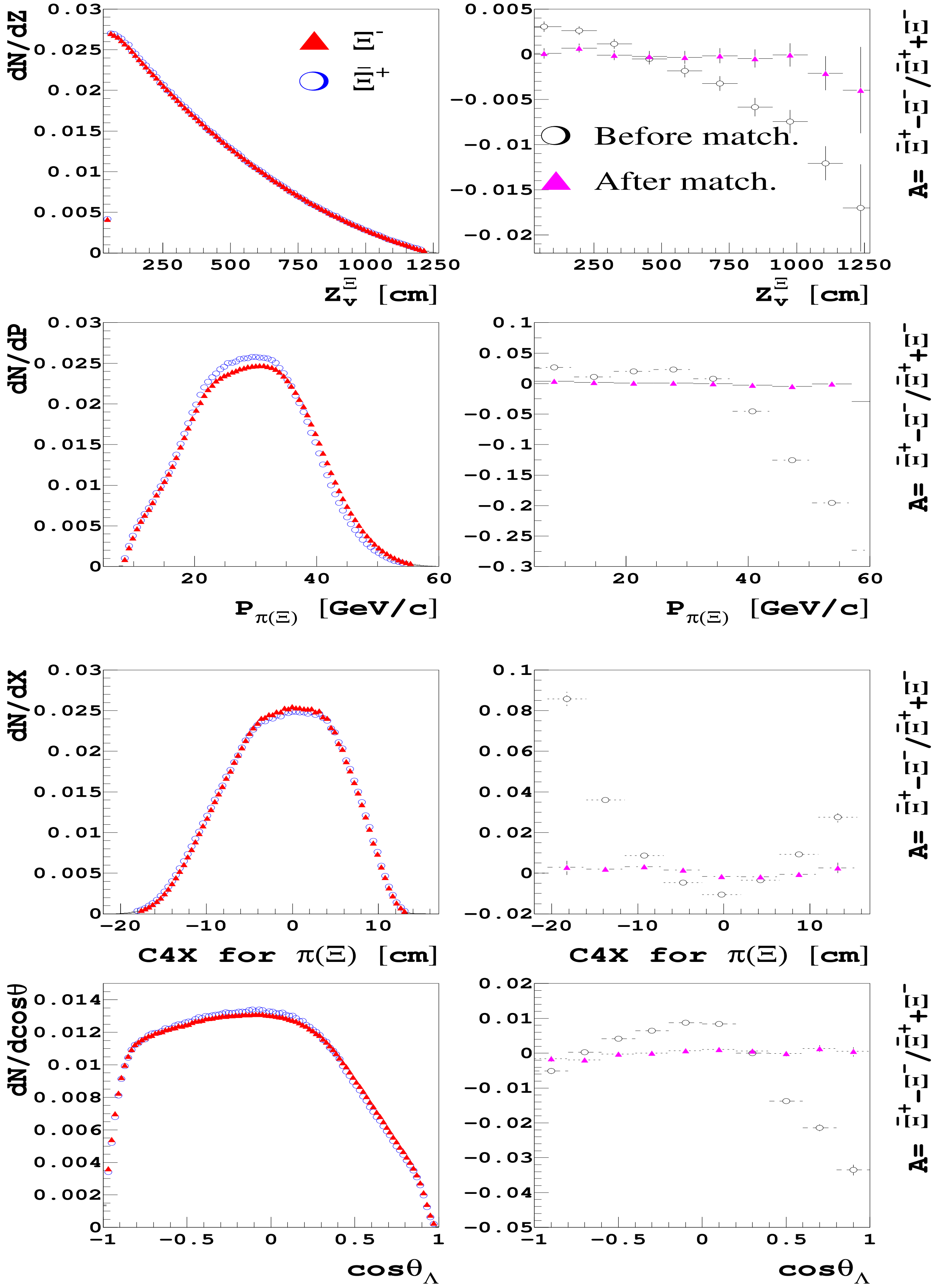
MATCHING PROCEDURE

- Variables used in the matching process
  - X_t,Y_t: position at the target
  - X_c,Y_c: position at the exit of the collimator
  - P_{Ξ}: magnitude of momentum

- Phase space density of $\overline{\Xi}^+$ matched to Ξ^- by weighting method



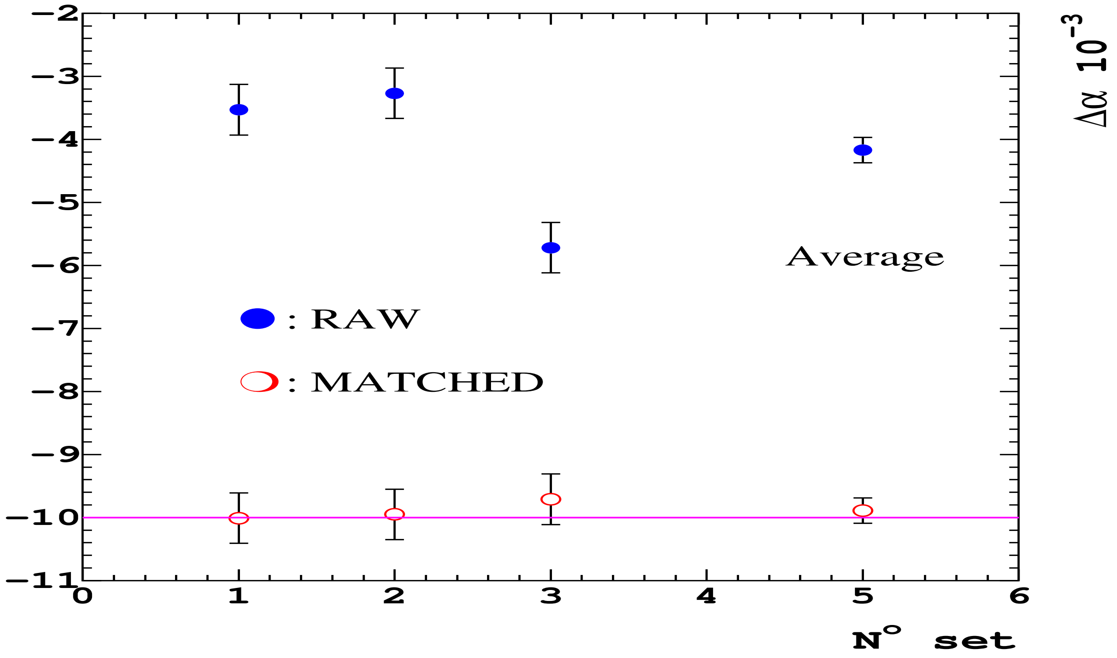
EFFECT OF MATCHING



MATCHING TESTED WITH MC

- **Three MC samples each based on $\overline{\Xi}^+$ and Ξ^- from data**

- **Introduction of CP violation in $\overline{\Xi}^+$:**
  $\Delta\alpha$ = $\alpha_{\Xi}\alpha_{\overline{\Lambda}}$ - $\alpha_{\Xi}\alpha_{\Lambda}$ = **- 10** $\times 10^{-3}$
  $A_{\Lambda\Xi}$ = - $\Delta\alpha$ / (2 $\alpha_{\Xi}\alpha_{\Lambda}$) = **- 17.1** $\times 10^{-3}$



- **Results :** $\Delta\alpha$ = **(-9.9** $\pm$ **0.2)** $\times 10^{-3}$

- **In terms of the asymmetry** $A_{\Lambda\Xi}$
  $A_{\Lambda\Xi}$ = **(-16.9** $\pm$ **0.4)** $\times 10^{-3}$

HYBRID MONTE CARLO

- **Hybrid Monte Carlo (HMC) is a method for unfolding the acceptance of a physical quantity to be determined, i.e. cos(θ) in this analysis.**

- **In the HMC program, for a given input event, Monte Carlo events are created using all measured quantities from the input event except cos(θ) which is uniformly generated.**

- **The HMC events are then subjected to the same software cuts as the input events.**

- **The cos(θ) distributions of the accepted HMC events are then adjusted by minimization to match those of the input events with a weight which is a function of $\alpha_\Xi \alpha_\Lambda$.**

VERIFICATION OF HYBRID MC

- **MC events created with $\alpha_\Lambda \alpha_\Xi = -0.2927$ (PDG)**
- **Determination of the input value with closest to reality conditions, i.e. multiple scattering, track reconstructions, etc**

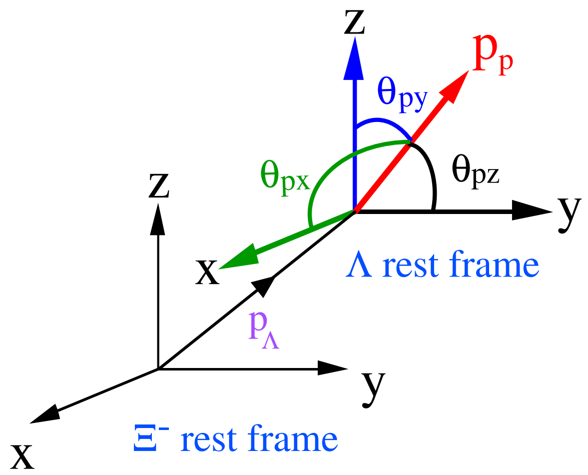
$$\alpha_\Lambda \alpha_\Xi = -0.2953 \pm 0.0020$$

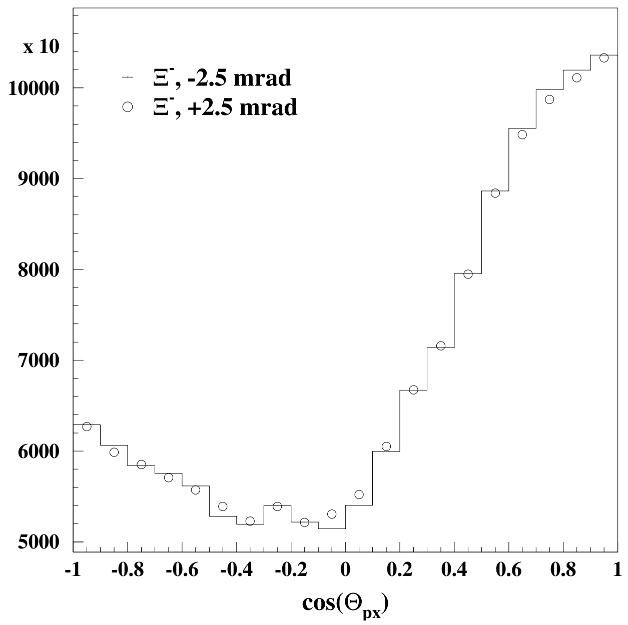
SYSTEMATICS

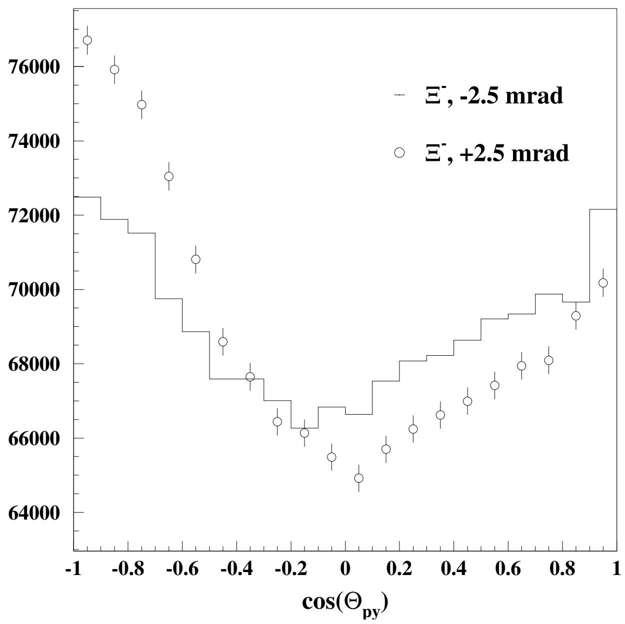
If not corrected for could cause false asymmetries between Ξ^- and $\overline{\Xi}^+$ decays

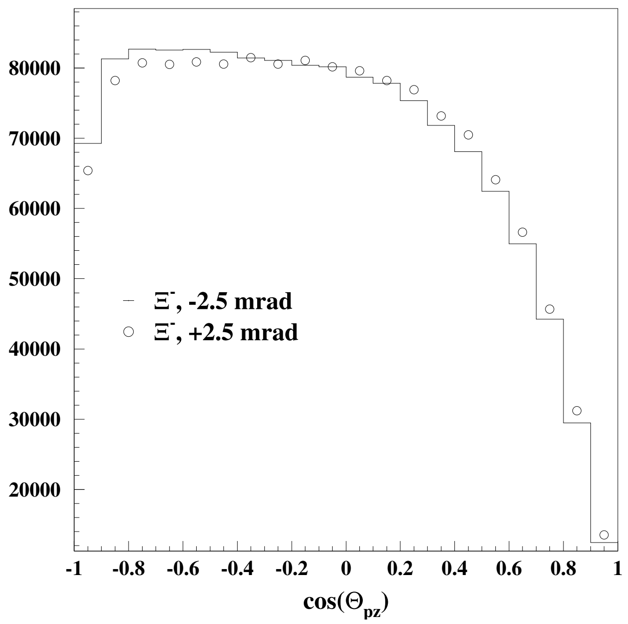
- **Nonzero Ξ^-, $\overline{\Xi}^+$ polarizations**
- **Different interaction cross sections between π^- and π^+ and between p and $\overline{p}$**
- **different backgrounds for Λ, Ξ^- versus $\overline{\Lambda}$, $\overline{\Xi}^+$**
- **Acceptance differences**
  - **targeting differences**
  - **magnetic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

EFFECT OF POLARIZATION



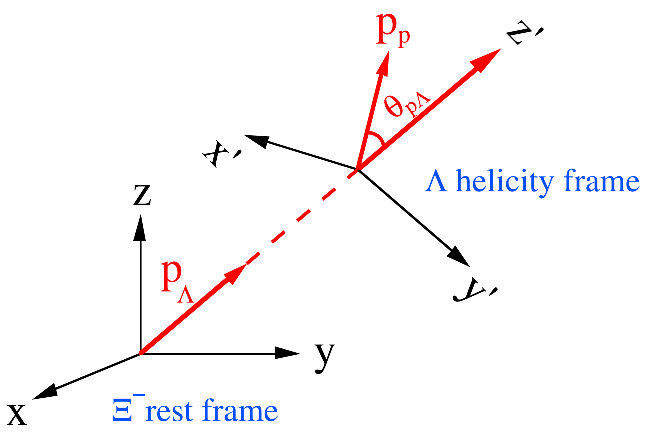


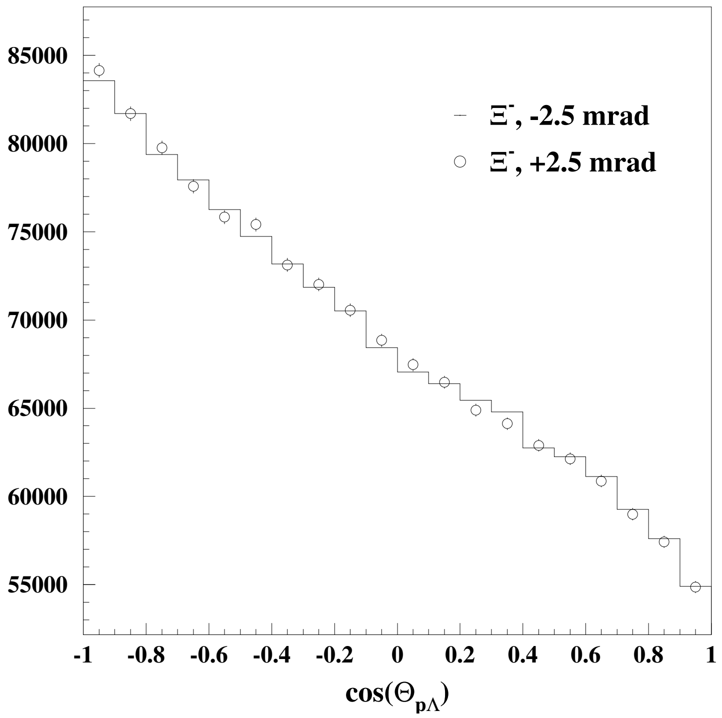




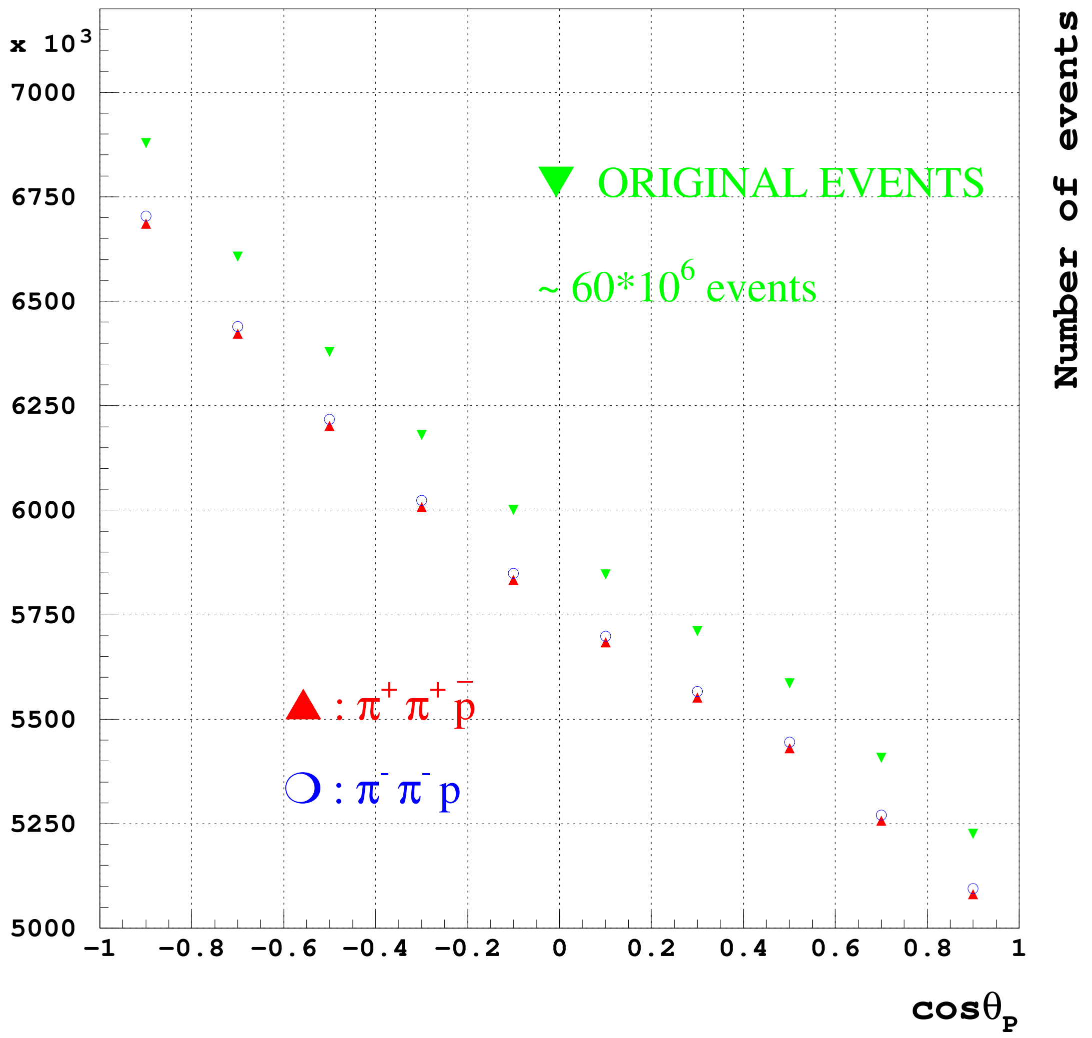
EFFECT OF POLARIZATION

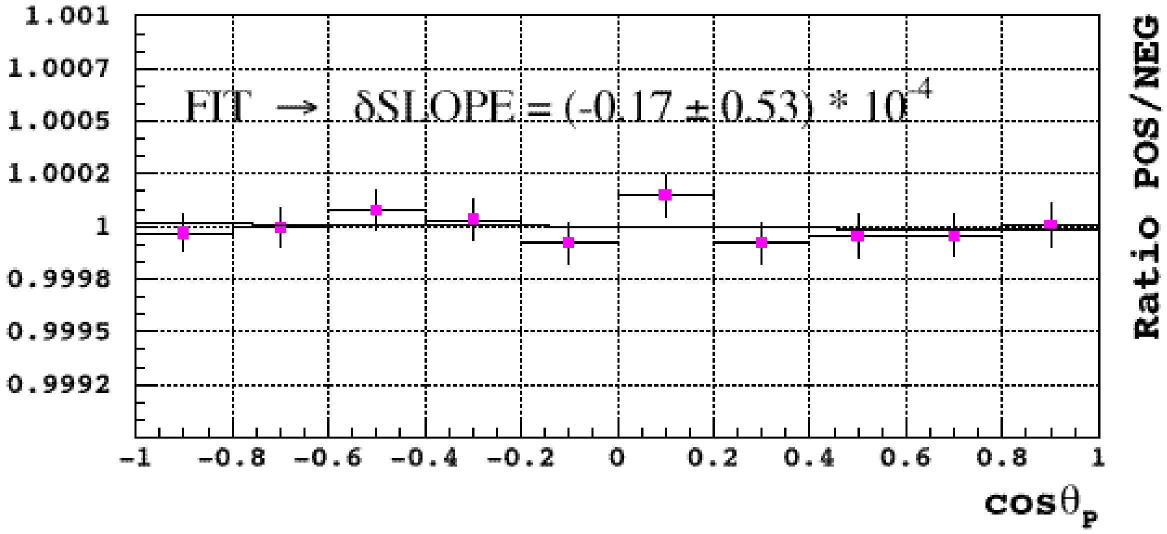
Ξ^- (-2.5 mrad) vs Ξ^- (+2.5 mrad)



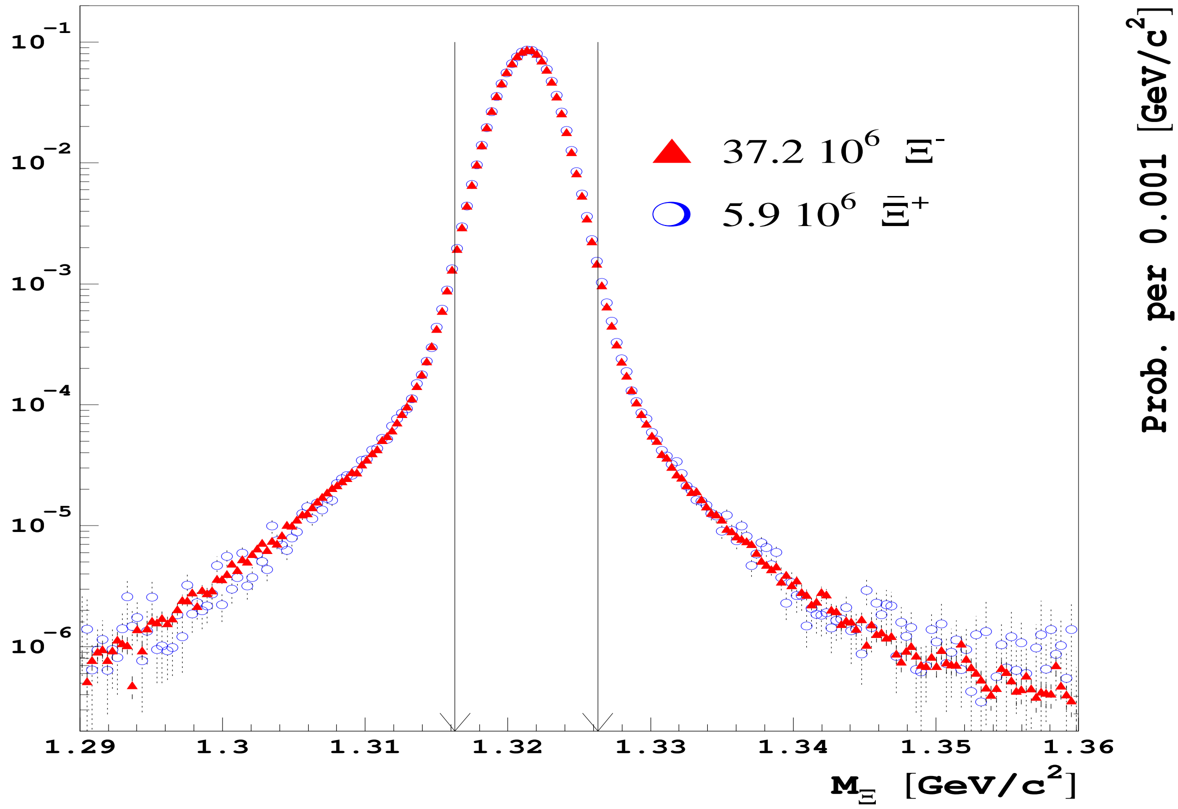


EFFECT OF DIFFERENCES IN PARTICLE AND ANTIPARTICLE INTERACTIONS





DIFFERENCES IN BACKGROUND



- **Measured differences in the slope of** $\cos\theta_p$ **in the sidebands, after matching process**
  - **Left sideband :** $\Delta\alpha$ **= (0.5** $\pm$ **1.0)** $\times 10^{-2}$
  - **Right sideband :** $\Delta\alpha$ **= (-0.9** $\pm$ **1.1)** $\times 10^{-2}$

- **B/S is about 3** $\times 10^{-3}$

Assumption: sideband background similar to background under the signal, then

$$\Delta\alpha \quad \leq \quad 1.2 \times 10^{-4}$$

CONCLUSIONS

- **Hyper$\mathcal{CP}$ had successful 1997 and 1999 runs and has collected the largest samples of Ξ^- and $\overline{\Xi}^+$ decays in the world.**

- **The projected statistical sensitivity to CP asymmetry in $\Xi,\ \Lambda$ decays is**

$$1.4 \times 10^{-4},$$

  two orders of magnitude better that the present limit and where some theories predict an effect.

- **Processing of data will continue for the next several months. Detailed systematic studies are in progress.**

- **The large samples of Ξ, Ω, and K decays allow us to make a variety of precise measurements and rare-decay searches.**