Searching for Direct CP Violation in Hyperon Decays Introduction to the HyperCP (E871) Experiment at FNAL

For E871 collaboration

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CP symmetry violation is one of the three ingredients to create a universe of matter only.

The three ingredients to create a universe of matter (Sakharov, 1967):

- Baryon number is not conserved.
- C and CP symmetry is not conserved.
- Non-equilibrium condition.

Searching for CP violation in Meson decays

- Theoretically, indirect CP violation can exist in the following meson systems,

$$K^0(d\bar{s}) \leftrightarrow \bar{K}^0(\bar{d}s)$$
$$B_d(d\bar{b}) \leftrightarrow \bar{B}_d(\bar{d}b)$$
$$B_s(s\bar{b}) \leftrightarrow \bar{B}_s(\bar{d}s)$$
$$D^0(c\bar{u}) \leftrightarrow \bar{D}^0(\bar{c}u)$$

  However, indirect CP violation has been observed only in the Kaon system.

- Direct CP violation, i.e. asymmetry in the decay of particle and anti-particle, has been studied only in the kaon decay but no final conclusion yet!

- CP violation outside the Kaon system has never been observed!

Study of direct CP violation in the neutral kaon decay

Experimentally this is studied through

$$\frac{\epsilon'}{\epsilon} \approx \frac{1}{6}(1 - |\frac{\eta_{00}}{\eta_{+-}}|^2)$$

where

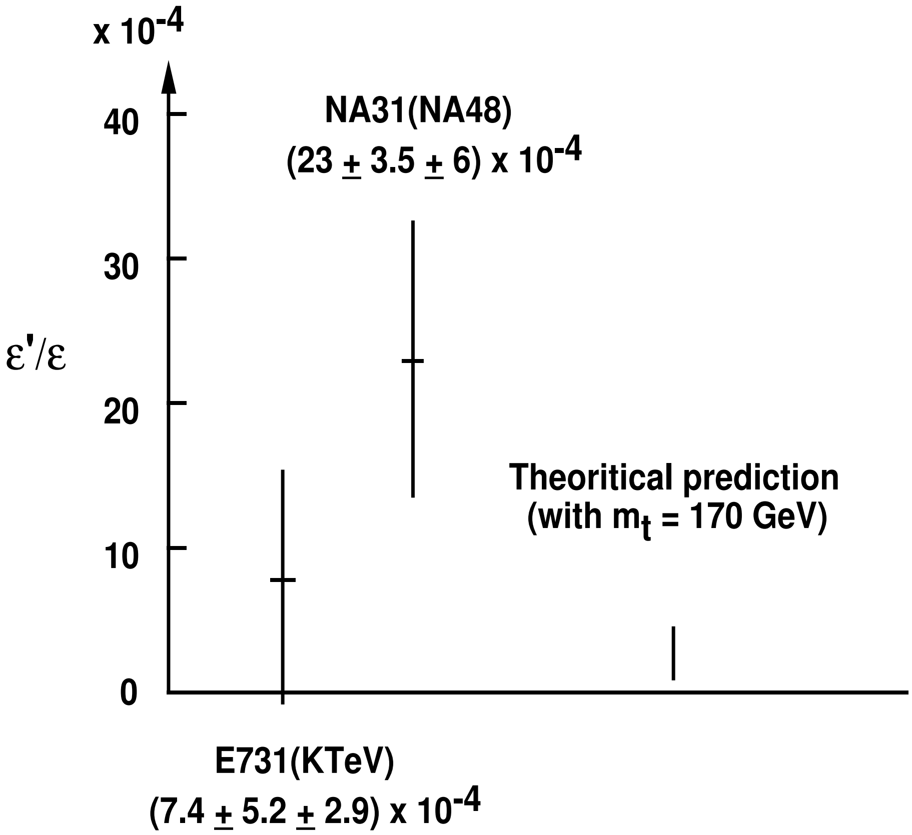
$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \approx \epsilon + \epsilon'$$

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \approx \epsilon - 2\epsilon'$$

Theory predict

$$\frac{\epsilon'}{\epsilon} \approx (0.6 - 4.8) \times 10^{-4}$$

Current results and future expectation of the study of direct CP violation in neutral kaon decays.



experiment	future expectation
KTeV (E731)	$(1-2)\times 10^{-4}$
NA48 (NA31)	$(1-2)\times 10^{-4}$

Searching for CP violation outside the kaon system

In B meson:

- KEK B
- SLAC B
- HERA B
- CDF, D0
- BTeV
- LHC B

In C meson:

- BTeV

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Searching for direct CP violation in the hyperon decays

- **The HyperCP (FNAL E871) experiment**

$$\Xi^- \to \Lambda^0\,\pi^- \qquad \text{and} \qquad \overline{\Xi}^+ \to \overline{\Lambda}^0\,\pi^+$$

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

Search for CP Violation in the Decays of $\Xi^-/\bar{\Xi}^+$ and $\Lambda/\bar{\Lambda}$ hyperons

The HyperCP Collaboration

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Basics of the hyperon decay

- Due to parity violation of the decay, the distribution of the daughter spin-$\frac{1}{2}$ baryon in the rest frame of the parent hyperon is

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \vec{P}_p \cdot \hat{p}_d).$$

  where $\vec{P}_p$ is the polarization of the parent hyperon and $\hat{p}_d$ is the daughter baryon momentum direction in the rest frame of the parent.

- The polarization of the daughter baryon $\vec{P}_d$ is given as

$$\vec{P}_d = \frac{(\alpha + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta(\vec{P}_p \times \hat{p}_d) + \gamma[\hat{p}_d \times (\vec{P}_p \times \hat{p}_d)]}{1 + \alpha \vec{P}_p \cdot \hat{p}_d},$$

- α, β, and γ are the Lee-Yang variables.

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

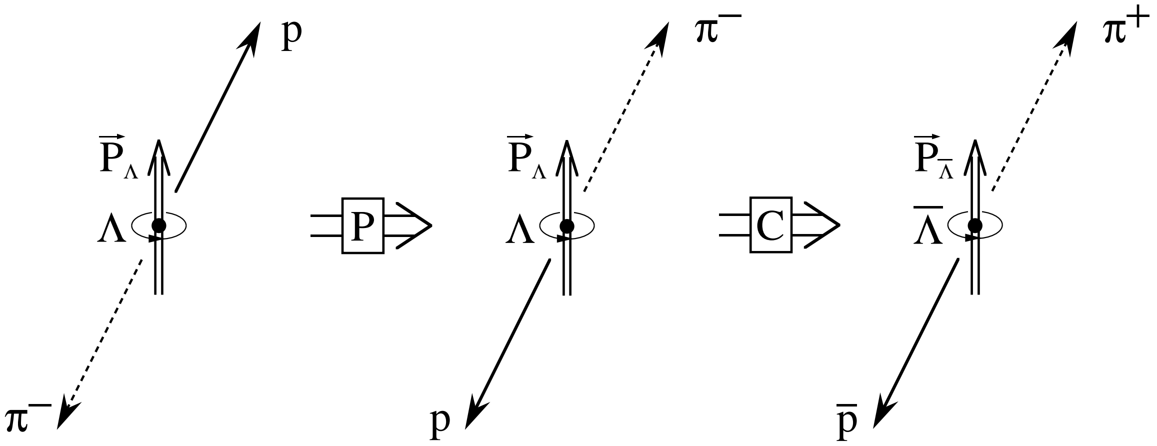
  where S and P are the S- and P-wave amplitudes of the final states.

CP asymmetry parameter

The CP asymmetry observable can be defined as

$$A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}.$$

since the α parameter changes sign under CP operation.



Strategy of E871

Note that in the case of an unpolarized parent hyperon, the polarization of the daughter baryon simplifies to

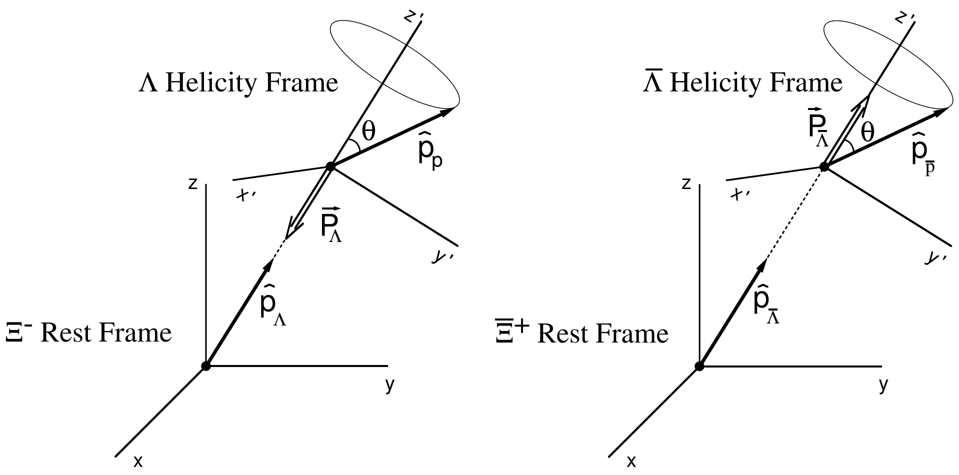
$$\vec{P}_d = \alpha \hat{p}_d.$$

If the Ξ (or $\bar{\Xi}$) is produced with no polarization then we have

$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda, \qquad \frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \alpha_\Xi \hat{p}_\Lambda \cdot \hat{p}_P).$$

Define the decay angle of the proton in the Λ rest frame to be θ then

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



What E871 measures

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

$$A_{\Lambda} \cong -\tan(\delta_1^P - \delta_1^S)\sin(\phi_1^P - \phi_1^S),$$
$$A_{\Xi} \cong -\tan(\delta_3^P - \delta_3^S)\sin(\phi_1^P - \phi_1^S),$$

where ϕ's are CP-violating weak phases, and δ's are strong rescattering phases.

Predictions of A_{Ξ} and A_{Λ}.

Model	A_{Ξ} $[10^{-4}]$	A_{Λ} $[10^{-4}]$
CKM Model	$-(0.1-1)$	$-(0.1-0.5)$
Weinberg	≈ -3.2	≈ -0.25
Superweak	≈ 0	≈ 0
LR (isoconjugate)	≈ 0.25	≈ -0.11
LR (with mixing)	< 1	< 7

Experimental results on A_Λ

Mode	Result	Experiment
$pp \to \Lambda X$, $\bar{p}p \to \overline{\Lambda}X$	0.02 ± 0.14	R608
$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	0.01 ± 0.10	DM2
$p\bar{p} \to \Lambda\overline{\Lambda}$	0.013 ± 0.022	PS185

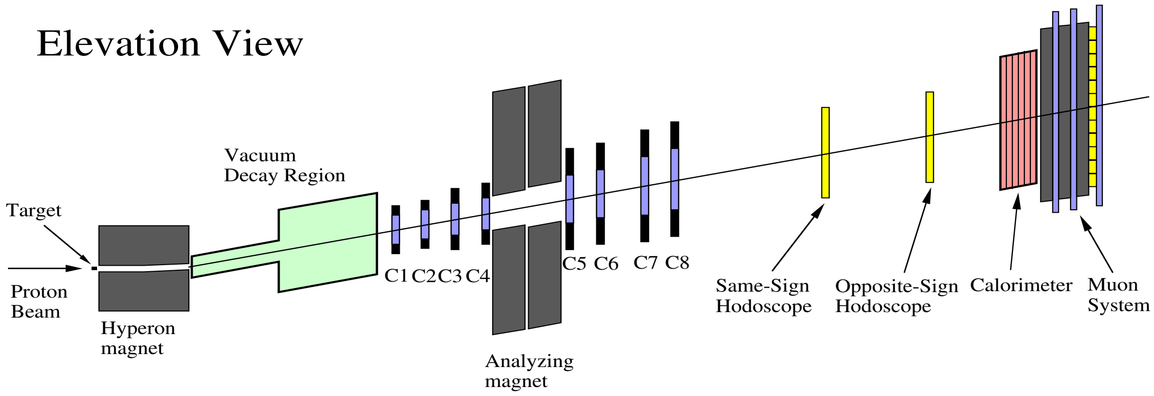
The goal of the HyperCP experiment

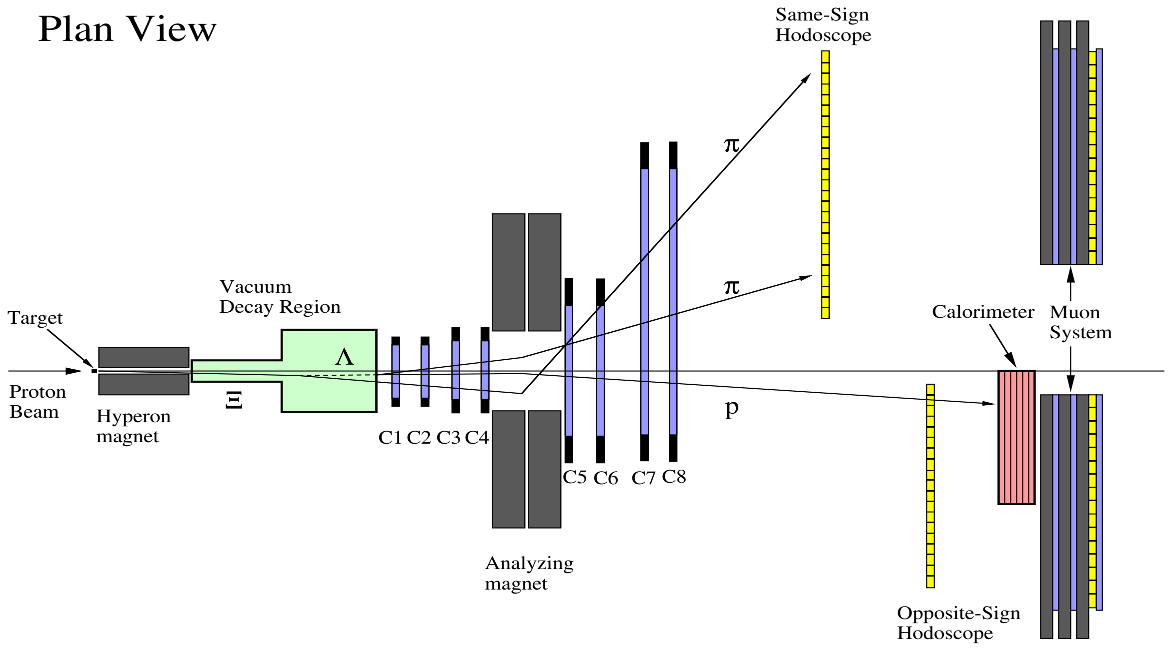
To reach the sensitivity of the order of 10^{-4} !

Need

- fast chambers with fine resolution
- simple trigger
- fast DAQ

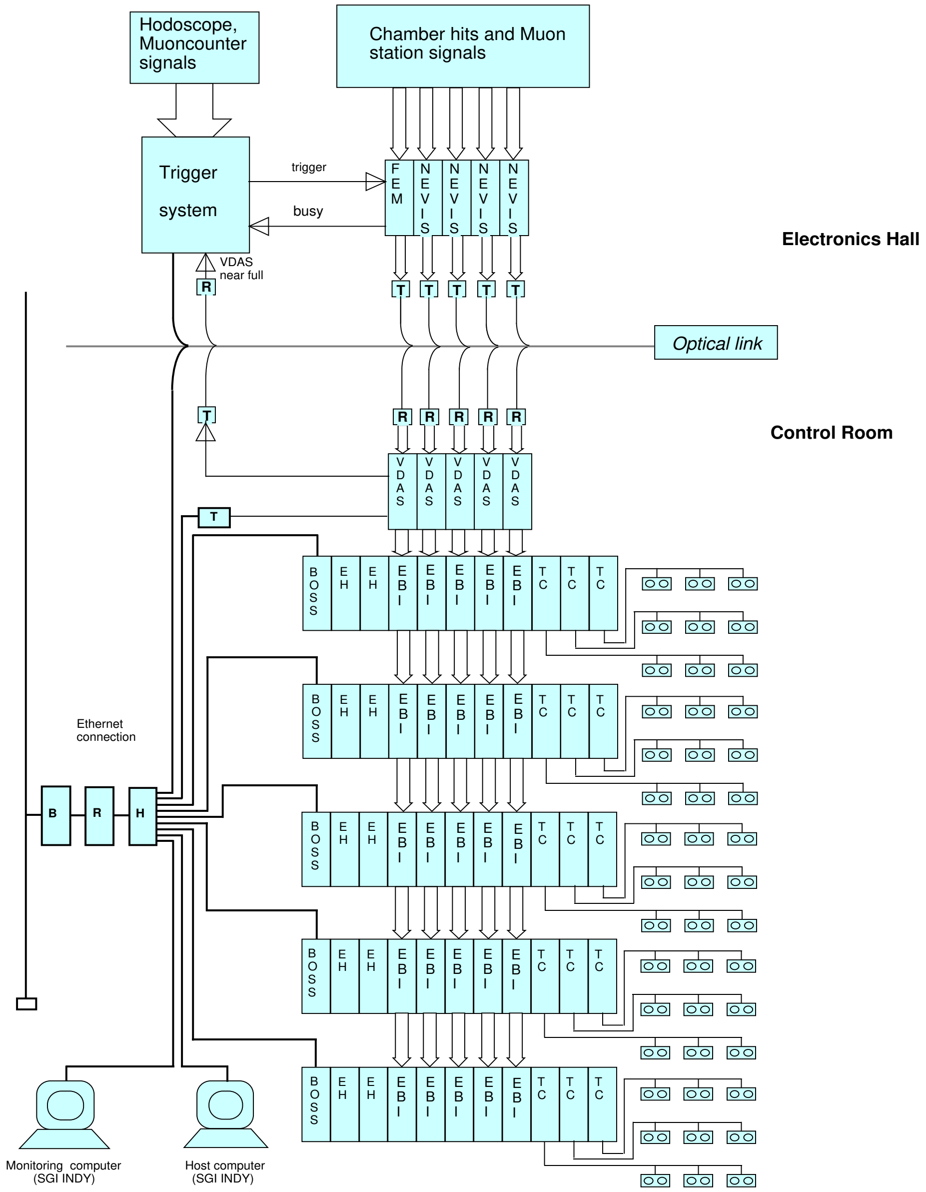
The E871/HyperCP Spectrometer





- 8 fast, narrow-pitch (1, 1.25, 1.5 and 2 mm) wire chambers (20,000 wires)
- Very high rate to tape DAQ
  1. 1,200,000 events/spill
  2. 13.5 MBytes/sec on 40 Exabyte 8505 tape drives, capable of 17 MB/s maximum.

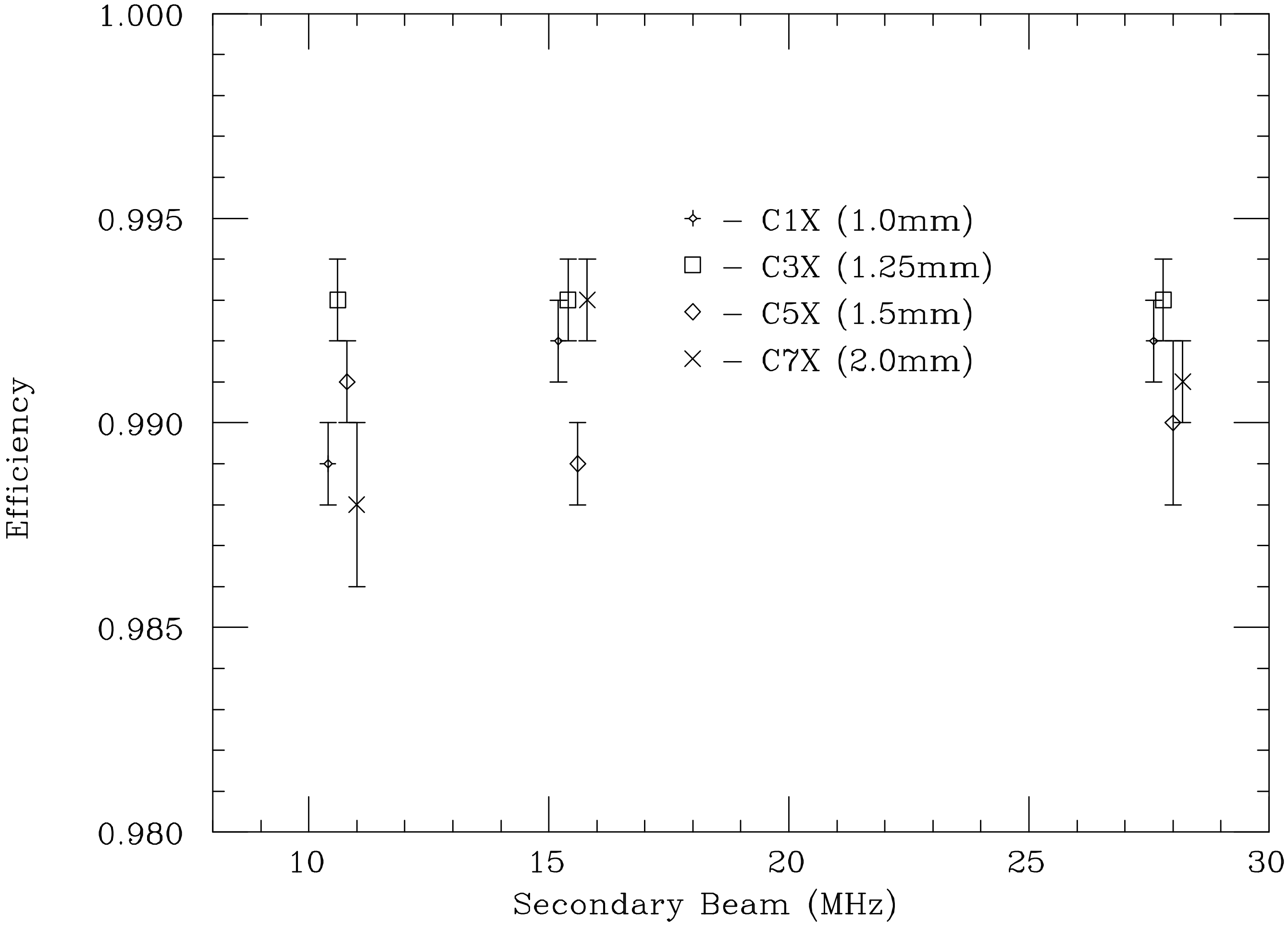
E871 DAQ hardware structure



- Optical link is used due to the long distance between Electronics Hall and the Control Room, which is 100 meter or so.

- There are 5 data paths and 5 DAQ crates working in parallel.

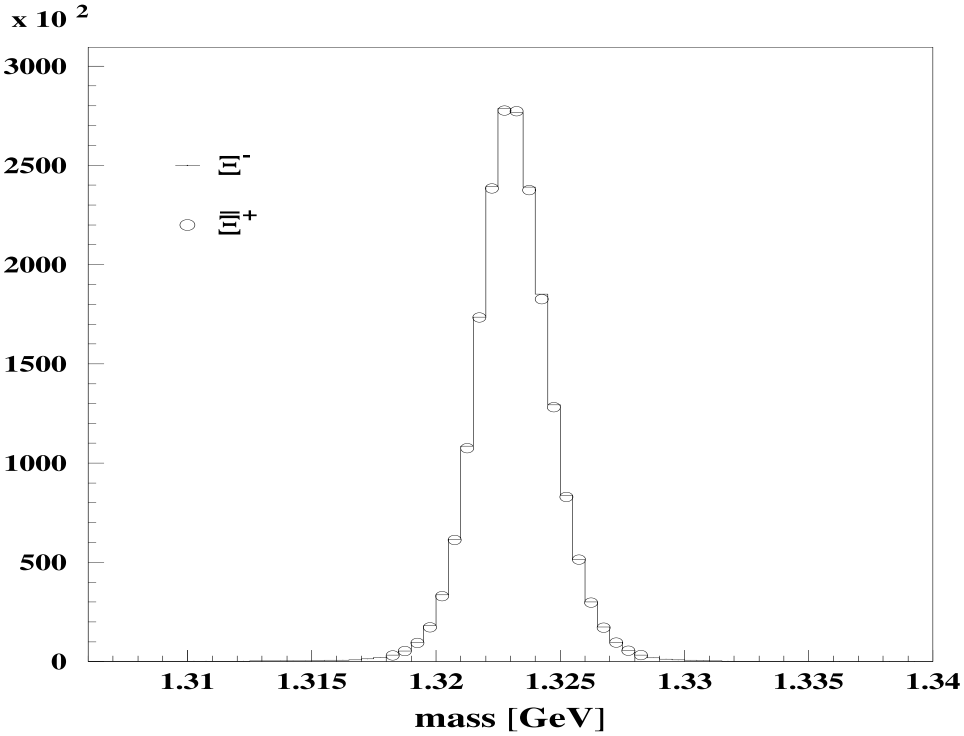
Chamber efficiency versus secondary beam intensities.



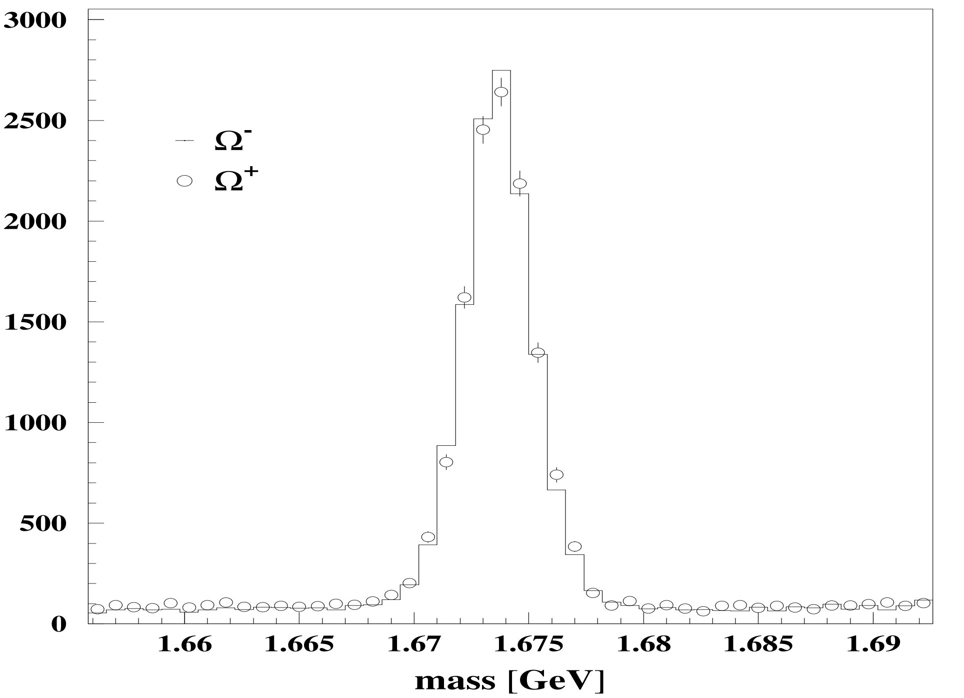
Number of events

Events on tape			
	Channeled beam polarity		
Trigger	+	−	Total
Cascade	24.5×10^9	14.9×10^9	39.4×10^9
All	48.8×10^9	25.6×10^9	74.4×10^9

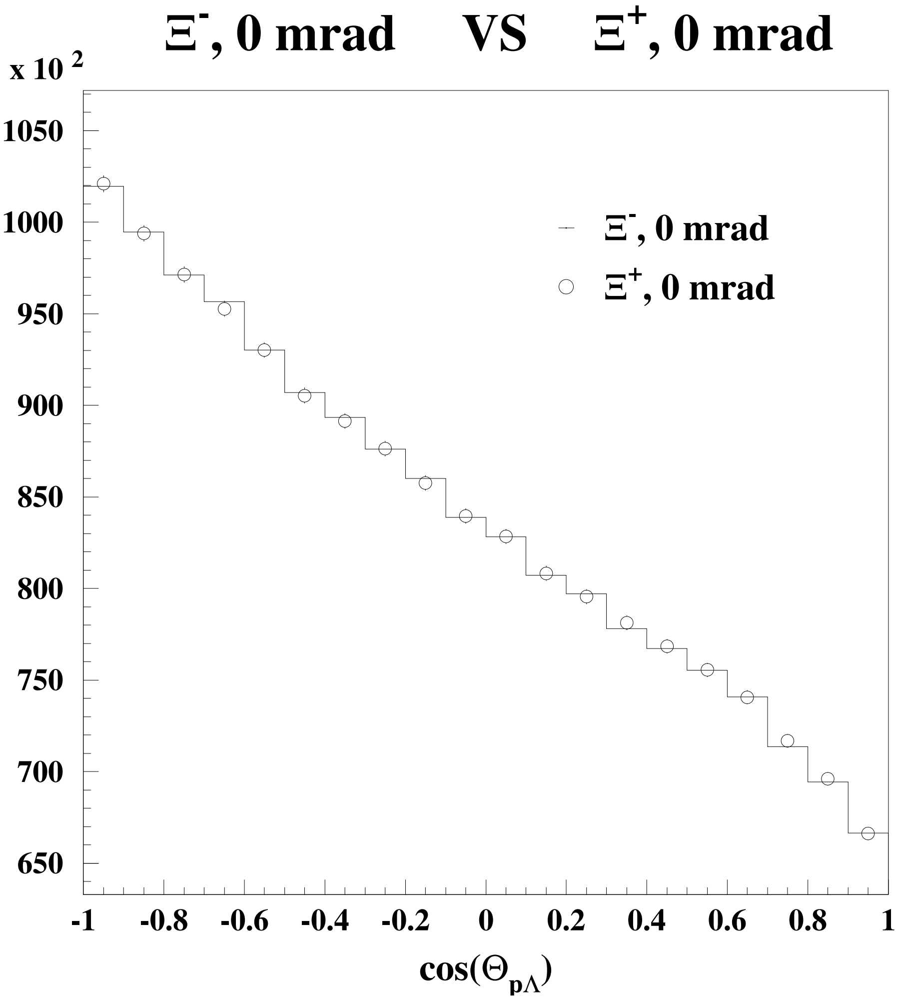
Expected Number of Reconstructed Events			
	Channeled beam polarity		
	+	−	Total
$\Xi \to \Lambda\pi$	284×10^6	1310×10^6	1.59×10^9



x 10 2
3000
2500
2000
1500
1000
500
0
Ξ^-
$\bar{\Xi}^+$
1.31
1.315
1.32
1.325
1.33
1.335
1.34
mass [GeV]



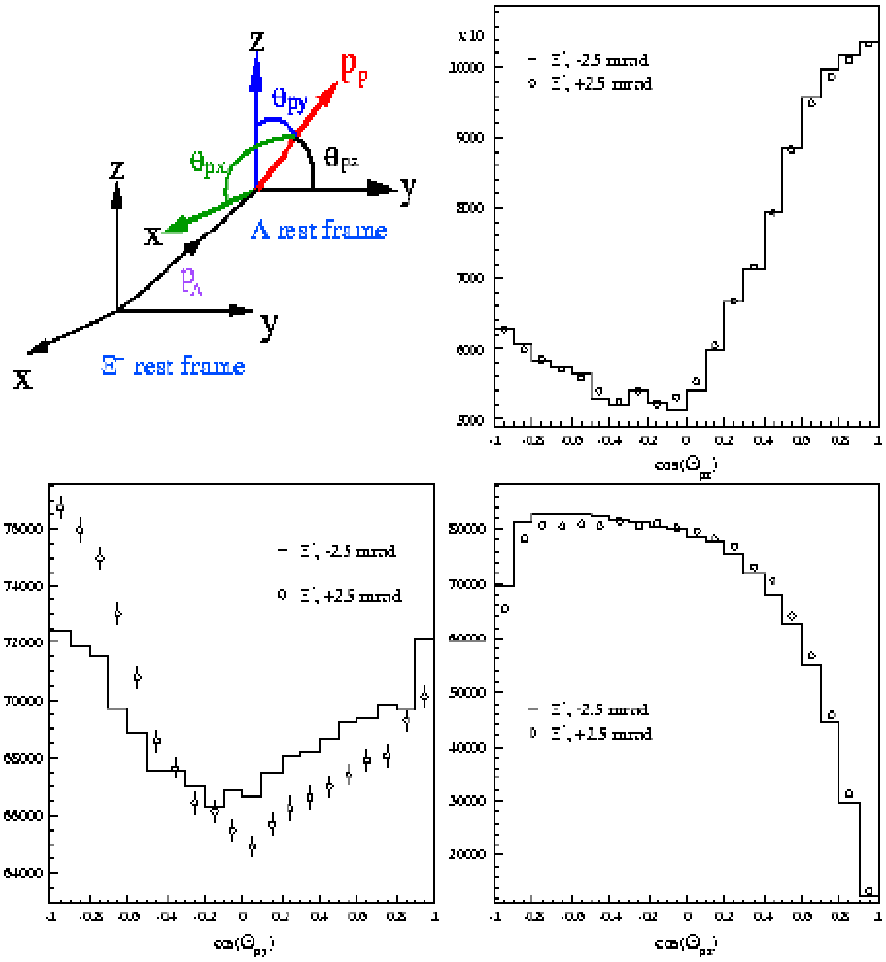
3000
2500
2000
1500
1000
500
0
Ω^-
Ω^+
1.66
1.665
1.67
1.675
1.68
1.685
1.69
mass [GeV]



No acceptance correction!

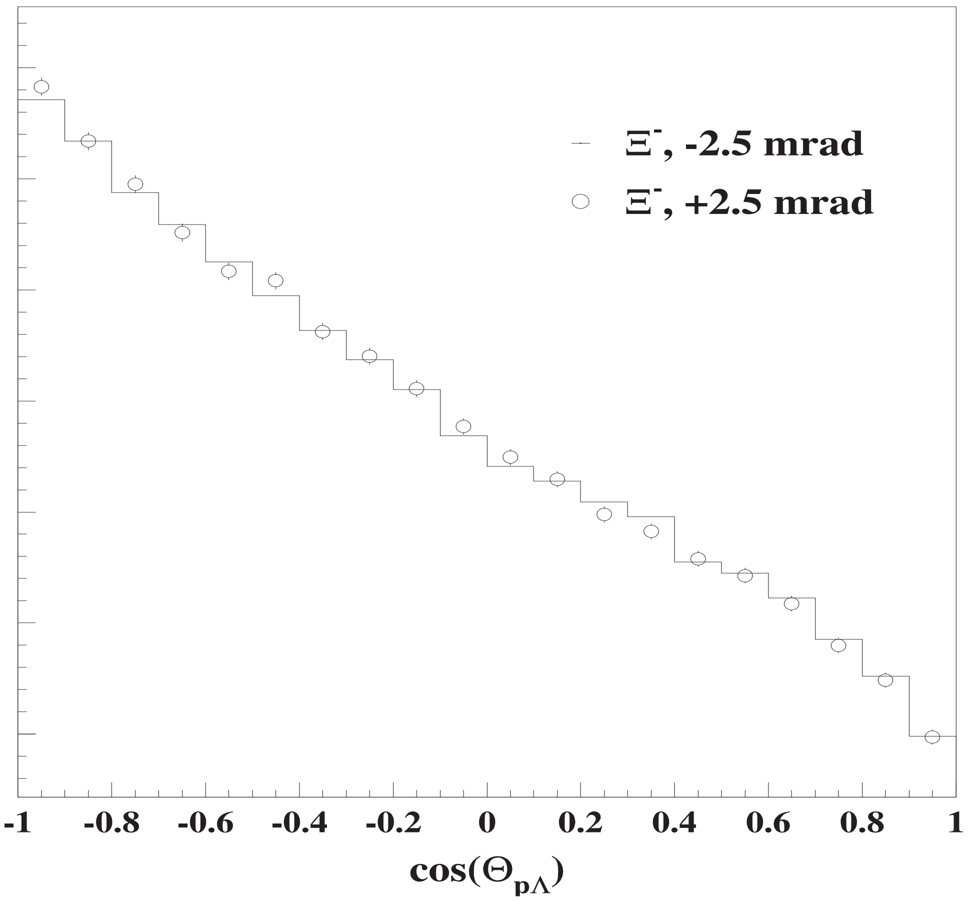
Study of possible biases

- acceptance difference between Ξ and $\bar{\Xi}$ decay.
- non-zero polarization of Ξ.
- differences in the particle anti-particle interaction rate.
- different backgrounds of the Λ and $\bar{\Lambda}$ and the Ξ and $\bar{\Xi}$.



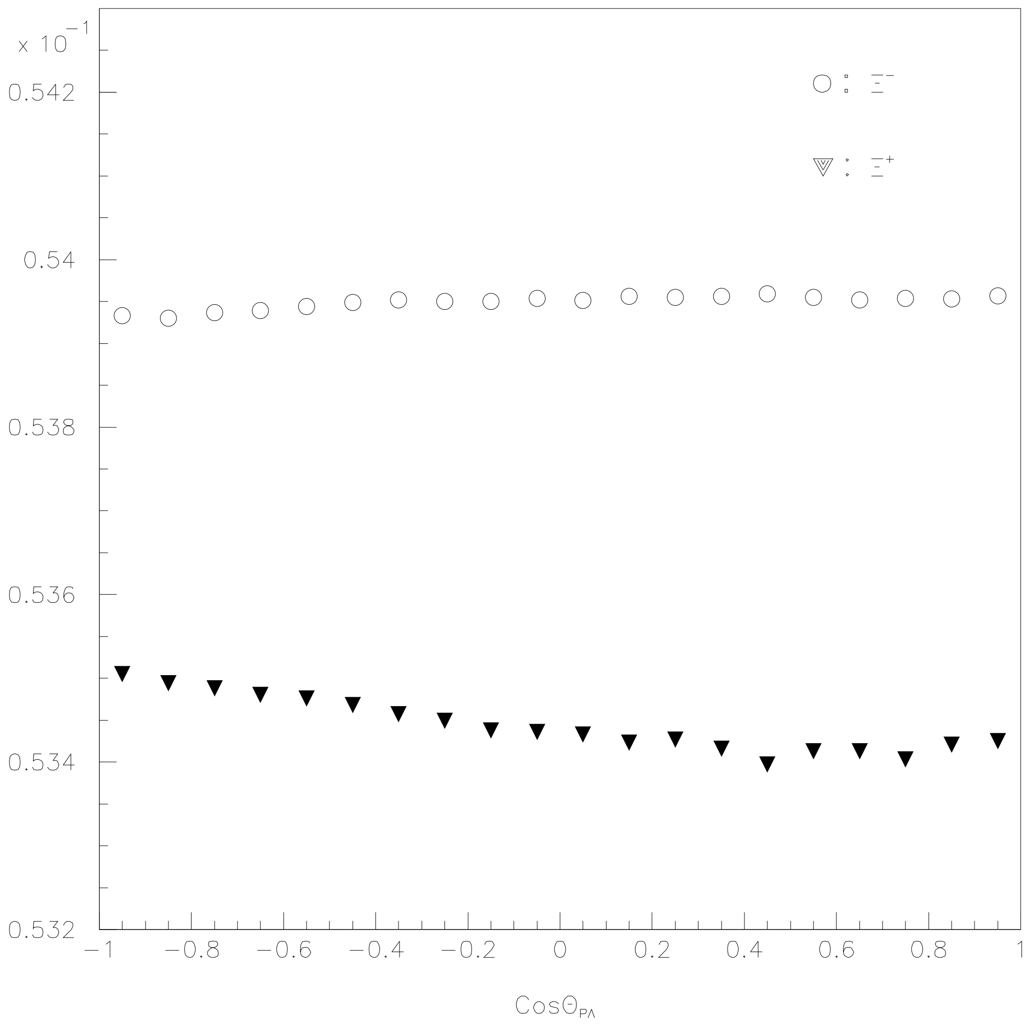
z
p_p
θ_{py}
θ_{px}
θ_{pz}
y
x
Λ rest frame
p_Λ
Ξ^- rest frame
x 10
Ξ^-, -2.5 mrad
Ξ^-, +2.5 mrad
cos(Θpz)
cos(Θpy)
cos(Θpx)

Ξ^-, -2.5 mrad VS Ξ^-, +2.5 mrad



The bias due to Ξ polarization should be small!

Due to the cross section difference between P/π^+ and $\bar{P}/\pi^-$ the distribution of $cos(\theta)$ is affected differently in Ξ^- and Ξ^+ decays.



- **Without correction** this induces bias of 1×10^{-4} in $A_{\Xi\Lambda}$.

Conclusion

- Statistically the current HyperCP data set can reach

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

  sensitivity. Study of systematic error is in progress.

- In the year of 1999 we expect to collect 4 times more data.

- With this huge sample of hyperon decays, E871 is an excelent place to search for direct CP violation.