# HyperCP Experiment : Search for direct CP Violation in Hyperons Decays

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Representing Hyper$\mathcal{CP}$ (FNAL E871) Collaboration

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# HyperCP (E871) Collaboration


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# Talk summary

- Introduction
- Description of the experiment
- Direct CP violation in hyperon decays
- Summary of the 1997 and 1999 runs
- Systematics
- Equalization
- Summary of the systematics (Preliminary)
- Preliminary Results
- Conclusions

# PHYSICS MOTIVATION

- Search for asymmetry, at the level of $10^{-4}$, due to direct CP violation in the decays :

$$\Xi^- \to \Lambda\,\pi^- \quad \hookrightarrow p\,\pi^- \qquad \textit{and} \qquad \overline{\Xi}^+ \to \overline{\Lambda}\,\pi^+ \quad \hookrightarrow \overline{p}\,\pi^+$$

- Search for direct CP violation outside the decays of $K_L \to 2\pi$ $(\epsilon'/\epsilon)$

- Probe interference between parity violating (S-wave) and conserving (P-wave) amplitudes. Sensitive to CP violation in parity conserving channel.

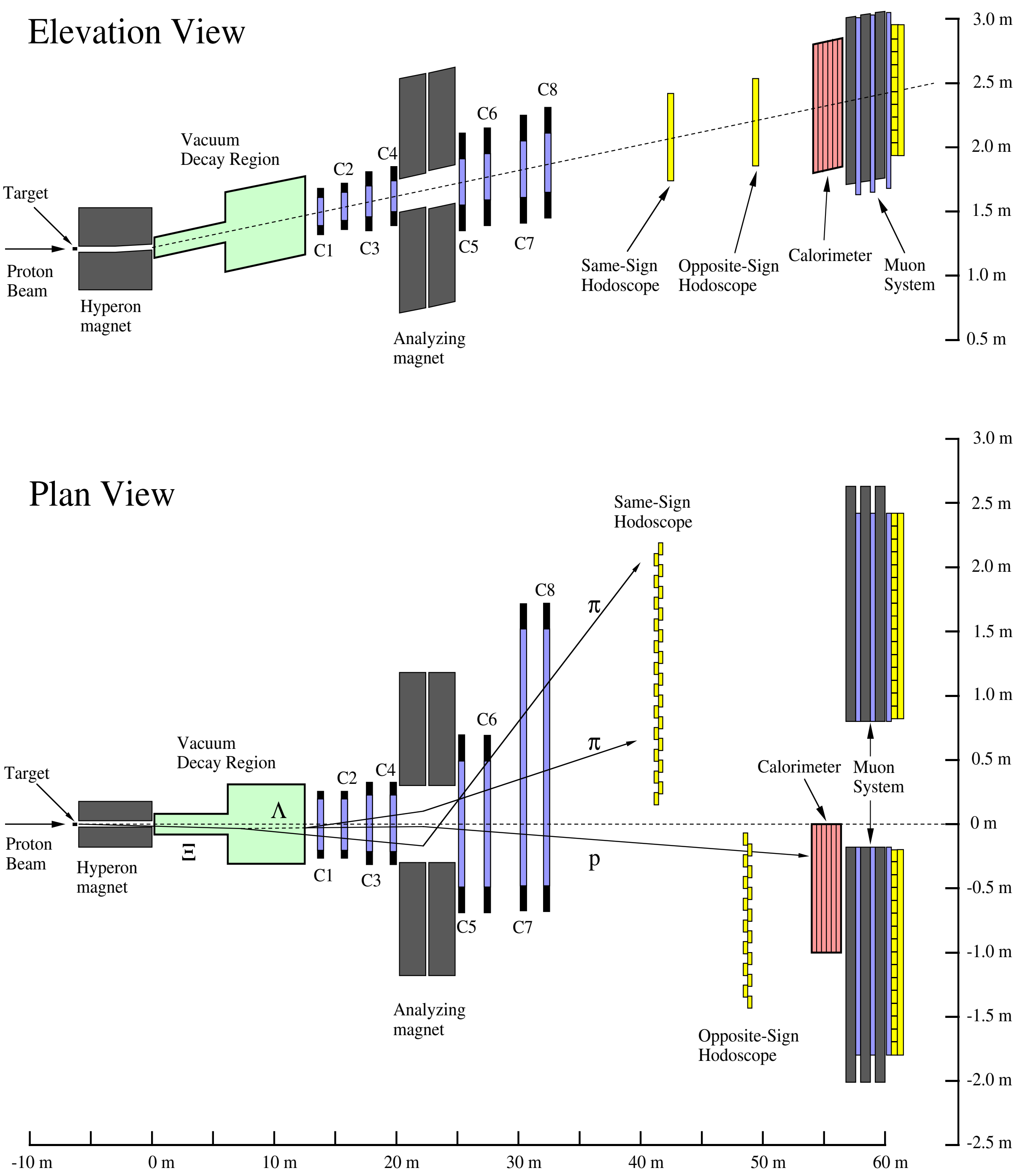
# DESCRIPTION OF THE EXPERIMENT

- **Production**
  - $*$ p (800 GeV/$c$) + Cu $\longrightarrow$ Hyperon + X
  - $*$ Production of hyperons at $0^o$ $\Longrightarrow$ **Unpolarized**
  - $*$ Momentum selection at $\approx$ 170 GeV/$c$

- **Spectrometer**
  - $*$ 13 m vacuum decay region
  - $*$ 8 fast narrow-pitch wire chambers (32 planes)
  - $*$ Analysis magnet made up of 2 dipoles
  - $*$ 2 planes of Scintillators (Hodoscopes)
  - $*$ High-rate DAQ (1997 : 13 MB/s or 63K events/s to tape)
  - $*$ Simple trigger (2 particles of opposite signs and calorimeter energy for $\Xi$ and K)

**From $\Xi^-$ to $\overline{\Xi}^+$ : invert the Analysis and Hyperon magnetic fields and change the target.**

# Hyper*CP* Spectrometer



# NON LEPTONIC HYPERON DECAYS

- **In the $\Delta$S = 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**

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

- **Decay parameters (Lee-Yang variables)**

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

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

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

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

- **The polarisation of the daughter is given by**

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

- **Then, for an unpolarized $\Xi$, $\alpha_\Xi$ is the magnitude of the longitudinal polarization of the $\Lambda$**

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

- **Then, the angular distribution of the proton in the $\Lambda$ rest frame is**

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{\mathcal{P}}_\Lambda \cdot \hat{q}_p) = \frac{1}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_p)$$

- **If CP is conserved**

$$\boxed{\begin{aligned} \alpha_{\overline{\Lambda}} &= -\alpha_\Lambda \\ \alpha_{\overline{\Xi}} &= -\alpha_\Xi \\ \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}} &= \alpha_\Xi \alpha_\Lambda \end{aligned}}$$

# Hyper$\mathcal{CP}$ APPROACH

- **Produce unpolarized $\Xi$'s to obtain $\Lambda$'s with longitudinal polarization $\alpha_\Xi$ from $\Xi$ decays**

$$\begin{array}{lllclll} \Xi^- & \to & \Lambda\,\pi^- & \quad \mathit{and} \quad & \overline{\Xi}^+ & \to & \overline{\Lambda}\,\pi^+ \\ & & \hookrightarrow p\,\pi^- & & & & \hookrightarrow \overline{p}\,\pi^+ \end{array}$$

- **In $\Lambda$ 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 the difference in slope**

$$\begin{aligned} R(\cos\theta_p) &= \frac{\epsilon_+(\cos\theta_p)}{\epsilon_-(\cos\theta_p)} \frac{(1 + \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}} \cos\theta_p)}{(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_p)} \\ \Delta\alpha &= \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}} - \alpha_\Lambda \alpha_\Xi \end{aligned}$$

- **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 $1 \times 10^{-4}$ statistical precision**

# AVAILABLE RESULTS AND THEORETICAL PREDICTIONS

- **Need to produce $\Lambda$, $\bar{\Lambda}$ with known polarizations**

| Experiment | Decay Mode | $\mathbf{A}_\Lambda$ |
|---|---|---|
| **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** | $\bar{p}p \to \Lambda\bar{\Lambda}$ | **-0.013 $\pm$ 0.022** |

- **Search for direct CP violation in $\Xi$ and $\Lambda$ 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** |

## THEORETICAL PREDICTIONS

| | $A_\Lambda$ $[10^{-4}]$ | $A_\Xi$ $[10^{-4}]$ |
|---|---|---|
| **CKM** | **(-0.5,-0.1)** | **(-1.0,-0.05)** |
| **Left-Right** | **(-0.1,6)** | **(-0.25,0.6)** |
| **SUSY** | **(-0.2,19)** | **-** |

# SUMMARY OF THE 1997 AND 1999 RUNS

| | 1997 Runs | 1999 Runs |
|---|---|---|
| **Number of tapes** | 9'376 | 18'838 |
| **Data Volume** | **38 TB** | **71 TB** |

**Projected number of reconstructed events**

| | |
|---|---|
| $\Xi^-$ | **2** $\times 10^9$ |
| $\overline{\Xi}^+$ | **0.5** $\times 10^9$ |
| $K^+$ | **0.32** $\times 10^9$ |
| $K^-$ | **0.13** $\times 10^9$ |
| $\Omega^-$ | **14** $\times 10^6$ |
| $\overline{\Omega}^+$ | **5.3** $\times 10^6$ |

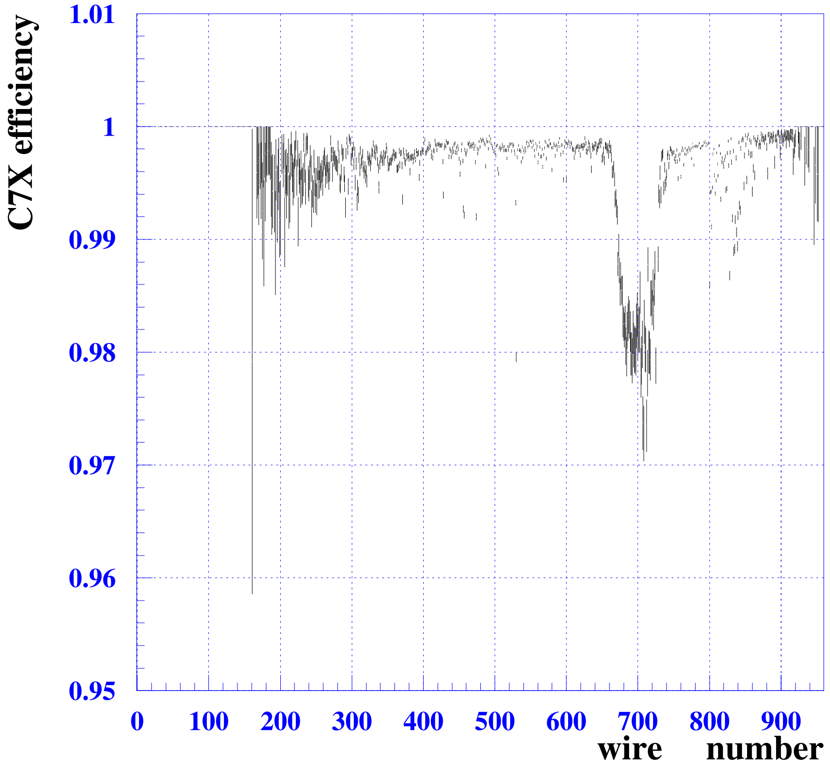
**Statistical precision :** $\delta(A_{\Xi\Lambda})$ **= 1.4** $\times 10^{-4}$

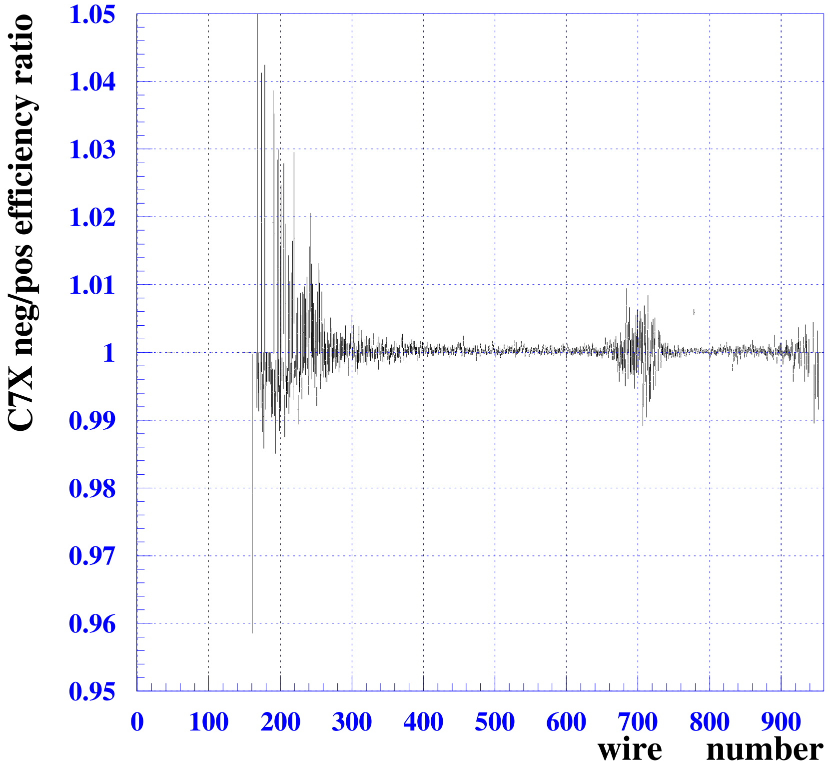
# SYSTEMATICS

If not corrected, they could cause false asymmetries between $\Xi^-$ and $\overline{\Xi}^+$

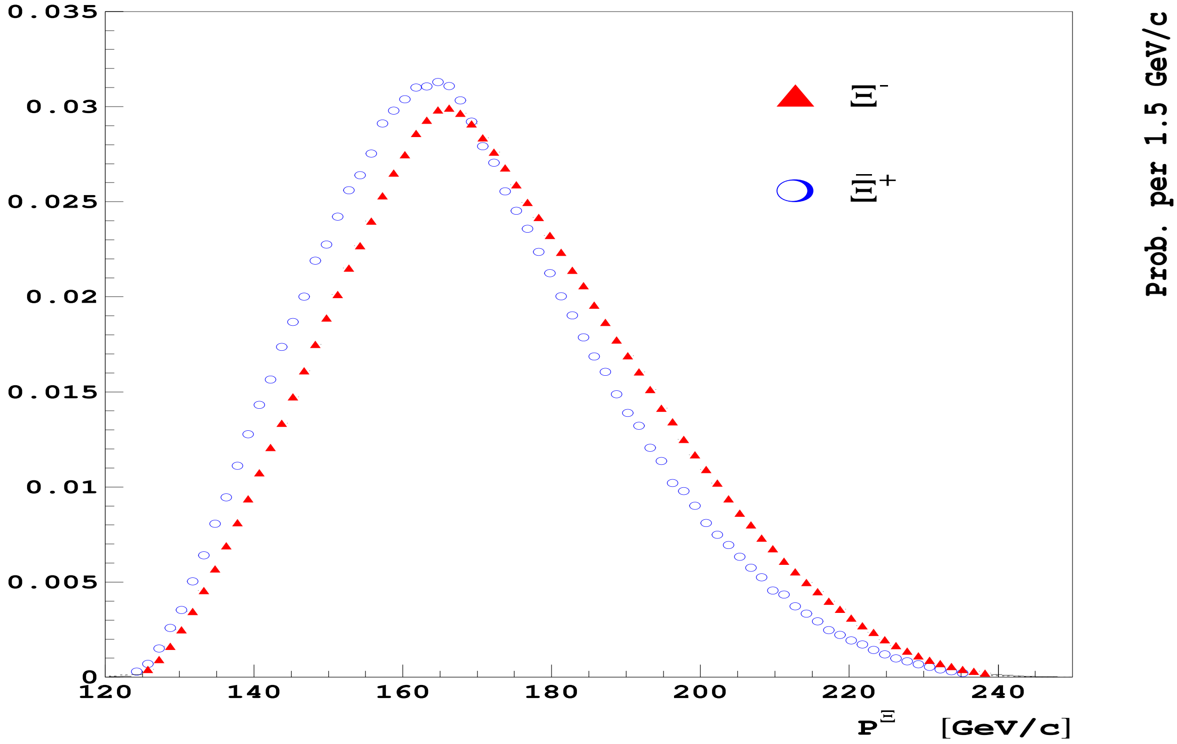
- **Acceptance differences**
  - ∗ **position and angle of beam on target**
  - ∗ **chamber and trigger efficiencies**
  - ∗ **production cross sections**
  - ∗ **magnetic field**
  - ∗ **Different interaction cross sections between $\pi^-$ and $\pi^+$ and between $p$ and $\overline{p}$**
- **Difference in polarization between $\Xi^-$ and $\overline{\Xi}^+$**
- **Different backgrounds for $\Lambda$, $\Xi^-$ versus $\overline{\Lambda}$, $\overline{\Xi}^+$**
- **Temporal changes**

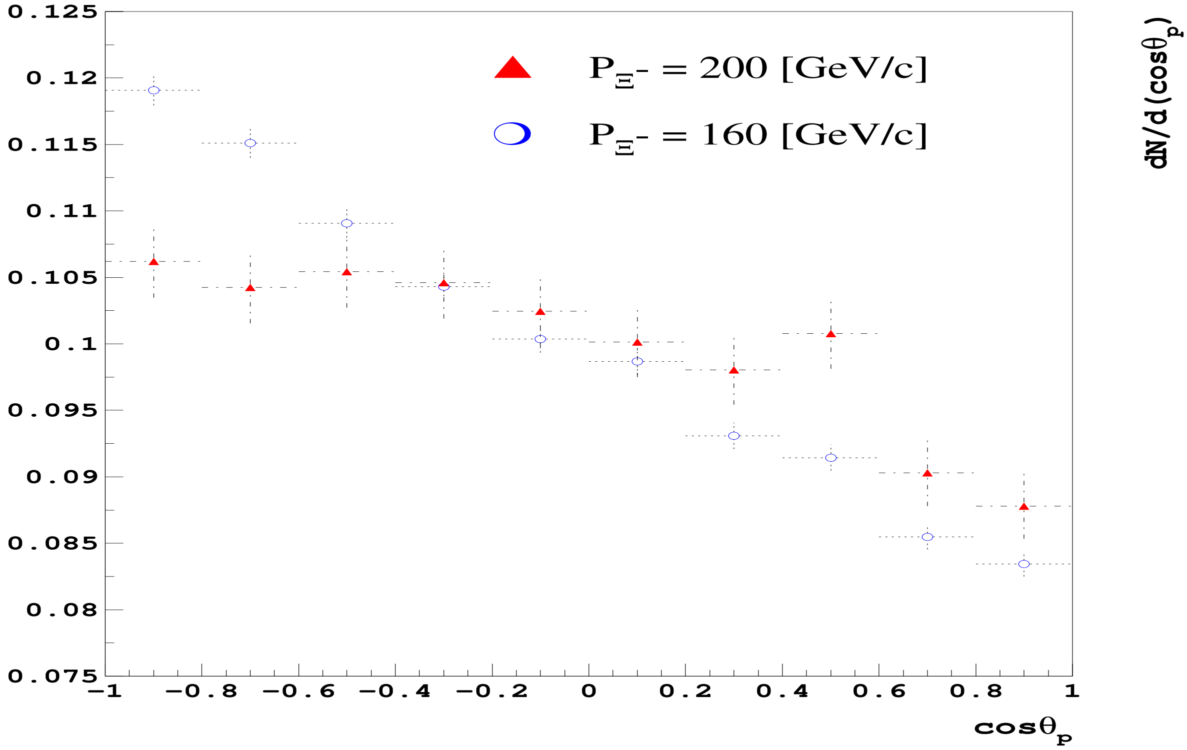
# EFFICIENCIES OF THE CHAMBERS



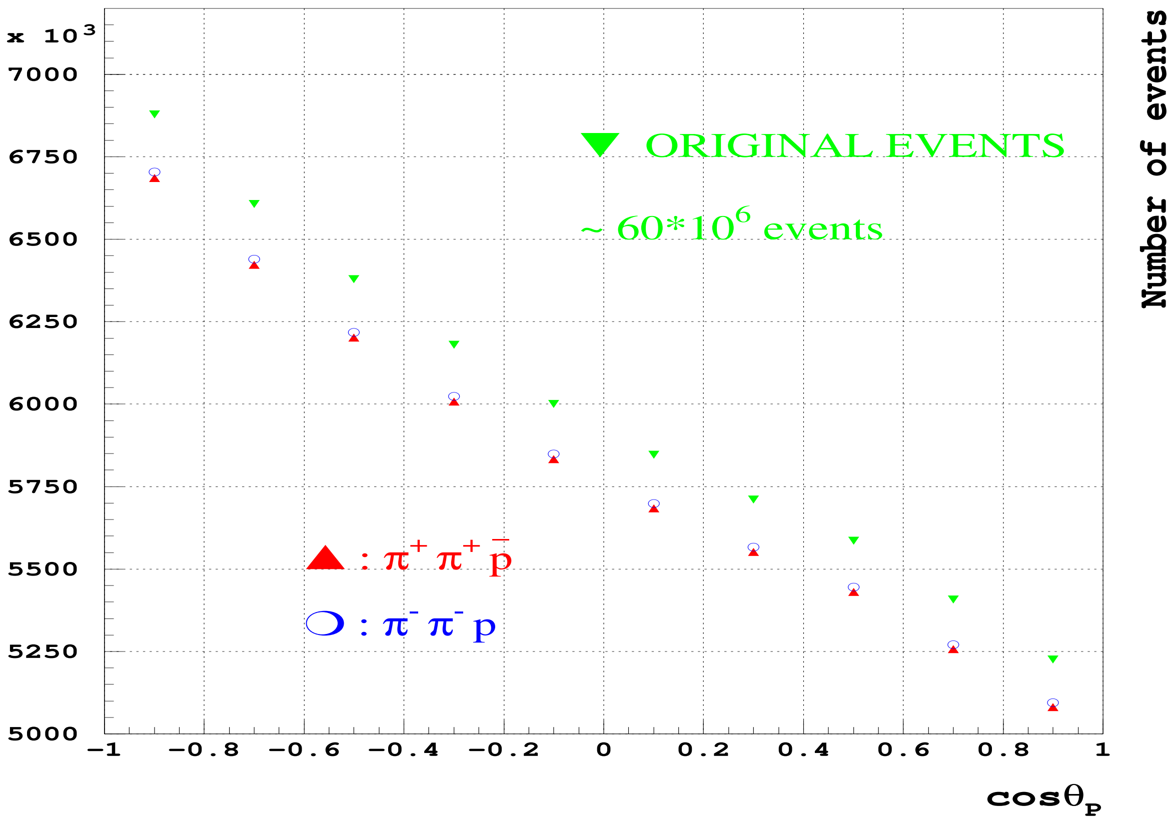



# DIFFERENCES IN PRODUCTION BETWEEN $\Xi^-$ AND $\overline{\Xi}^+$



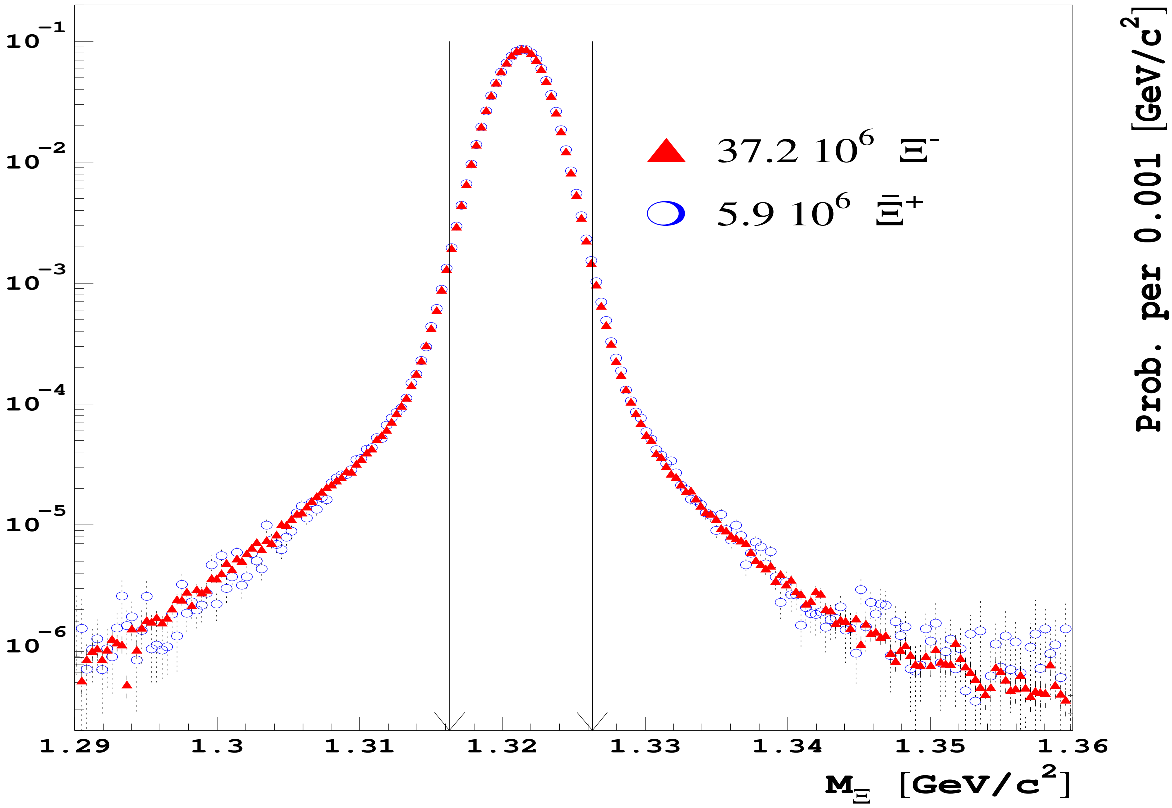
# SYSTEMATICS DUE TO INTERACTION




- **A MC based on the reconstructed $\Xi^-$ events shows an upper limit in the difference of the slopes of**

$$\boxed{\Delta\alpha = \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}} - \alpha_{\Xi}\alpha_{\Lambda} = (0.17 \pm 0.53) \times 10^{-4}}$$

# DIFFERENCES IN BACKGROUND : AFTER EQUALIZATION




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

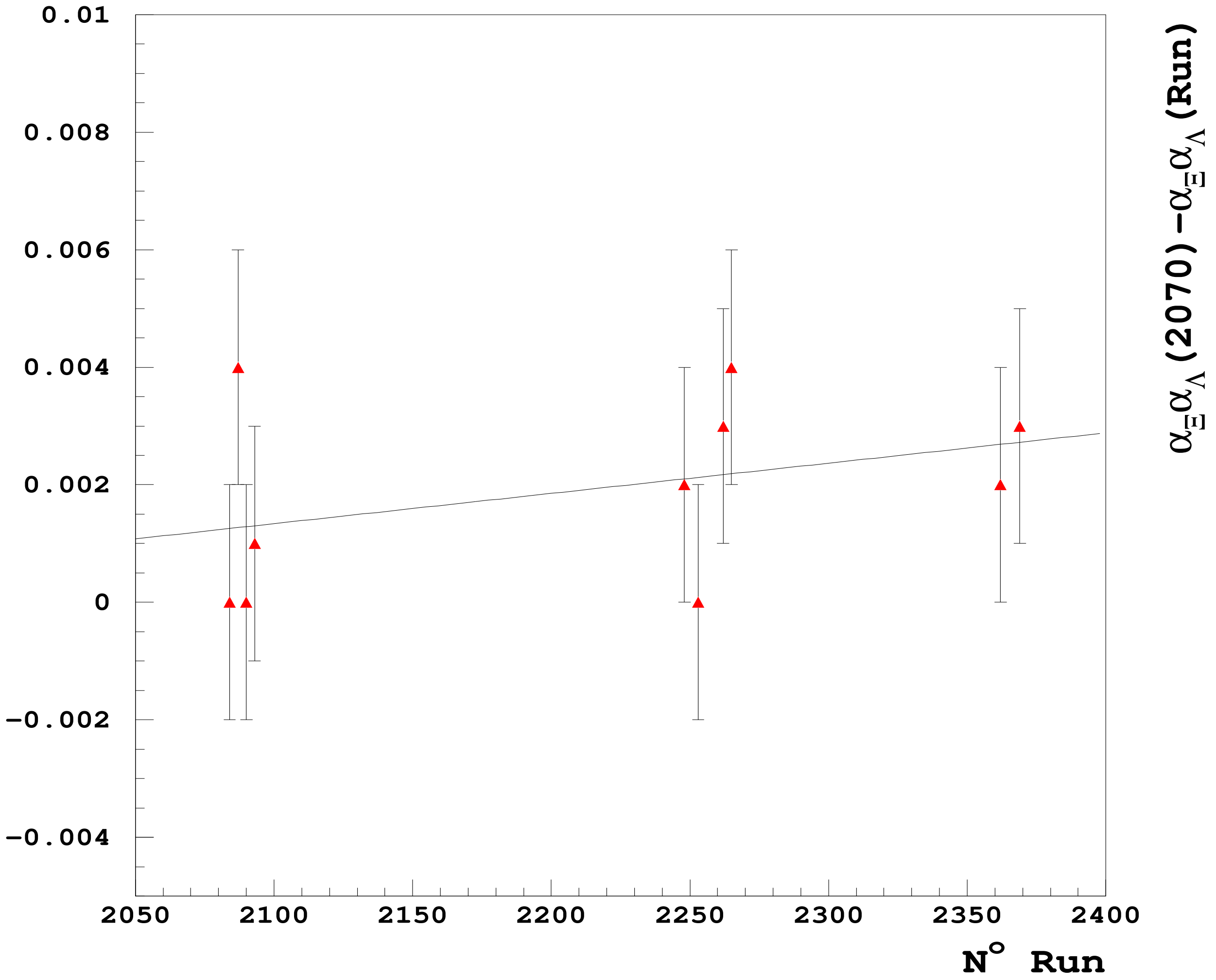
- **B/S is about 3 $\times 10^{-3}$**

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

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

# TEMPORAL CHANGES

**Differences in $\alpha_\Xi \alpha_\Lambda$ measured between run 2070 ($\Xi^-$) with other $\Xi^-$ runs**




**No systematic effects have been observed on the measure of $\alpha_\Xi \alpha_\Lambda$ vs time**

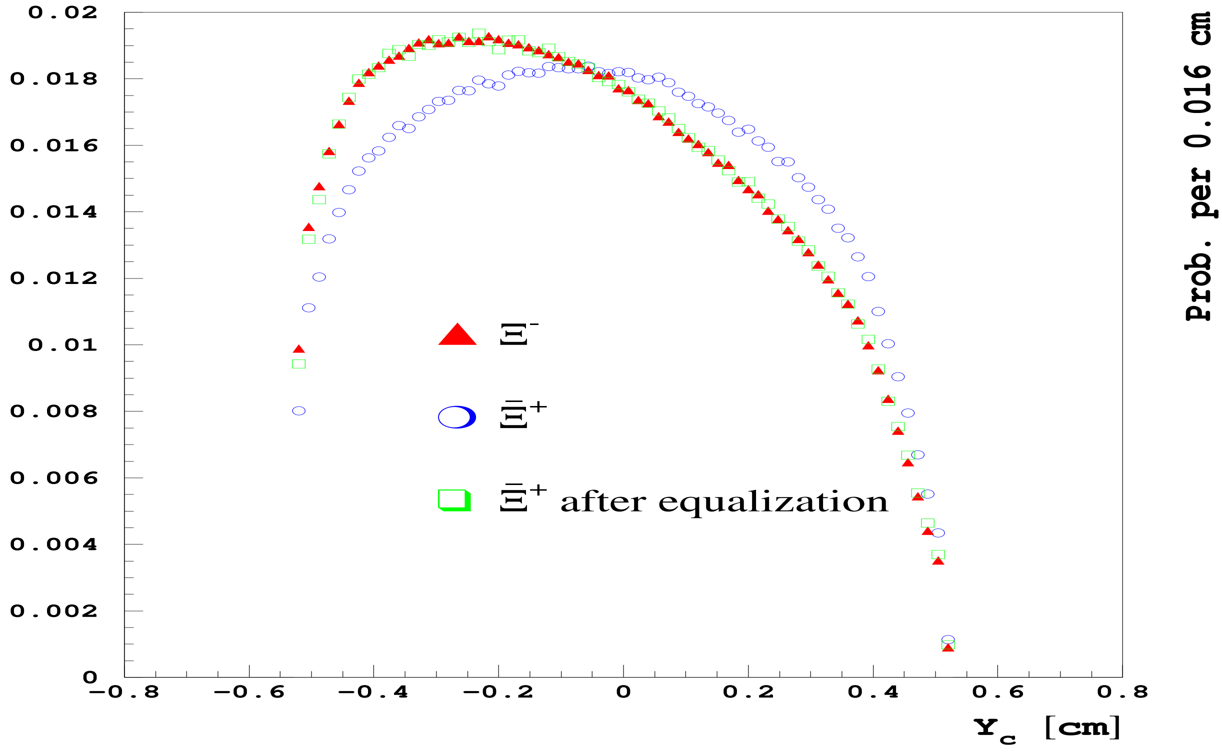
$$\boxed{\Delta\alpha(RUN) \quad = \quad (0.52 \pm 0.58) \times 10^{-5}}$$

# EQUALIZATION PROCESS

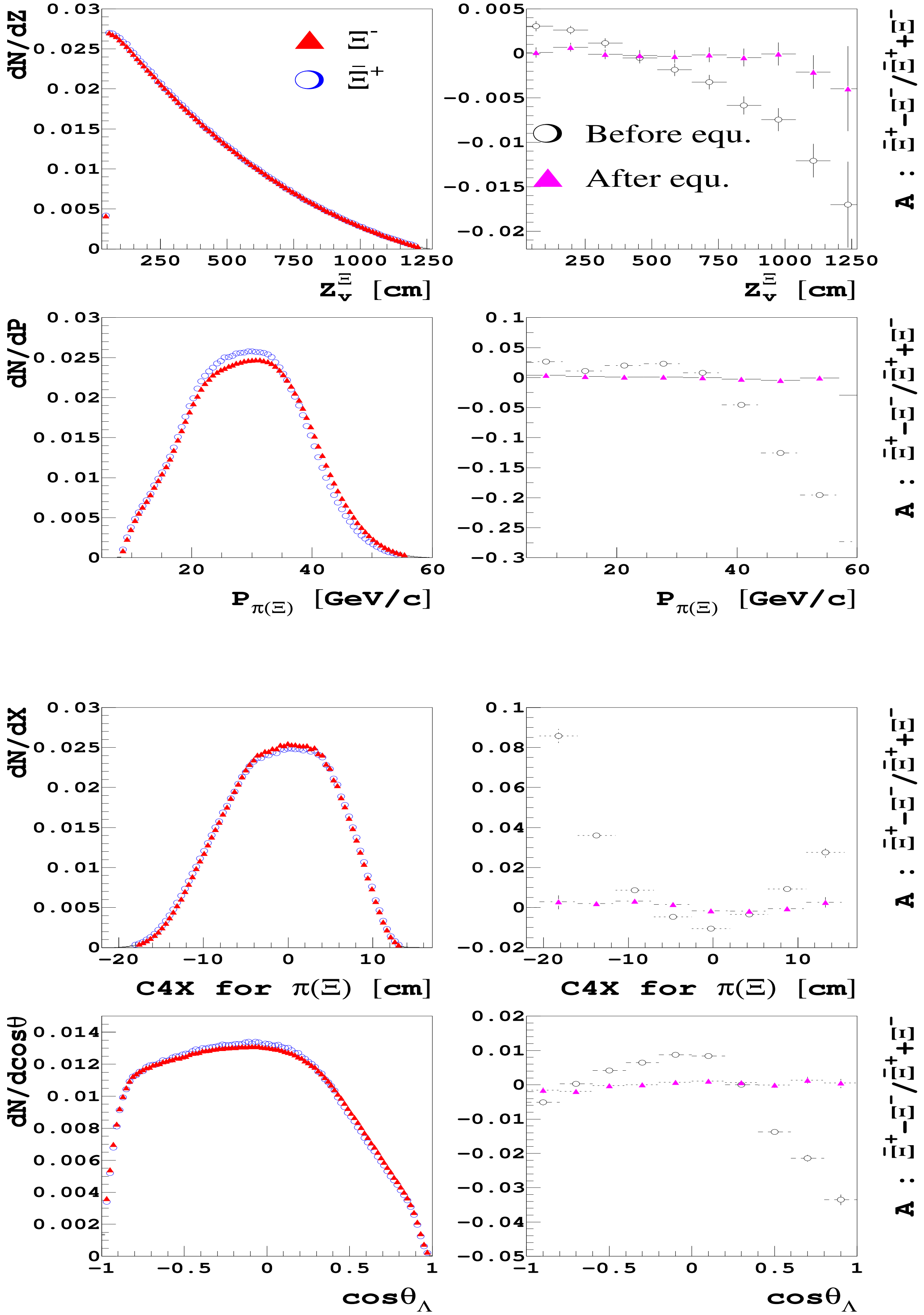
- **Variables used for the equalization process**
  - $*$ $X_t$ **: transverse coordinate of the origin at target**
  - $*$ $Y_t$ **: vertical coordinate of the origin at target**
  - $*$ $X_c$ **: transverse coordinate of the exit point at collimator**
  - $*$ $Y_c$ **: vertical coordinate of the exit point at collimator**
  - $*$ $P_\Xi$ **: momentum**

- **Phase space divided in** $12 \times 10^6$ **cells**

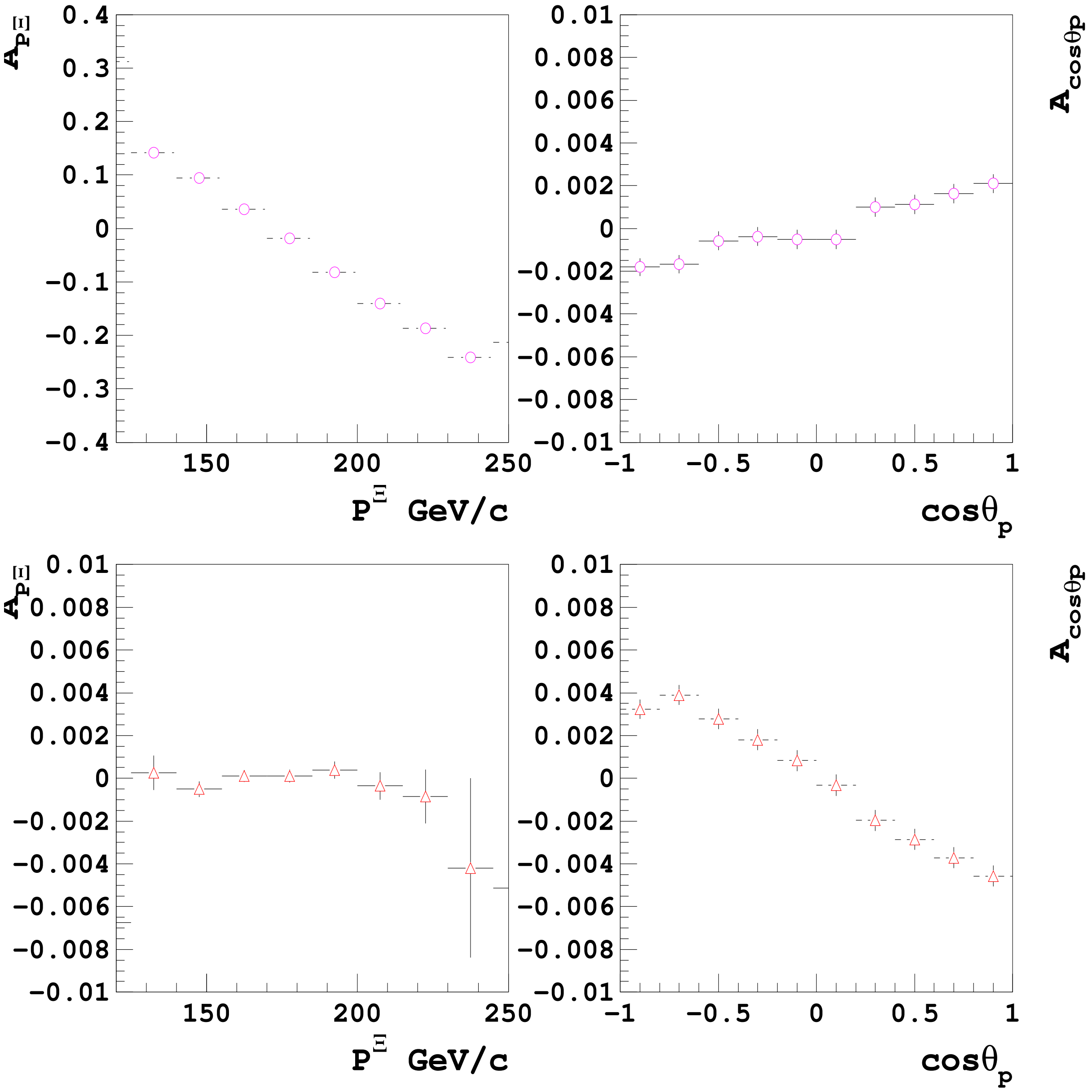
- **Phase space density of** $\bar{\Xi}^+$ **equalized to** $\Xi^-$ **by weighting method**



# EFFECTS OF THE EQUALIZATION



# ACCEPTANCE ⟺ CP VIOLATION




○ ⇒ *Raw asymmetries between MC, based on reconstructed $\overline{\Xi}^+$ and $\Xi^-$ (DATA)*

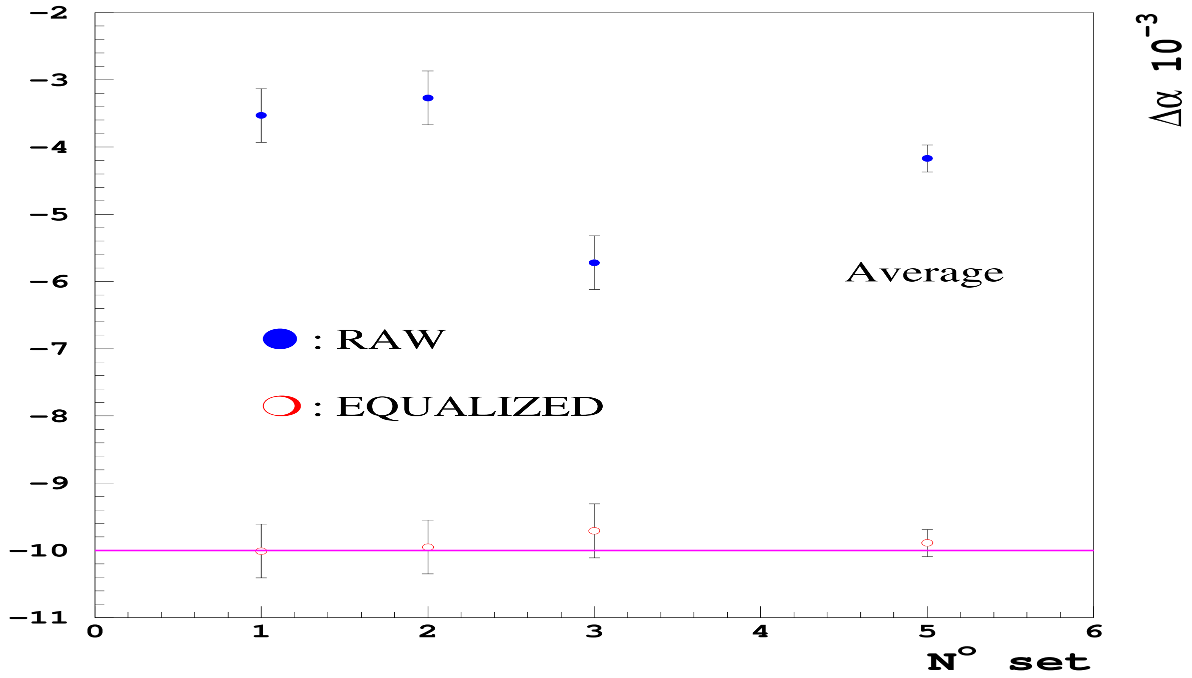
△ ⇒ *Asymmetries between MC of $\overline{\Xi}^+$. The 2 samples differ in $\alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}$ by* **$\Delta\alpha$ = 0.01**

# EQUALIZATION PROCESS TESTED WITH HYBRID MC

- **3 MC each based on** $1^{\cdot}000^{\cdot}000$ $\overline{\Xi}^+$ **and** $6^{\cdot}000^{\cdot}000$ $\Xi^-$ **from DATA**

- **Each MC has** $\sim 20^{\cdot}000^{\cdot}000$ $\overline{\Xi}^+$ **and** $\sim 150^{\cdot}000^{\cdot}000$ $\Xi^-$

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




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

- **In terms of the Asymmetry** $\mathcal{A}_{\Xi\Lambda}$

$$\boxed{\mathcal{A}_{\Xi\Lambda} = (\mathbf{-16.9} \pm \mathbf{0.4}) \times 10^{-3}}$$

# SUMMARY OF THE SYSTEMATICS

**In terms of the asymmetry** $\delta(\mathcal{A}_{\Xi\Lambda}) = \frac{\Delta\alpha}{2\alpha_\Xi\alpha_\Lambda}$

| | |
|---|---|
| *x and y Displacement at target* | $< 1.5 \times 10^{-3}$ |
| *Equalization process* | $< 0.4 \times 10^{-3}$ |
| *Interactions* | $< 0.9 \times 10^{-4}$ |
| *Temporal changes* | $< 0.5 \times 10^{-4}$ |
| *Backgrounds* | $< 2.1 \times 10^{-4}$ |

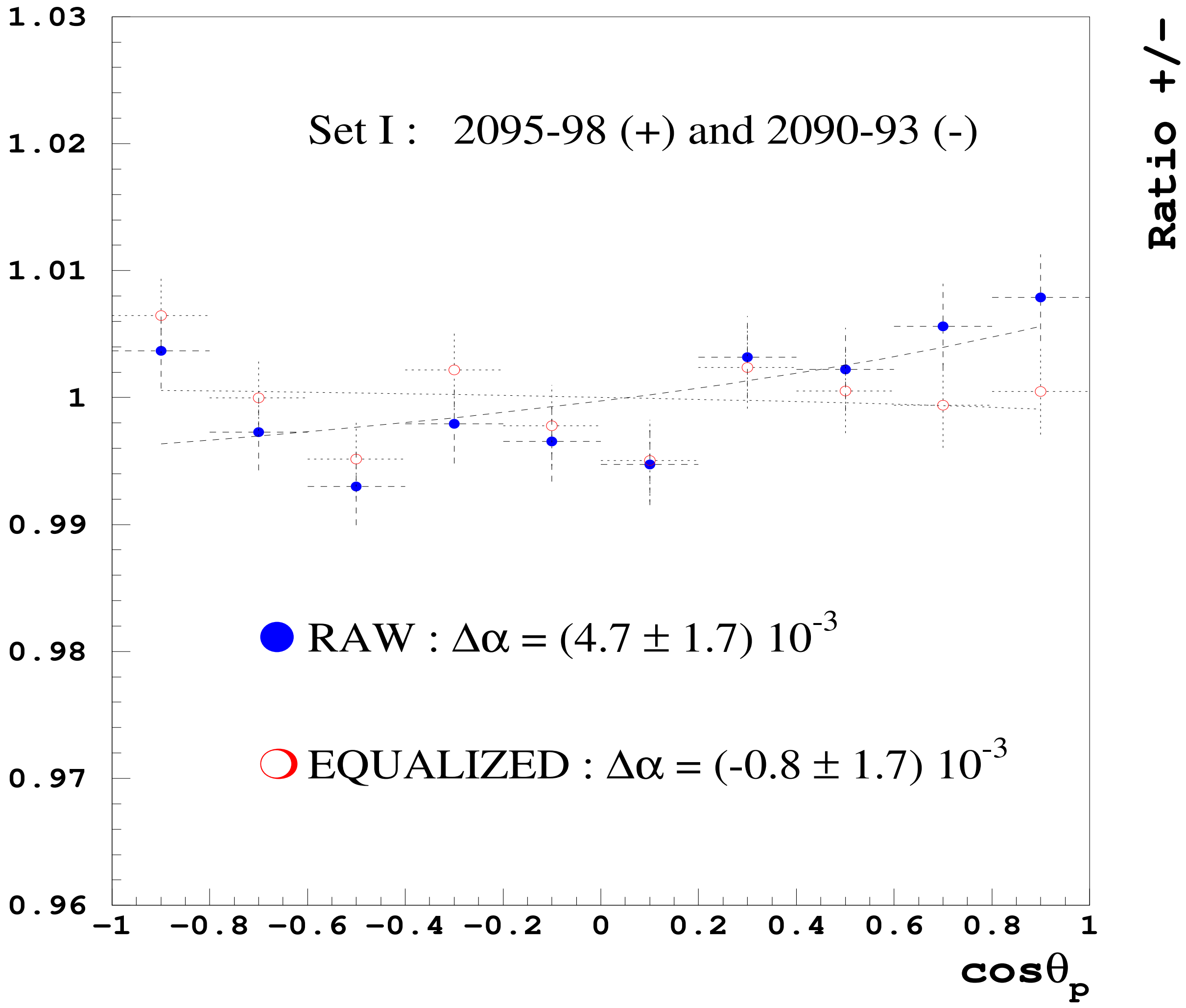
***TOTAL*** $< 1.6 \times 10^{-3}$

# PRELIMINARY RESULTS

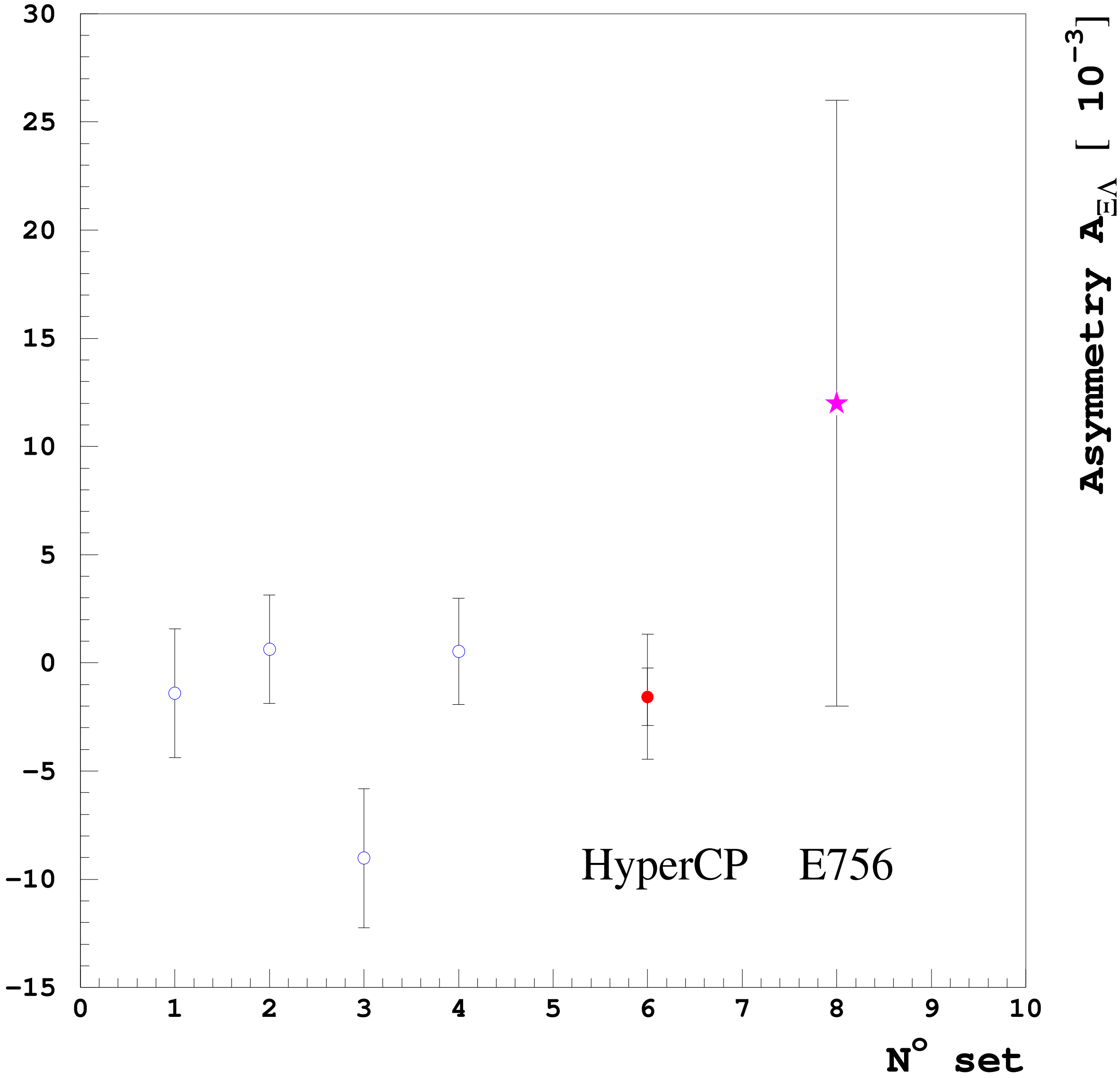
## The data sets and the total number of events remaining after all cuts :

| Set | $\overline{\Xi}^+$ | $\Xi^-$ | Nb. events of $\overline{\Xi}^+$ | Nb. events of $\Xi^-$ |
|---|---|---|---|---|
| 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 % ($\Xi^-$) of the data**



# PRELIMINARY RESULTS




$$\boxed{\mathcal{A}_{\Xi\Lambda} \quad = \quad (-1.6 \pm 1.3 \pm 1.6) \times 10^{-3}}$$

**stat. syst.**

# CONCLUSIONS

- ***HyperCP*** **had successful 1997 and 1999 runs and has collected the largest samples of** $\Xi^-$ **and** $\overline{\Xi}^+$ **decays in the world. The projected statistical sensitivity to CP asymmetry is 1.4** $\times\, 10^{-4}$**.**

- **Detailed systematic studies are in progress. Analysis of the entire data set should push them well below an upper present limit of 1.6** $\times\, 10^{-3}$**.**

- **We studied and tested a method to cope with the differences in production between** $\Xi^-$ **and** $\overline{\Xi}^+$**. This method could be applied in principle to the entire sample.**

- **A preliminary result of the asymmetry in the decays of** $\Xi$ **and** $\Lambda$**, based on 1.7** $\%$ **of the data, is consistent with zero**

$$\mathcal{A}_{\Xi\Lambda} = (\mathbf{-1.6} \pm 1.3^{stat.} \pm 1.6^{syst.}) \times 10^{-3}$$