# HyperCP Experiment : Search for direct CP Violation in the Decays of $\Xi^-/\overline{\Xi}^+$ and $\Lambda/\overline{\Lambda}$ Hyperons

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

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# Talk summary

- Physics Motivation
- Description of the apparatus
- Direct CP violation in hyperon decay
- Preliminary data will be presented to illustrate systematics
- Status of the hybrid MC
- Other physics topics
- Conclusions

# PHYSICS MOTIVATION

- Perform a sensitive search for direct CP violation in the decays :

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

  at the level of $10^{-4}$ !!!

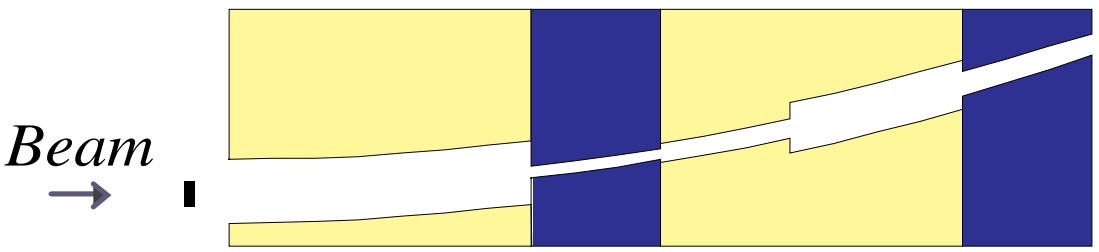
## WHY Ξ HYPERONS FOR CPV SEARCH ?

- Search for direct CP violation outside the decays of $K \rightarrow 2\pi$

- Hyperons can be produced in large quantities $\Rightarrow$ small statistical error.

- The spectrometer can be fairly simple $\Rightarrow$ should minimize the systematic effects.

# Production of Hyperons




$$p\ (800\ \text{GeV/c}) + Cu \rightarrow \text{Hyperon} + X$$

Central orbit momentum = 157 GeV/c at 1.67 T
Bend angle = 19.5 mrad

$\Omega$ , $\Xi$ , $\Sigma$ , produced at $0^0$ are unpolarized

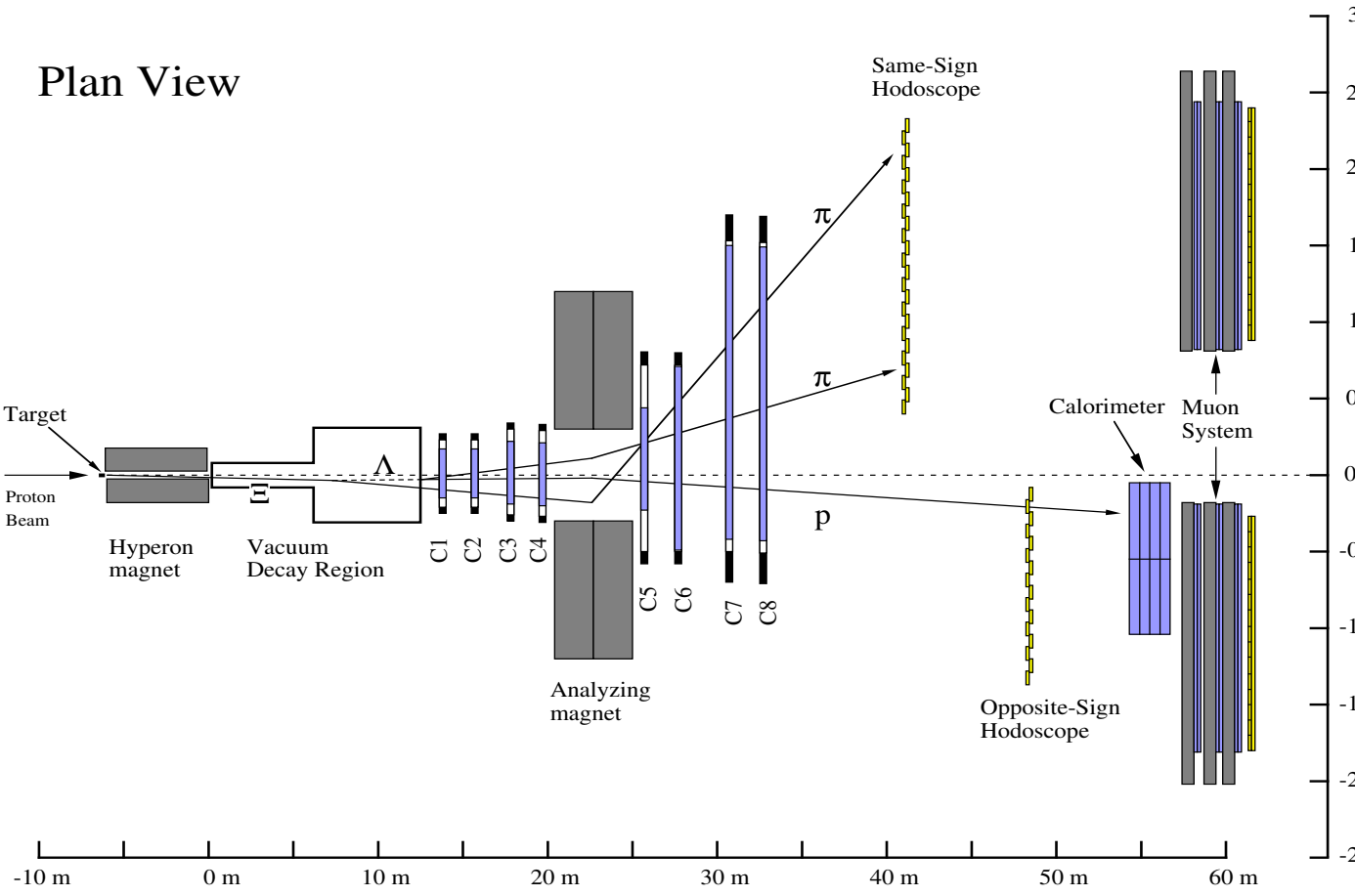
Beam incidence can be varied in the horizontal plane from - 2.5 mrad to 2.5 mrad to produce a small vertical polarization *P*

$$P \propto p_t$$

With 6 cm Cu and negative selection
or
2.2 cm Cu and positive selection

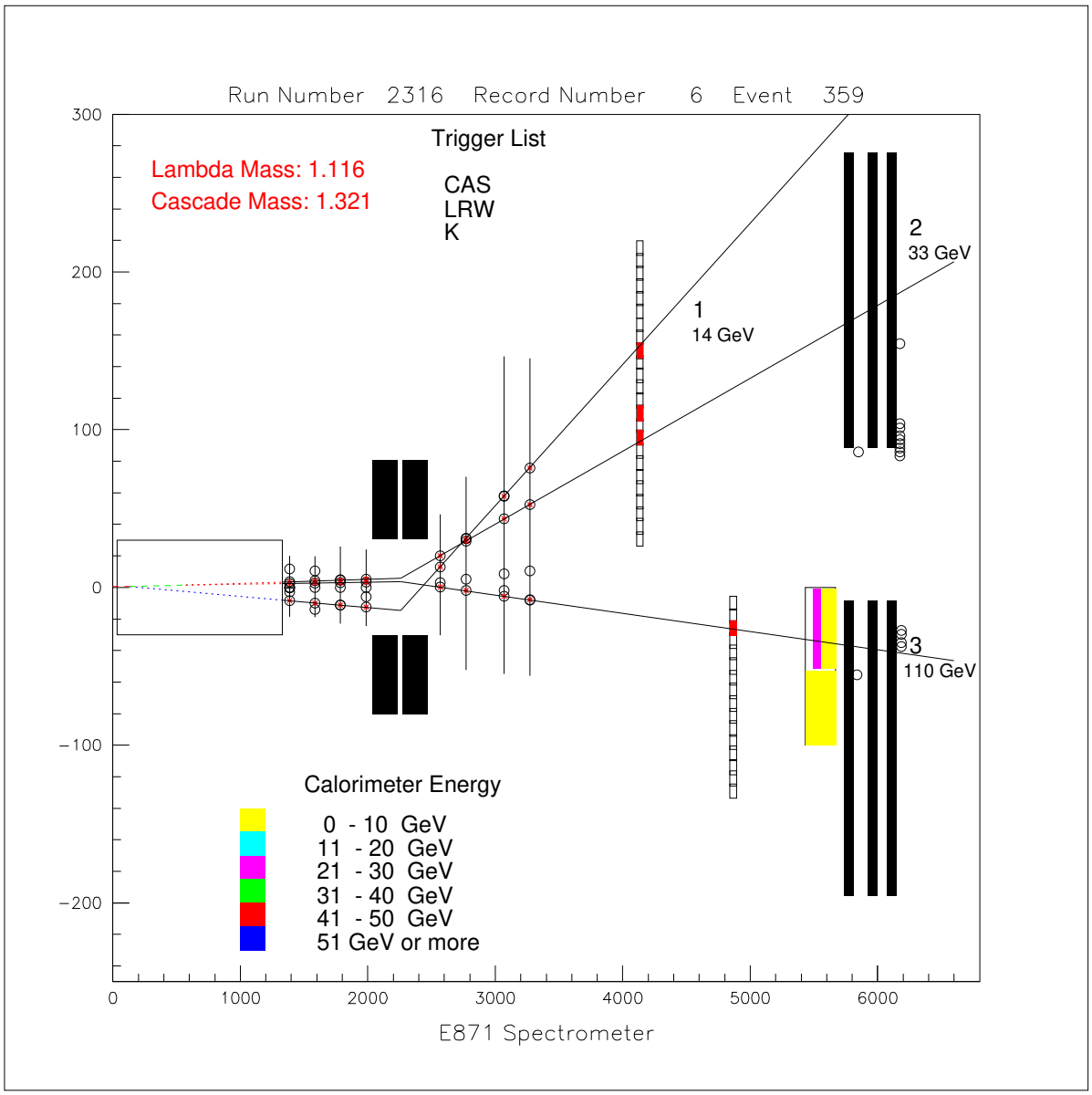
$1.5\ 10^{11}$ p/spill on target gives about 14 MHz at exit
(p , $\pi$ , $\kappa$ and hyperons)

# Hyper*CP* Spectrometer

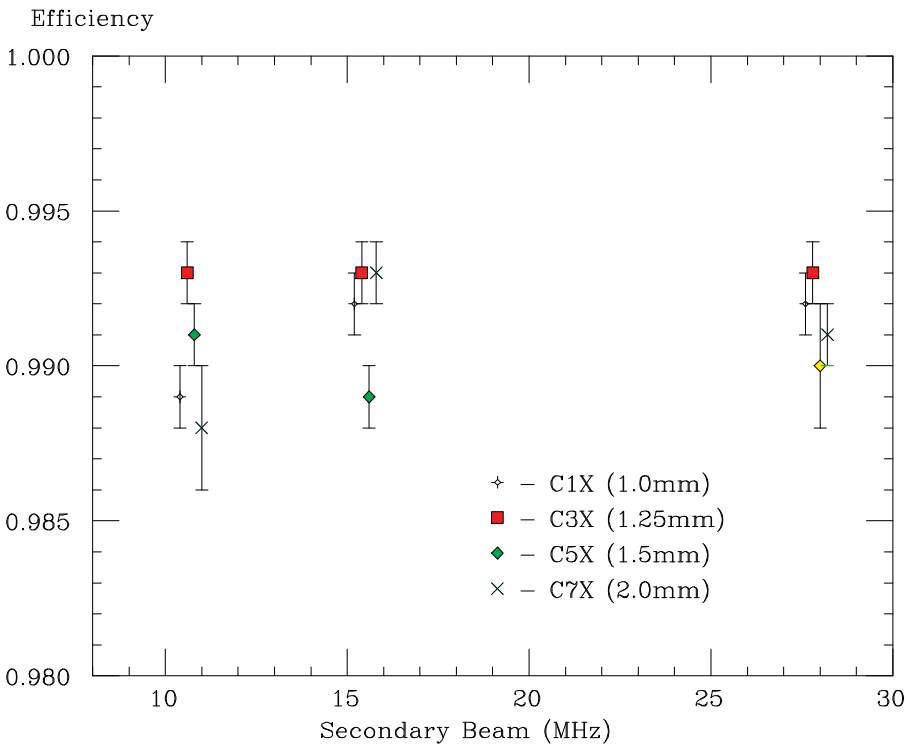



- 8 fast narrow-pitch wire chambers (32 planes)
- High-rate DAQ (13 MB/s or 63K events/s to tape)
- Simple trigger (2 particles of opposite signs and calorimeter energy for Ξ and K)

# A TYPICAL EVENT DISPLAY



# Performance of the spectrometer




- Average efficiency 0.992 independent of rate
- No evidence of aging
- Fast, all the signal within 2 buckets (2 x 18.9 ns) in front chambers and 5 buckets in rear chambers

| 14 MHz channeled beam | negative | positive |
|---|---|---|
| Trigger rate | 30 KHz | 25 KHz |
| $\Xi \rightarrow \Lambda\pi$ yield | 1600 Hz | 150 Hz |
| $K \rightarrow \pi\pi\pi$ yield | 100 Hz | 120 Hz |

# NONLEPTONIC 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**

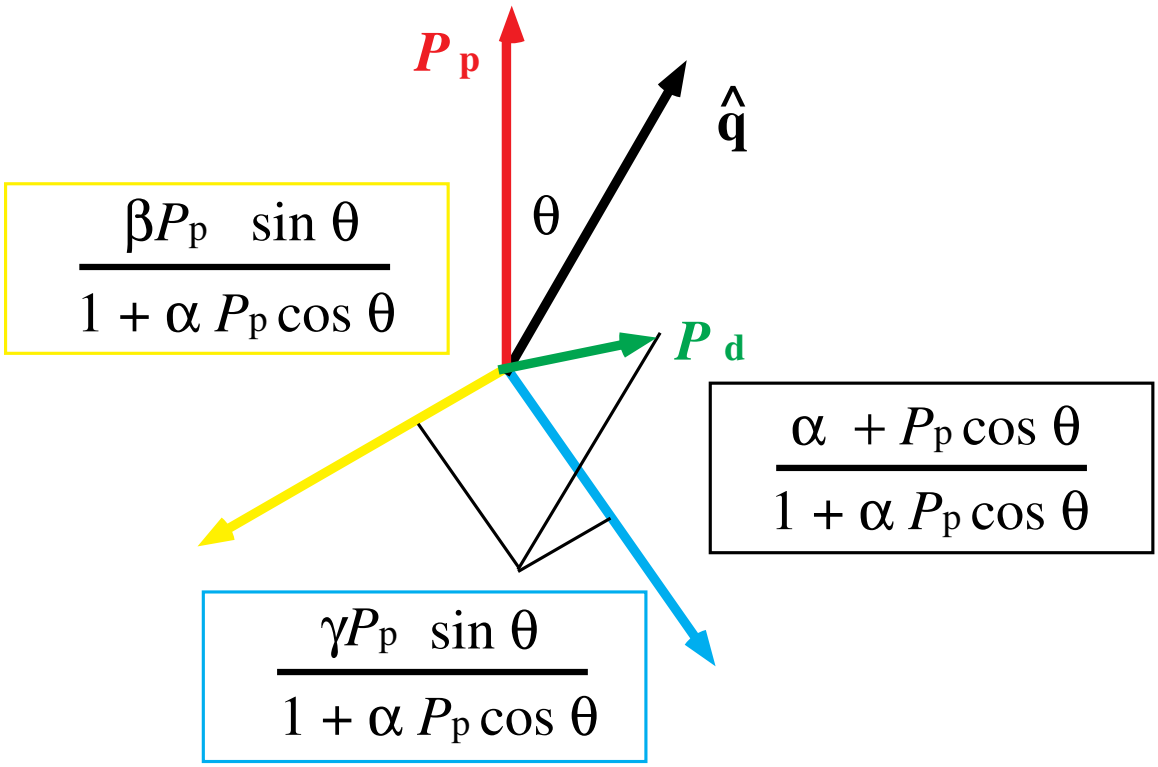
- **Decay parameters (Lee-Yang variables) :**

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

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

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

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



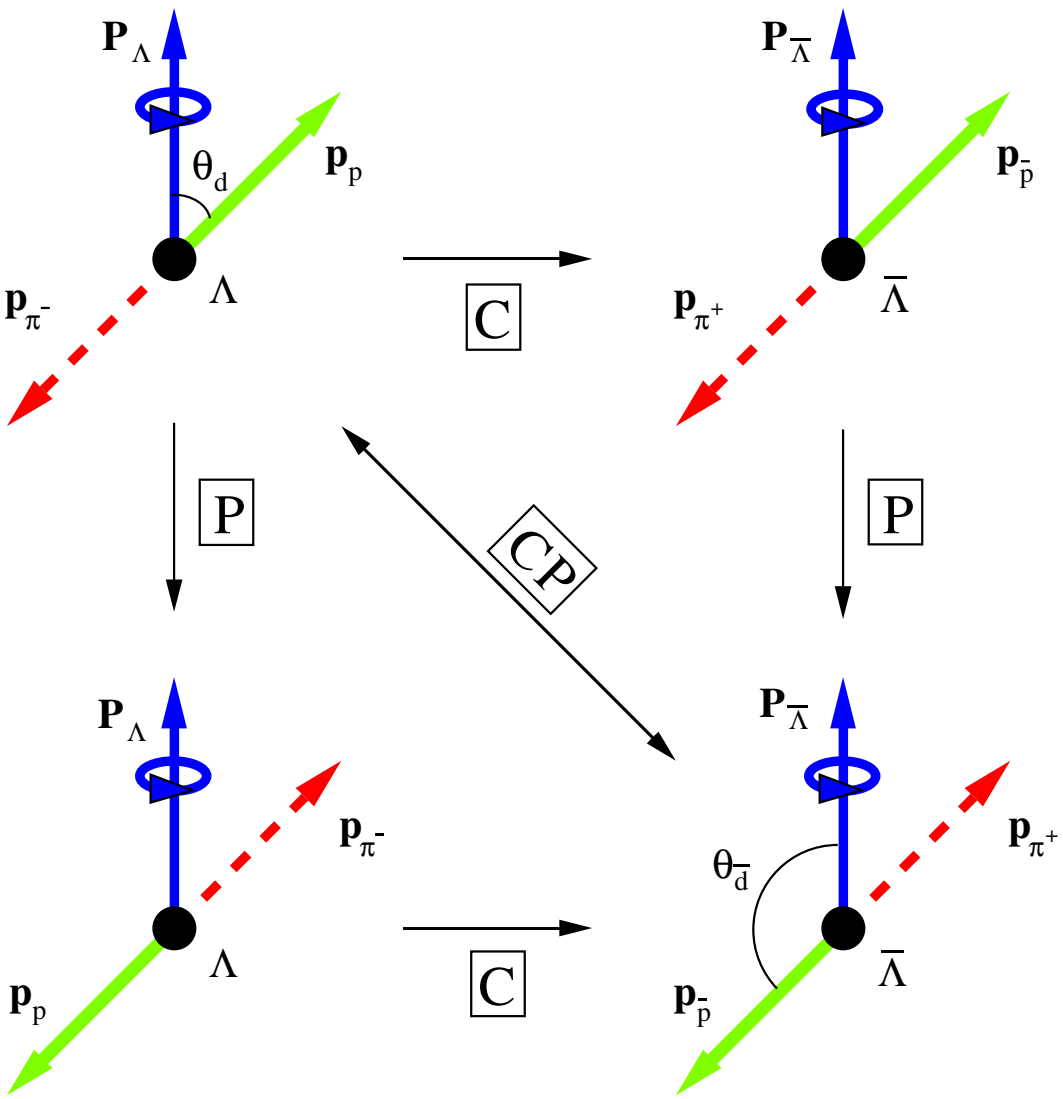

$$\vec{\mathcal{P}}_d = \frac{(\alpha + \vec{\mathcal{P}}_p \cdot \hat{q})\hat{q} + \beta\vec{\mathcal{P}}_p \times \hat{q} + \gamma\hat{q} \times (\vec{\mathcal{P}}_p \times \hat{q})}{(1 + \alpha\vec{\mathcal{P}}_p \cdot \hat{q})}$$

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

- **For an unpolarized parent baryon $\alpha$ is the magnitude of the longitudinal polarization of the decay baryon**

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

# CP IN HYPERON DECAYS




$$\alpha_{\bar{\Lambda}} = -\,\alpha_{\Lambda}$$

$\Lambda \rightarrow p\pi$ decay under CP transformation

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

| Experiment | Decay Mode | $A_\Lambda$ |
|---|---|---|
| R608 at ISR | $pp \to \Lambda X, \bar{p}p \to \bar{\Lambda} X$ | -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 |

# Hyper$\mathcal{CP}$ APPROACH

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

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

**identified via decays**

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

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

# THEORETICAL PREDICTIONS

- **Superweak model predicts**

## No $\Delta$S=1 CP violation

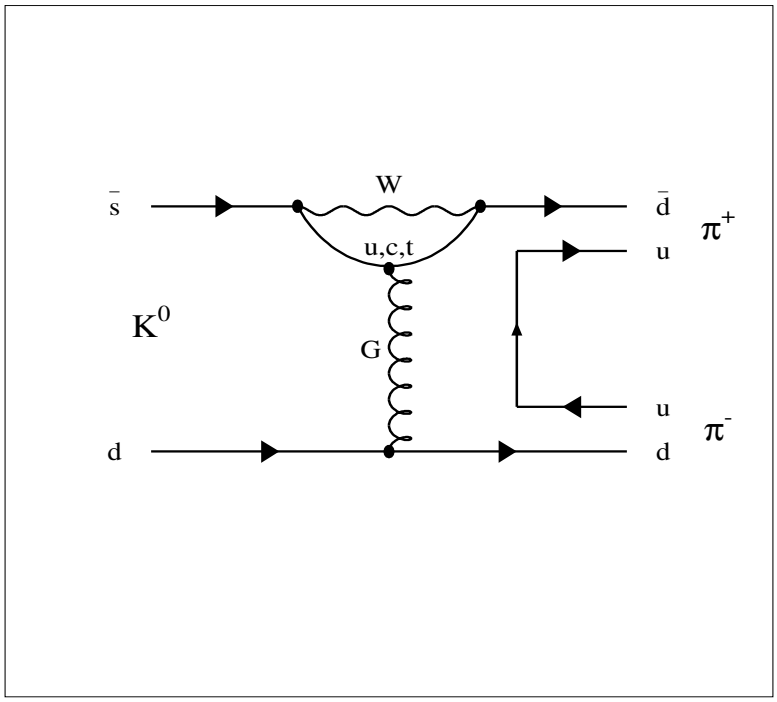
- **For $\Lambda \to p\,\pi$ decay**

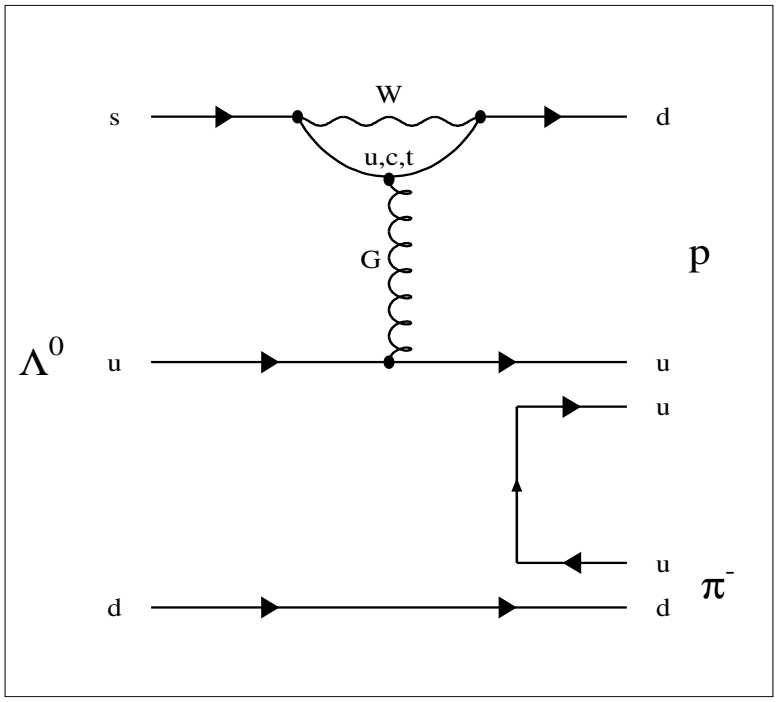
| | $\Delta_\Lambda$ | $A_\Lambda$ | $B_\Lambda$ |
|---|---|---|---|
| **CKM** | $< 10^{-6}$ | $(-5,-1) \times 10^{-5}$ | $(0.6,3) \times 10^{-4}$ |
| **Weinberg** | $-8 \times 10^{-6}$ | $-2.5 \times 10^{-5}$ | $1.6 \times 10^{-3}$ |
| **Left-Right** | **0** | $(-0.1,6) \times 10^{-4}$ | $7 \times 10^{-4}$ |

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

| | $\Delta_\Xi$ | $A_\Xi$ | $B_\Xi$ |
|---|---|---|---|
| **CKM** | **0** | $(-10,-0.5) \times 10^{-5}$ | $(10,1) \times 10^{-3}$ |
| **Weinberg** | **0** | $-3.2 \times 10^{-4}$ | $3.8 \times 10^{-3}$ |
| **Left-Right** | **0** | $(-2.5,6) \times 10^{-5}$ | $-3.1 \times 10^{-4}$ |

# DIRECT ΔS=1 CP VIOLATION IN KAON AND HYPERON DECAYS



- **A non-zero value of $\epsilon'/\epsilon$ is due to interferences between CP phase and the phases of the Isospin amplitudes (I=0 or I=2).**

- **A non-zero value of $A_\Lambda$ is due to interferences between CP phase and the phases of the Isospin amplitudes ($\Delta$I= 1/2 or $\Delta$I=3/2) and the phases of the S-wave and P-wave amplitudes.**

## MAIN DIFFERENCES ?

| $\epsilon'/\epsilon$ | $A_{\Lambda\Xi}$ |
|---|---|
| **Large cancellation between electroweak and strong penguin diagrams at large top mass** | **No such cancellation** |
| **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** |

# STATUS OF DATA ANALYSIS

- **Data collected between April and September of 1997 should yield**

$$1.2 \times 10^9 \text{ reconstructed } \Xi^-$$
$$0.3 \times 10^9 \text{ reconstructed } \overline{\Xi}^+$$

- **Since the end of the run:**
  - **Study, optimize and decide on official reconstruction code;**
  - **Bring up farm-processing code;**
  - **Determine various run-dependent parameters such as alignment constants, magnetic field maps, efficiencies etc.**

- **Preliminary event reconstruction has been done on Fermilab farms. Processed about 10% of the data with a total of 7,000 MIPS**

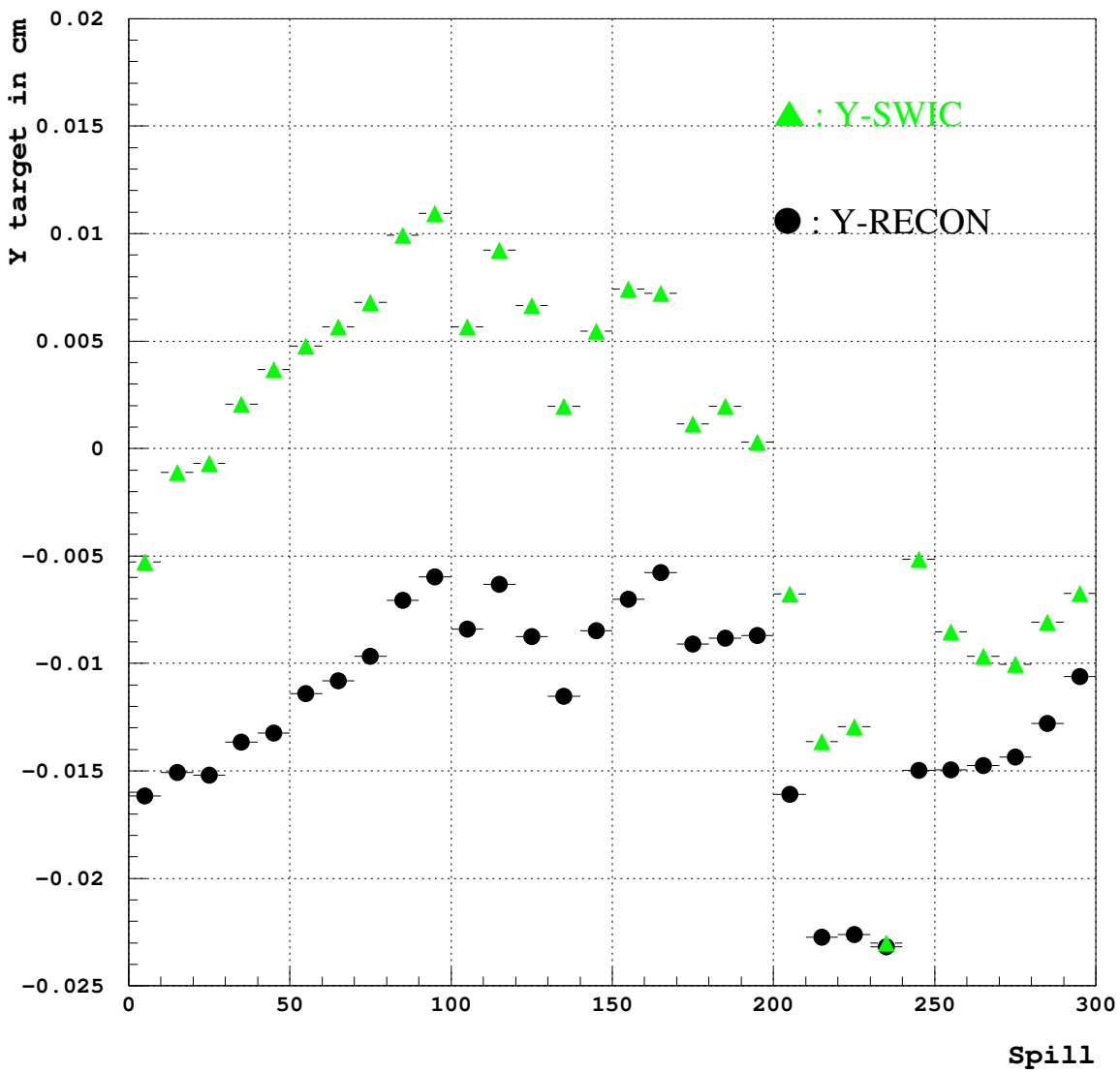
- **Start processing with the new reconstruction package and 20,000 MIPS. About 90% of the entire data set has already been processed**

# SYSTEMATICS

- **Acceptance differences**
  - **position and angle of beam on target**
  - **production cross sections**
  - **magnetic field**
  - **chamber efficiency**
  - **trigger efficiency**
  - **temporal changes**
- **different backgrounds for $\Lambda$, $\Xi^-$ versus $\overline{\Lambda}$, $\overline{\Xi}^+$**
- **Nonzero $\Xi^-$, $\overline{\Xi}^+$ polarizations**
- **Different interaction cross sections between $\pi^-$ and $\pi^+$ and between $p$ and $\overline{p}$**
- **data are VERY PRELIMINARY and are shown only to illustrate some aspects of the analysis**

# Position of beam

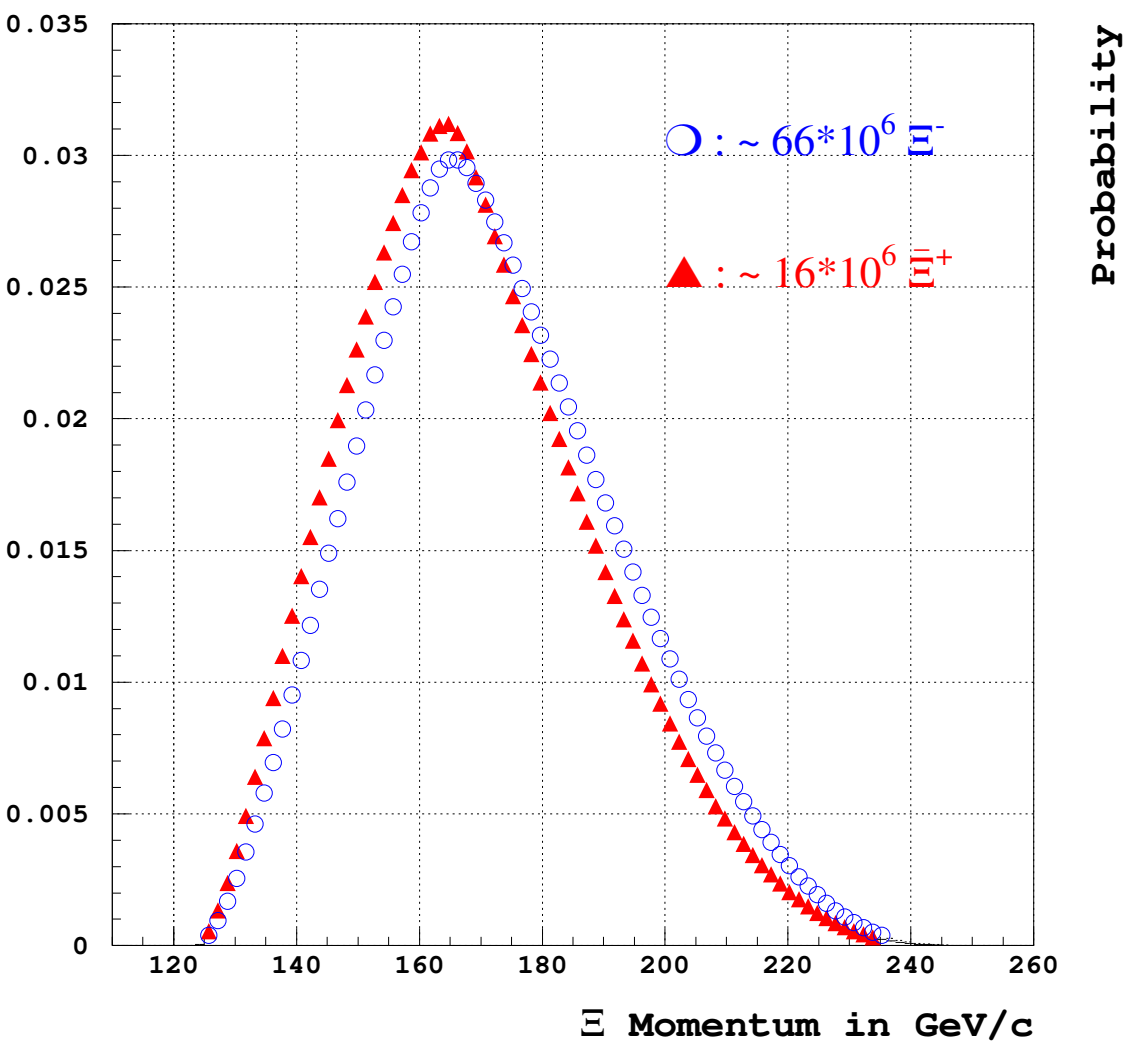
- **Change in beam position can lead to acceptance differences**




- **Y position of the beam as function of spill number. Measured by primary beam chambers and from the reconstruction of Ξ events**

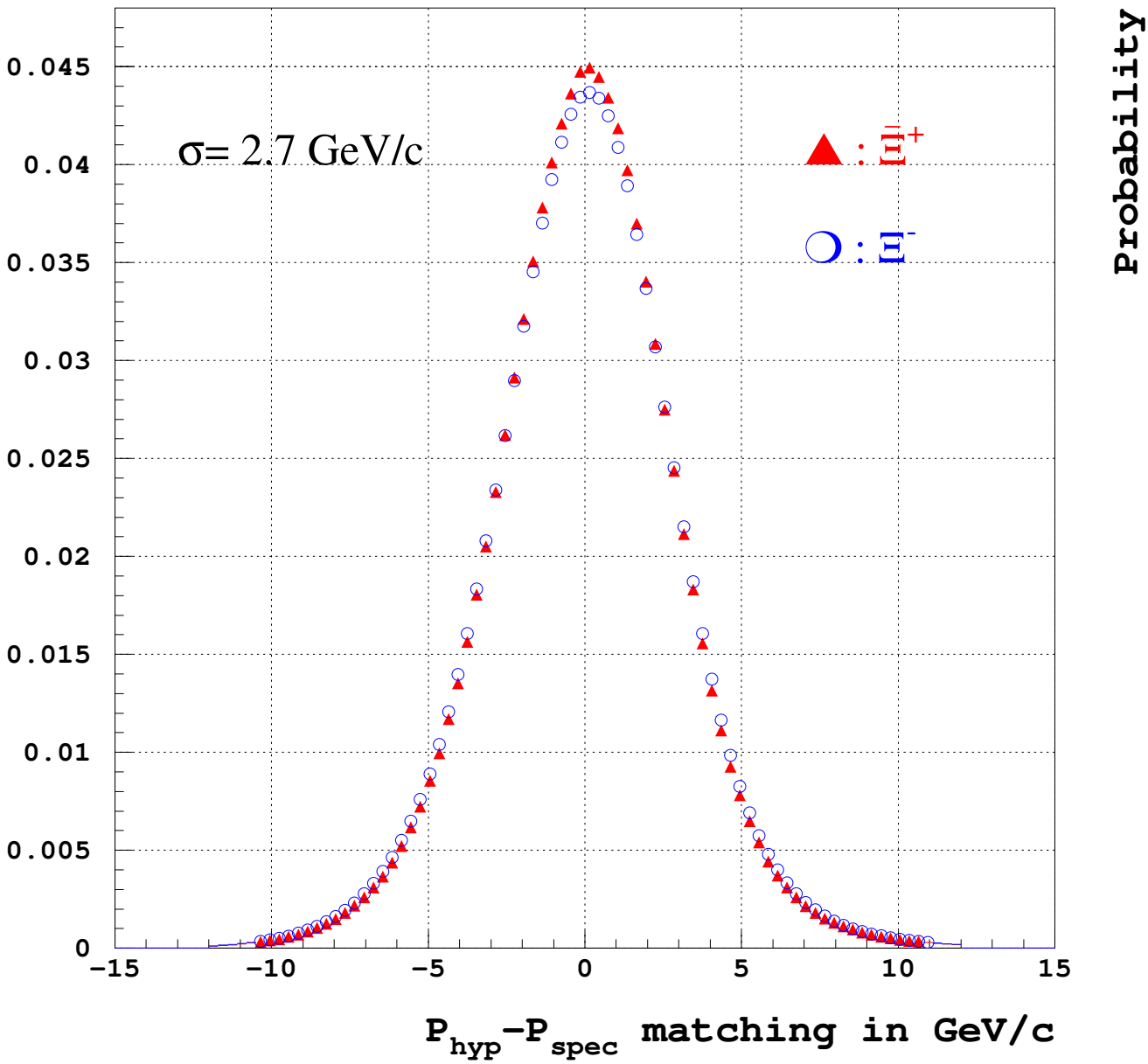
# Production cross sections

- **Differences in production dynamic can induce acceptance differences**



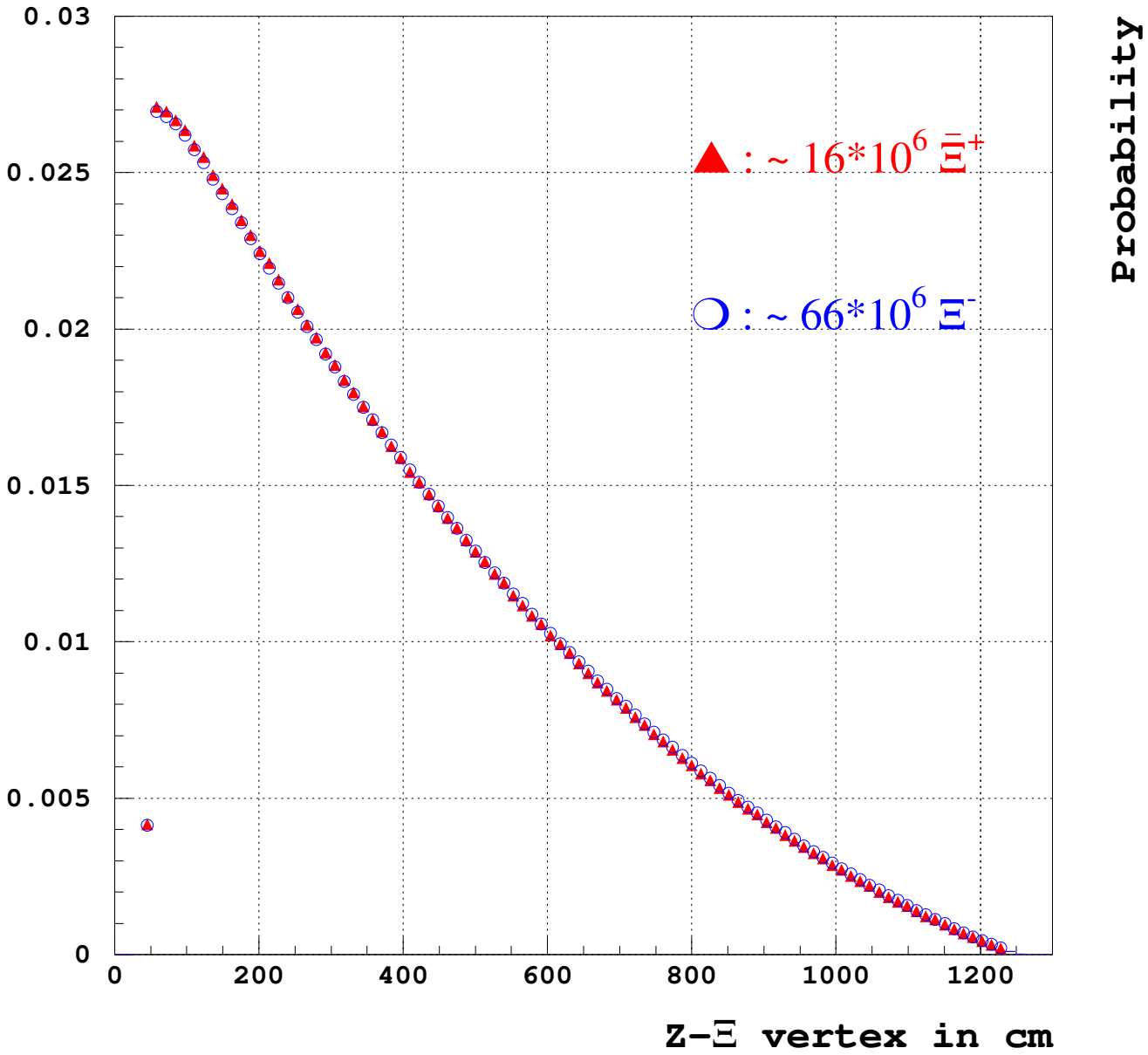

- **Momentum spectra for $\Xi^-$ and $\bar{\Xi}^+$ normalized to the same number of events**

# Magnetic fields control




- For a pointlike target the momentum of a particle is determined by its position and direction at the collimator exit, this can be used to calibrate the hyperon magnet.

# Ξ decay vertices distribution

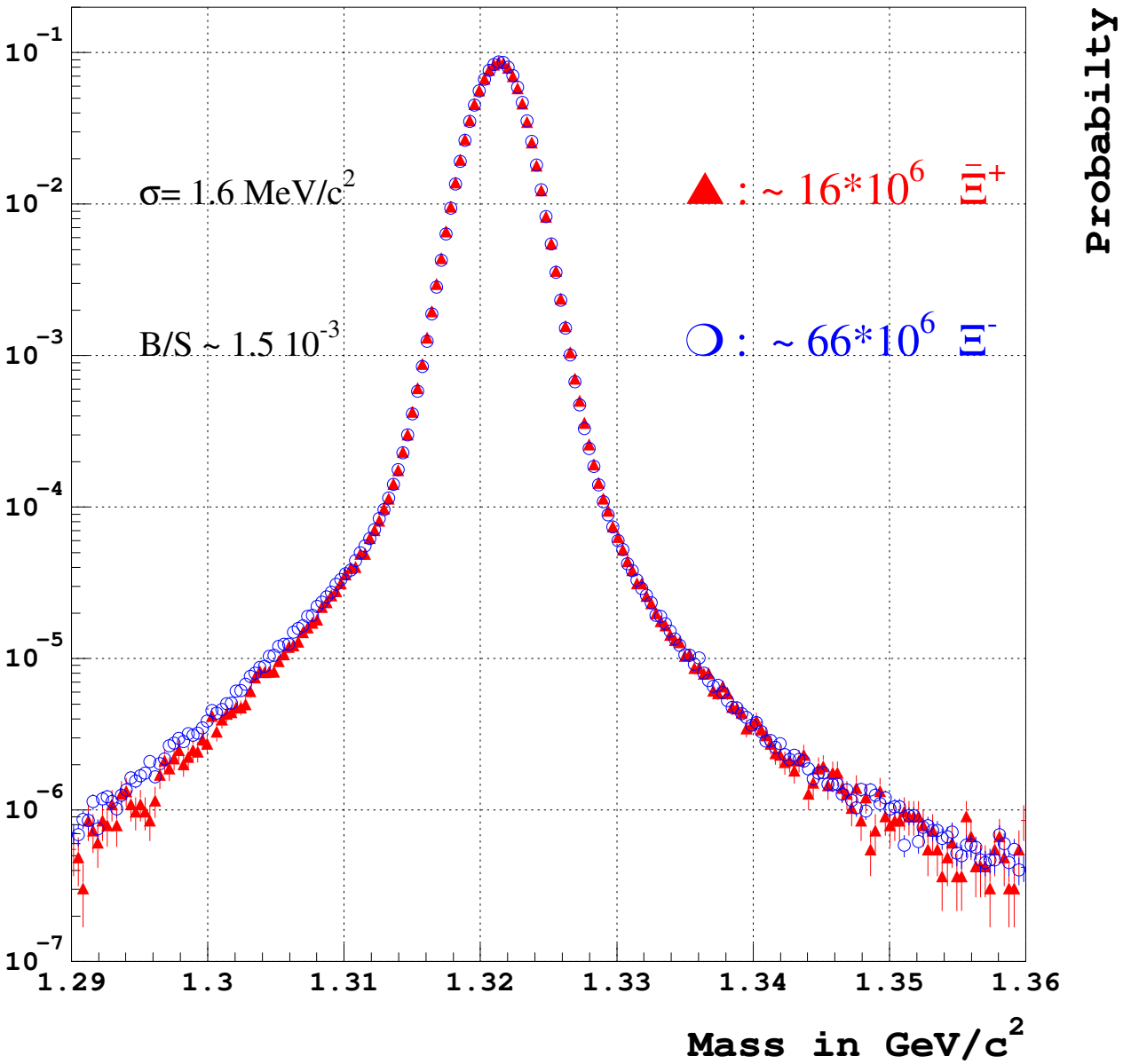



- Data for $\Xi^-$ and $\overline{\Xi}^+$ have been normalized to the same number of events
- Very similar dispite different momentum distributions

# Main sources of the $\Xi$ backgrounds

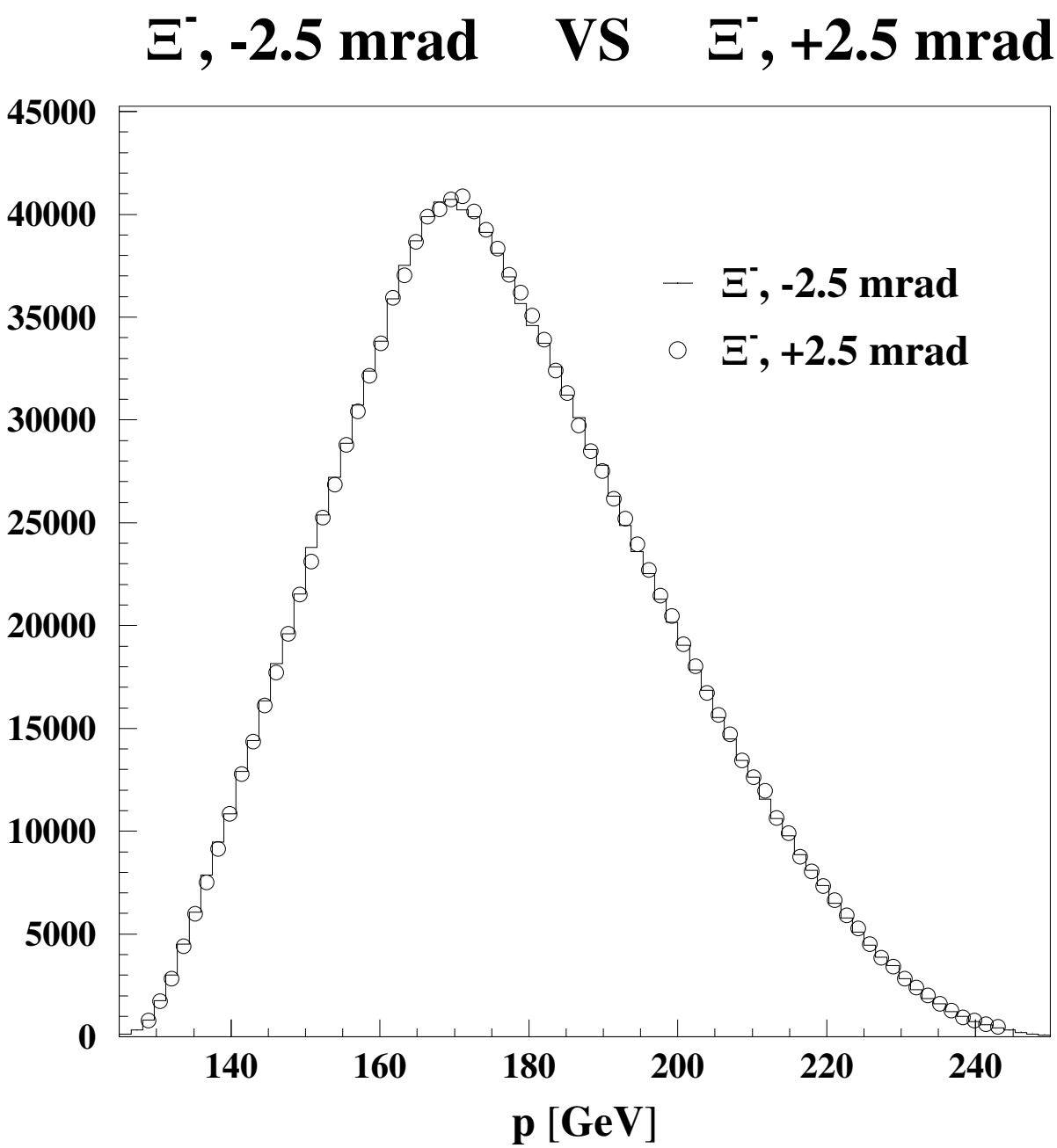
- **Hits misidentification $\rightarrow$ Bad reconstruction of the real $\Xi$ event**
- **Track misidentification**
- **Particle misidentification between the 2 $\pi$**
- **Semi-leptonic decay of $\Xi$.**
  **Example : $\Xi \rightarrow \Lambda e^{-} \overline{\nu_e}$**
  **Typical BR of $\sim 10^{-4}$**
- **Other particle decays reconstructed as $\Xi$.**
  **Example : $\Omega \rightarrow \Lambda \pi$**

# Mass spectra for $\Xi^-$ and $\overline{\Xi}^+$

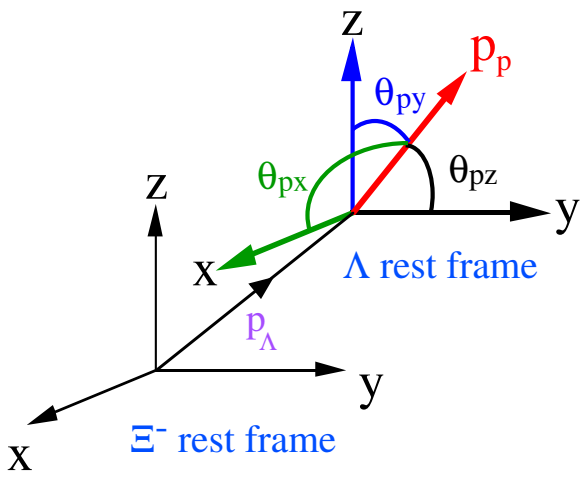


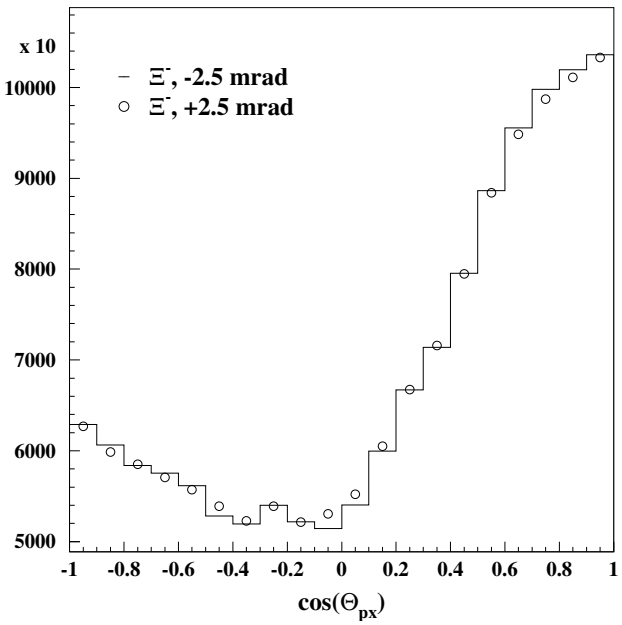

- **Background under the mass peak is about $1 \times 10^{-3}$ and tails are very similar for both charges**

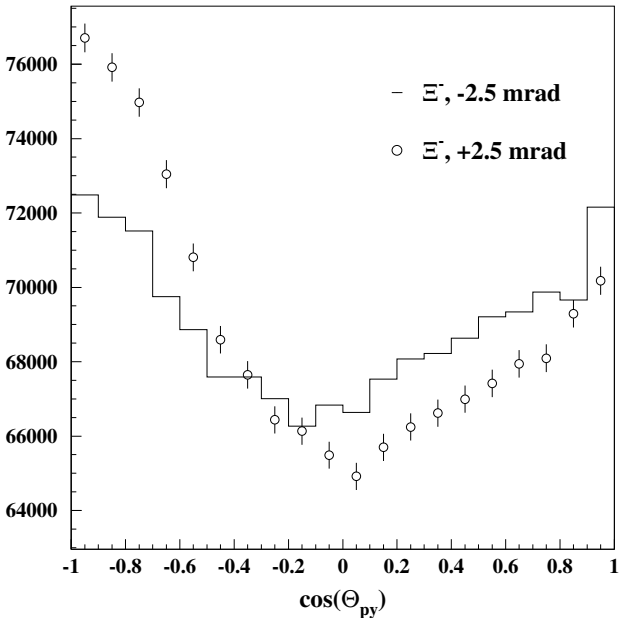
# Decay of $\Xi$ with small vertical polarization

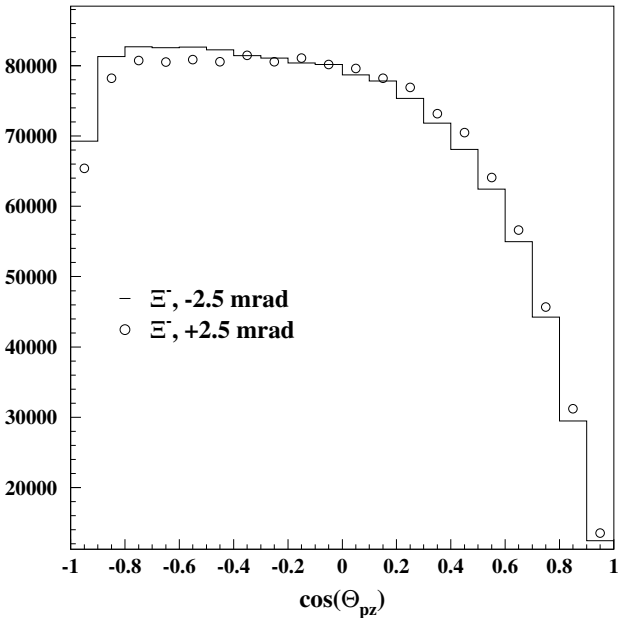



- **Production at $\pm 2.5$ mrad in the horizontal plane. Vertical polarization but in opposite direction for the two sets.**



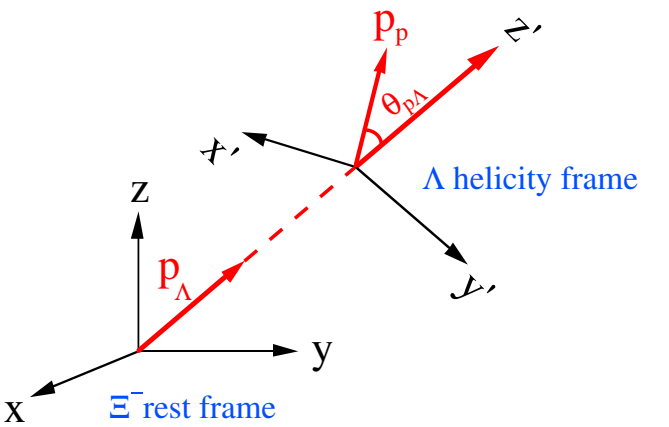



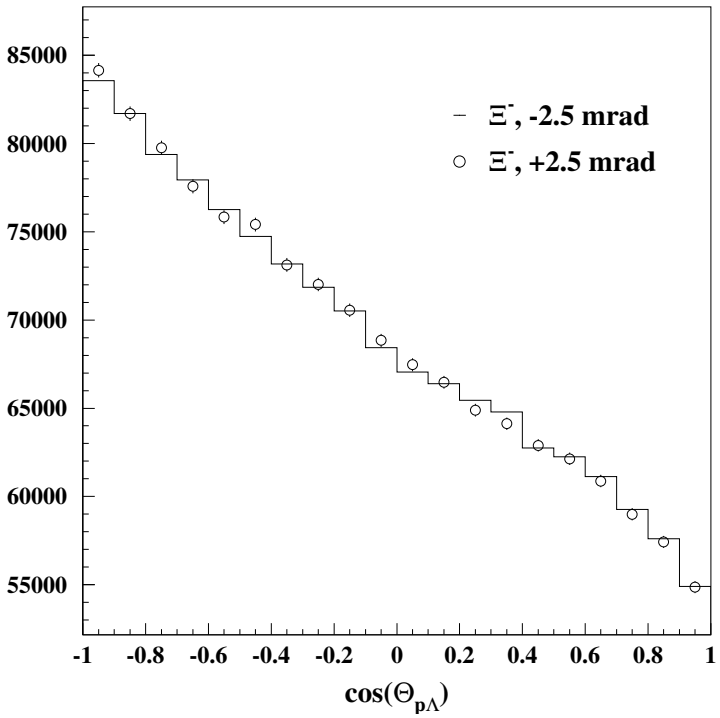




- **The effect of the small polarization is clearly seen in the $cos(\theta_{py})$ distribution in the $\Lambda$ rest frame**

## $\Xi^-$ (-2.5 mrad) vs $\Xi^-$ (+2.5 mrad)

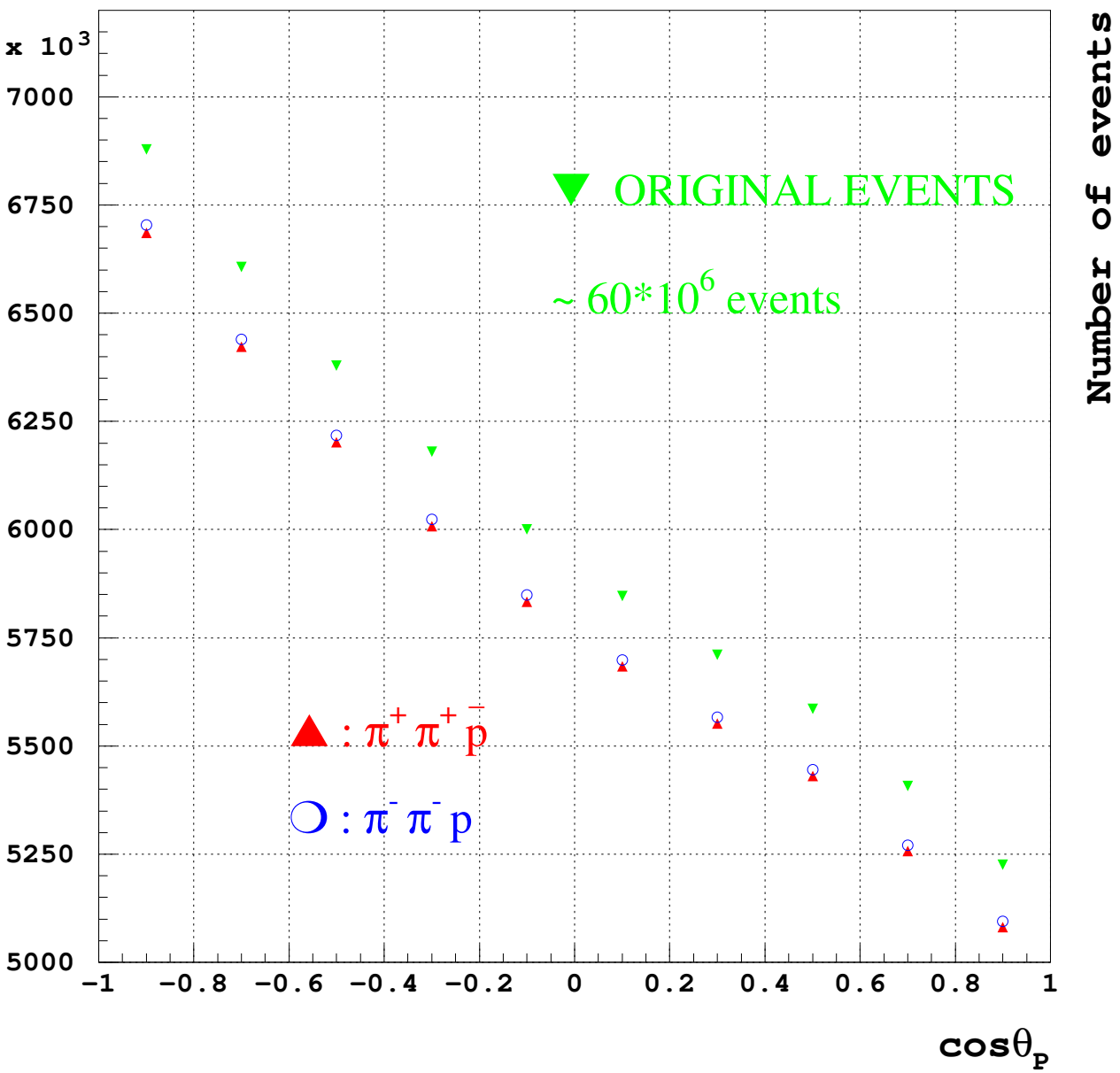



- **In the $\Lambda$ helicity frame the effect of the small polarization on the $cos(\theta_{p\Lambda})$ distribution is highly diluated**
- **Monte-Carlo studies show that a 1% polarization only modifies the slope of the $cos(\theta_{p\Lambda})$ at the $2 \times 10^{-4}$ level**

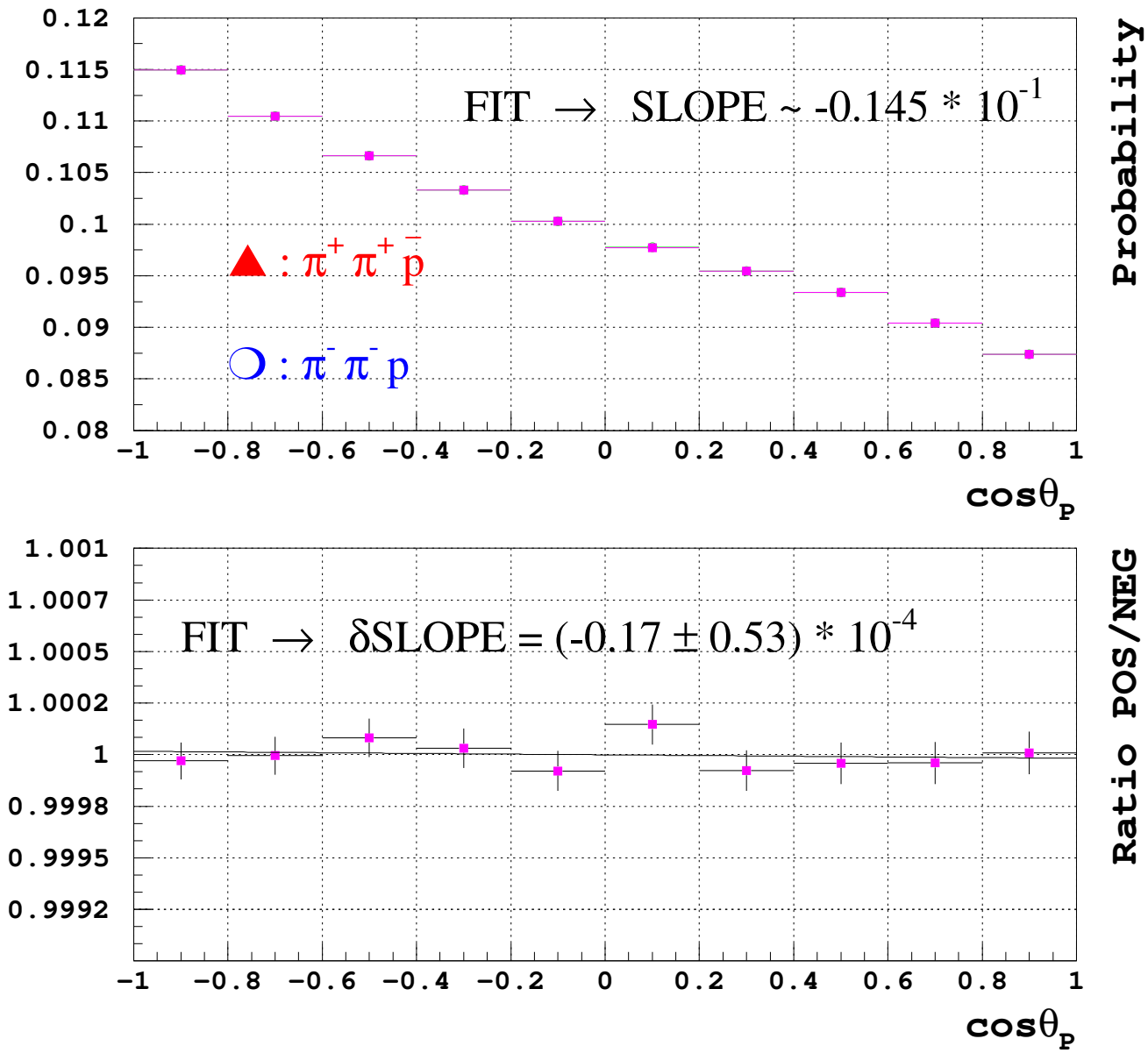
# Interactions

***Systematics due to Interaction Differences***



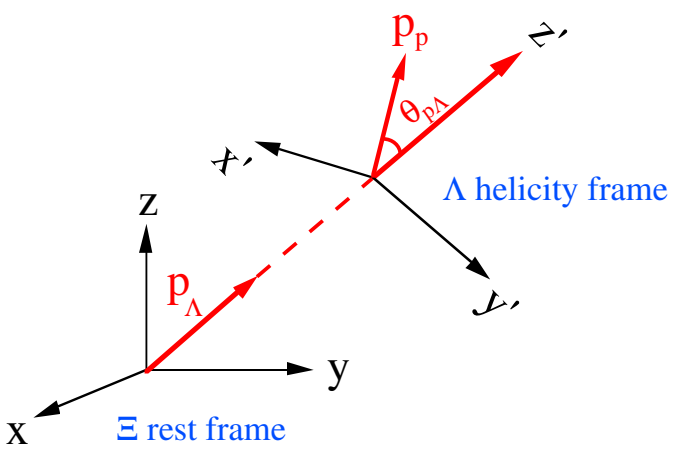

- **Simulation of the total cross-section interaction ⇒ Up bound estimation**

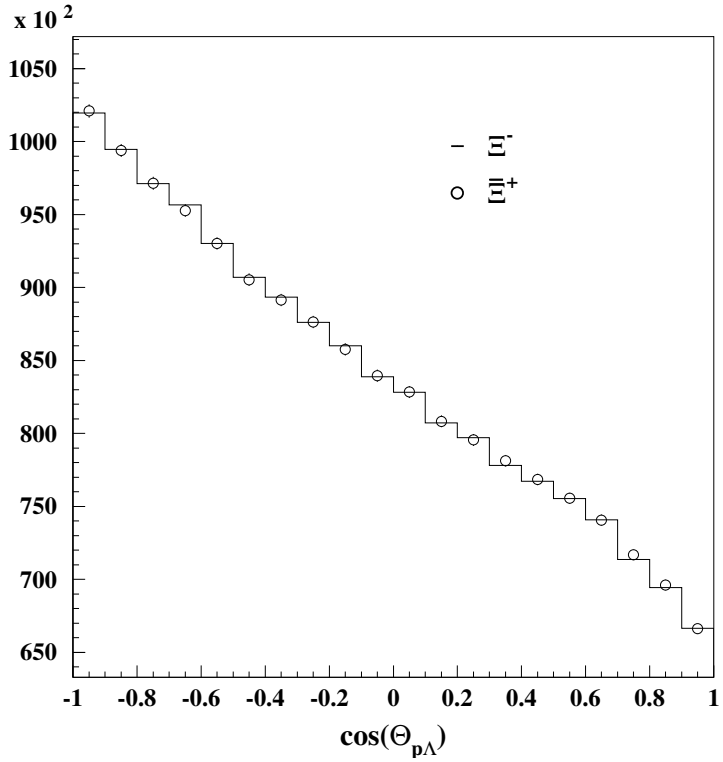
## *Systematics due to Interaction Differences*




- **For a given sample of Ξ events, using actual cross-sections, the number of remaining events (interaction of one of the decay particles) for both charges as function of $cos\theta_{p\Lambda}$**
- **The ratio shows very low $cos\theta_{p\Lambda}$ dependency**

$\Xi^-$ (0 mrad) vs $\overline{\Xi}^+$ (0 mrad)




- **This is the uncorrected plot which will be used for CP violation in hyperon decay**
- **A lot more work is needed before any number can be quoted about CP violation**

# STATUS OF THE HYBRID MC

## GOAL OF THE HYBRID MC ?

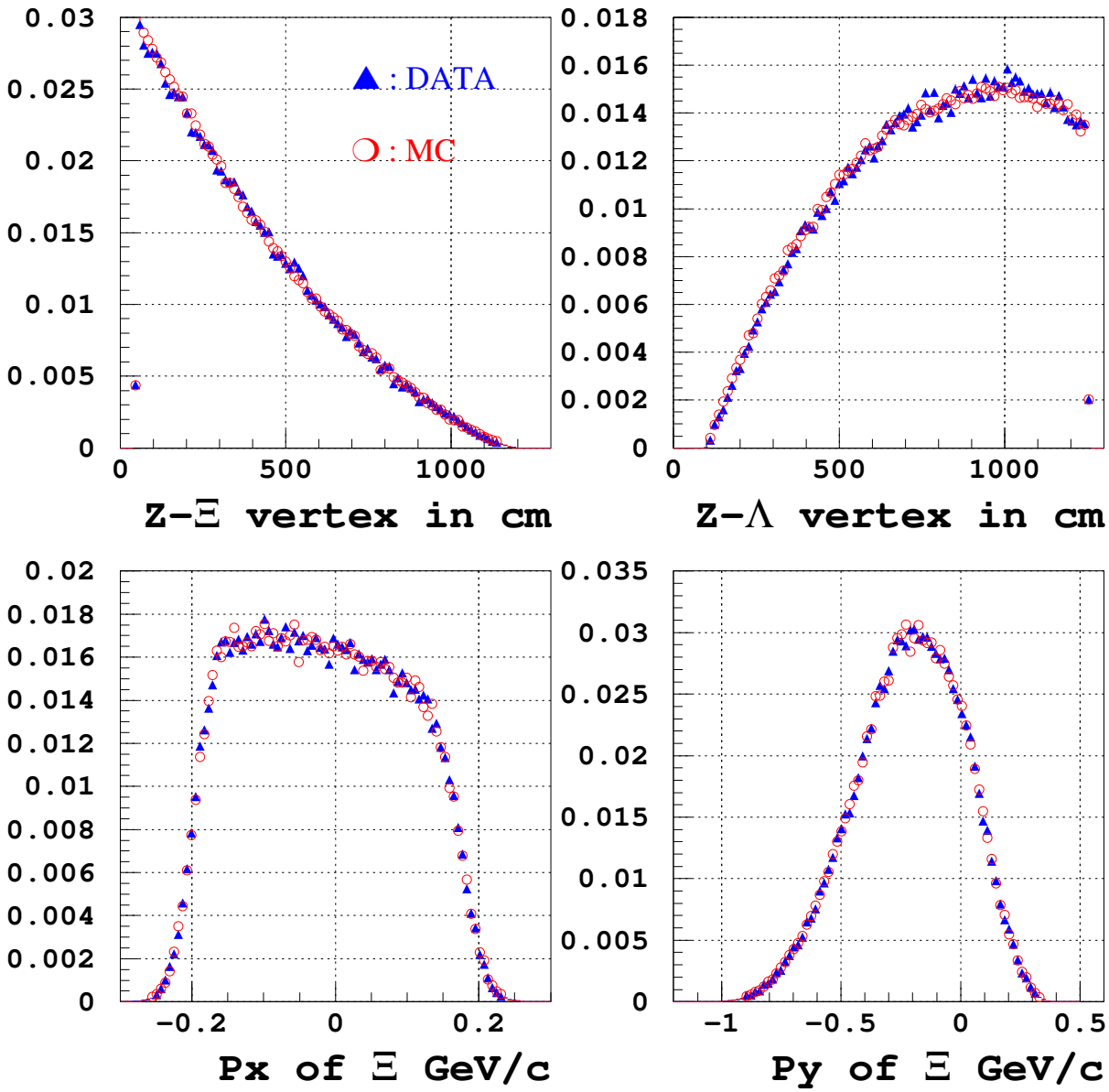
**Correct for acceptance $\Rightarrow$ Don't need a MC at the $10^{-4}$ level !**

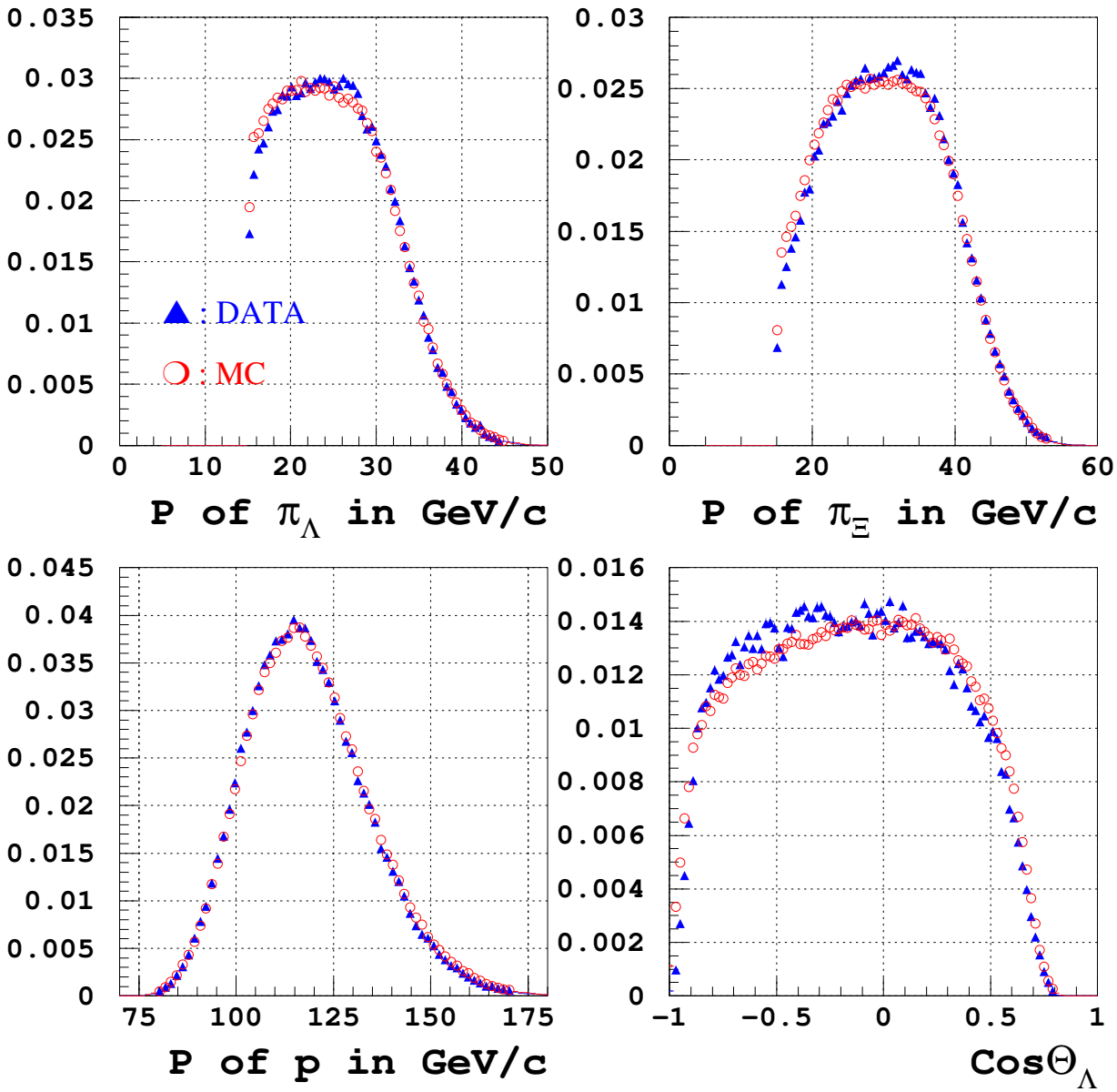
- **Consider the exit point at the collimator $(X_c, Y_c)$ and the vector momentum $\vec{P}_\Xi$ from a reconstructed event.**

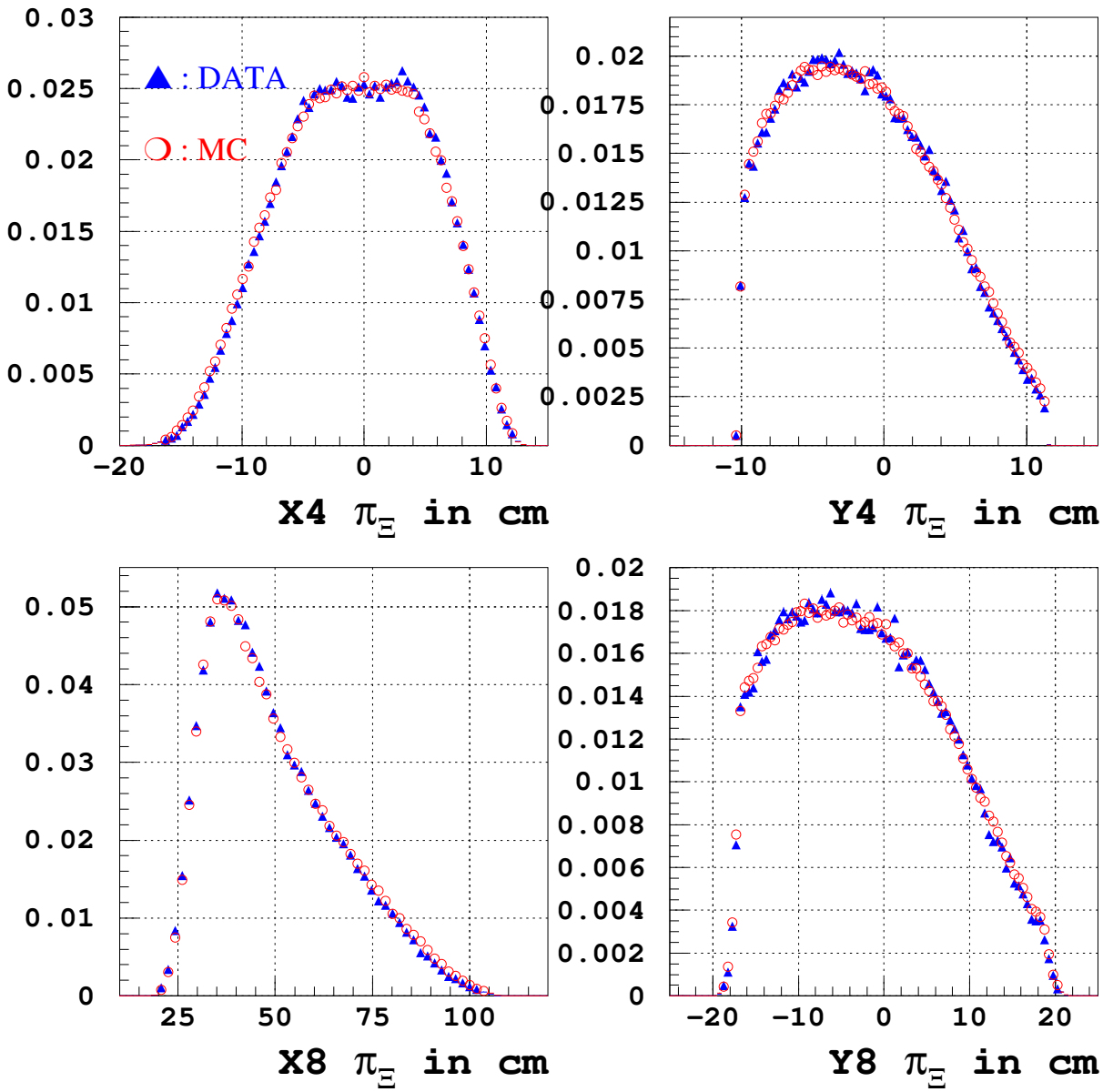
**THEN :**

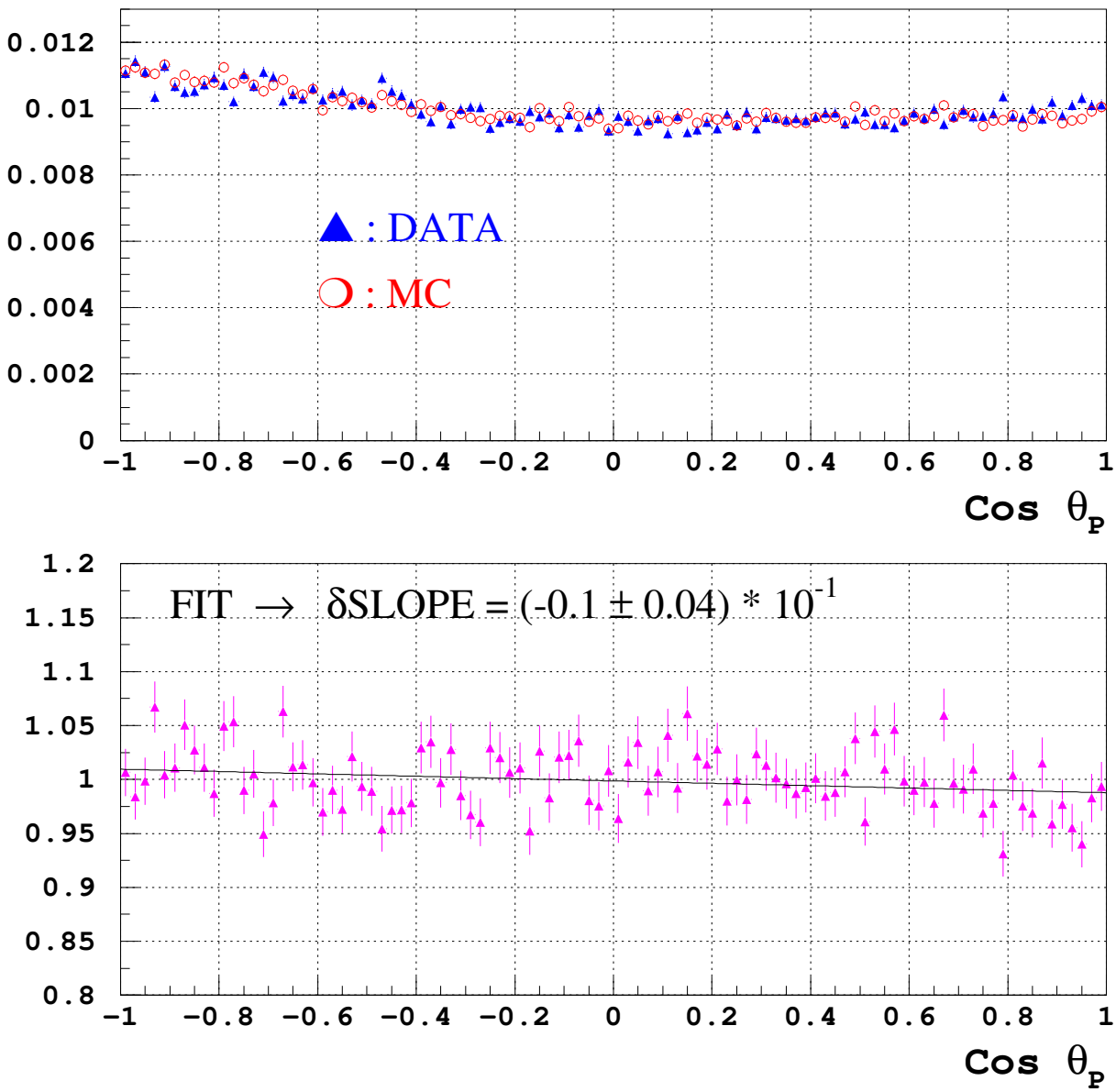
- **Consider the life time of $\Xi$ and $\Lambda$.**
- $\vec{Pol}_\Xi = 0 \Rightarrow$ **Decay distribution controlled by** $\alpha_\Xi\ \alpha_\Lambda$

- **Mainly geometric MC**
- **Hodoscopes efficiency**
- **NO Chamber and Calorimeter efficiency**
- **NO real tracking simulation**


▲ : DATA
○ : MC
Z–Ξ vertex in cm
Z–Λ vertex in cm
Px of Ξ GeV/c
Py of Ξ GeV/c


▲ : DATA
○ : MC
P of $\pi_\Lambda$ in GeV/c
P of $\pi_\Xi$ in GeV/c
P of p in GeV/c
Cos$\Theta_\Lambda$


▲ : DATA
❍ : MC
X4 $\pi_\Xi$ in cm
Y4 $\pi_\Xi$ in cm
X8 $\pi_\Xi$ in cm
Y8 $\pi_\Xi$ in cm




- $\alpha_\Lambda = 0.642 \pm 0.013,\ \epsilon_{rel} = 2\%$

- $\alpha_\Xi = -0.456 \pm 0.014\ ,\ \epsilon_{rel} = 3\%$

# OTHER PHYSICS TOPICS

- **CPV**
  - **In the $K$ / $\overline{K}$ system: K $\rightarrow 3\pi$**
  - **In the $\Omega$ / $\overline{\Omega}$ system: $\Omega^- \rightarrow \Lambda\, K^-$**

- **Production**
  - **Production cross sections, A-dependence and particle ratios of $\pi$, K, hyperons and their anti-particles**
  - **Production polarization of hyperons and anti-hyperons at low $x_F$ and low $p_T$**
  - **Search for parity violation**

- **Decays**
  - **Precision measurements of decay parameters, $\alpha$ (and $\beta$) of $\Xi \rightarrow \Lambda\pi$, and $\Omega \rightarrow \Lambda K$ decays**
  - **Search for $\Delta$S=2 decays**
    - $\Xi^- \rightarrow p\pi^-\pi^-$
    - $\Omega^- \rightarrow \Lambda\pi^-$
  - **Search for $\Delta$S=3 decay**
    - $\Omega^- \rightarrow p\pi^-\pi^-$
  - **Search for forbidden or rare decays**
    - $K^- \rightarrow \pi^-\mu^+\mu^-$
    - $K^- \rightarrow \pi^+\mu^-\mu^-$
    - $\Sigma^- \rightarrow p\mu^-\mu^-$
    - $\Sigma^+ \rightarrow p\mu^+\mu^-$
    - $\Xi^- \rightarrow p\mu^-\mu^-$

- **Discrete Symmetries**

  - **Search for CP violation**

    - **Asymmetry $B_\Xi$ for $\Xi^- \to \Lambda\pi^-$ decay**

  - **Search for T violation**

    - **edm of $\Xi$ hyperon**

  - **CPT test**

    - **Difference in masses in $\Xi, \Omega, \Lambda$, and K systems**
    - **Difference in lifetimes in $\Xi, \Omega$ and $\Lambda$ system**
    - **Difference in $\Xi^-$ and $\overline{\Xi}^+$ magnetic moments**

# 1999 RUN

- **Data taking in Summer 1999**

- **The goal:**
  **at least 4 times more data**

$$\delta A_{\Lambda\Xi} \lesssim 1 \times 10^{-4}$$

- **Improvements:**

  * **further optimize the performance of PWC**
  * **reduce dead-time of readout system**
  * **increase throughput of DAQ to $\sim$40 Mb/s**

# CONCLUSIONS

- **Hyper$\mathcal{CP}$ had a successful 1997 run and has collected the world largest sample of $\Xi^-$ and $\overline{\Xi}^+$.**

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

$$2 \times 10^{-4},$$

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

- **It will also improve by one order of magnitude in the asymmetry in the slope of the Dalitz plot for the $K \to 3\pi$ decay with a projected sensitivity of**

$$6.8 \times 10^{-4}$$

- **E871 is running again and expects to reach**

$$1 \times 10^{-4} \textbf{ or better}$$

  **sensitivity in $A_{\Lambda\Xi}$**