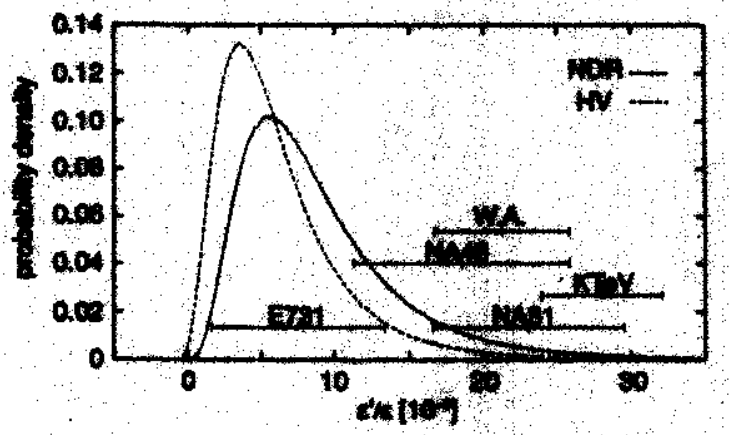
K.S. Nelson
Hyperon99

Experimental Search for $\mathcal{CP}$ Violation in Hyperon Decays

- Direct $\mathcal{CP}$ violation in K_L now firmly established experimentally. The theoretical situation is not as clear.



S. Bosch et al.
hep-ph/9904408

- Strong hint of $\mathcal{CP}$ violation in B decays.

- The Standard Model also predicts $\mathcal{CP}$-odd effects in hyperon decays, although at the $\mathcal{O}(10^{-5})$ level.

  $\Longrightarrow$ sensitivity to new physics

Phenomenology of Non-Leptonic Hyperon Decays

The ($\Delta S = 1$) decays of spin-1/2 Hyperons

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

proceed through a mixture of S and P waves.

In terms of the S and P wave amplitudes the decay can be described by the partial rate

$$\Gamma = G_F^2 m_\pi^4 \frac{p_d(E_d + m_d)}{4\pi m_p}(|S|^2 + |P|^2)$$

and the decay parameters

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

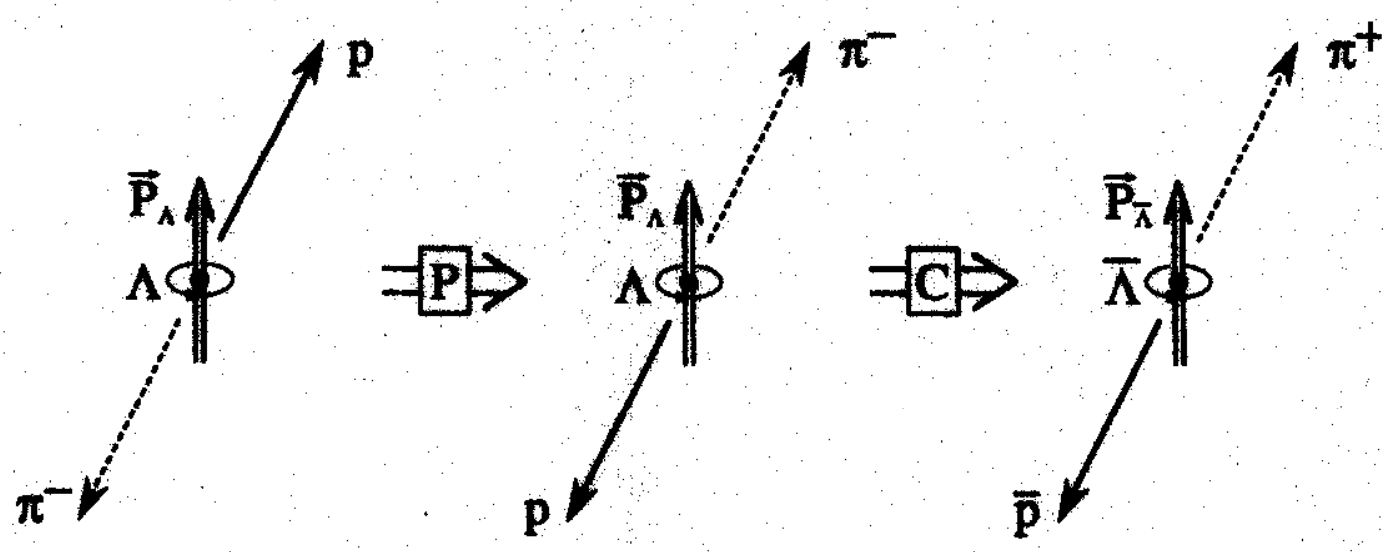
Note $\alpha^2 + \beta^2 + \gamma^2 = 1$

Averaging over the daughter baryon's spin, the decay distribution in the parent hyperon's rest frame is

$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_p \vec{\mathbf{P}}_p \cdot \hat{\mathbf{q}}) = \frac{1}{4\pi}(1 + \alpha_p P_p \cos\theta_d)$$

where $\vec{\mathbf{P}}_p$ is the parent hyperon polarization, and $\hat{\mathbf{q}}$ is the daughter baryon momentum unit vector.

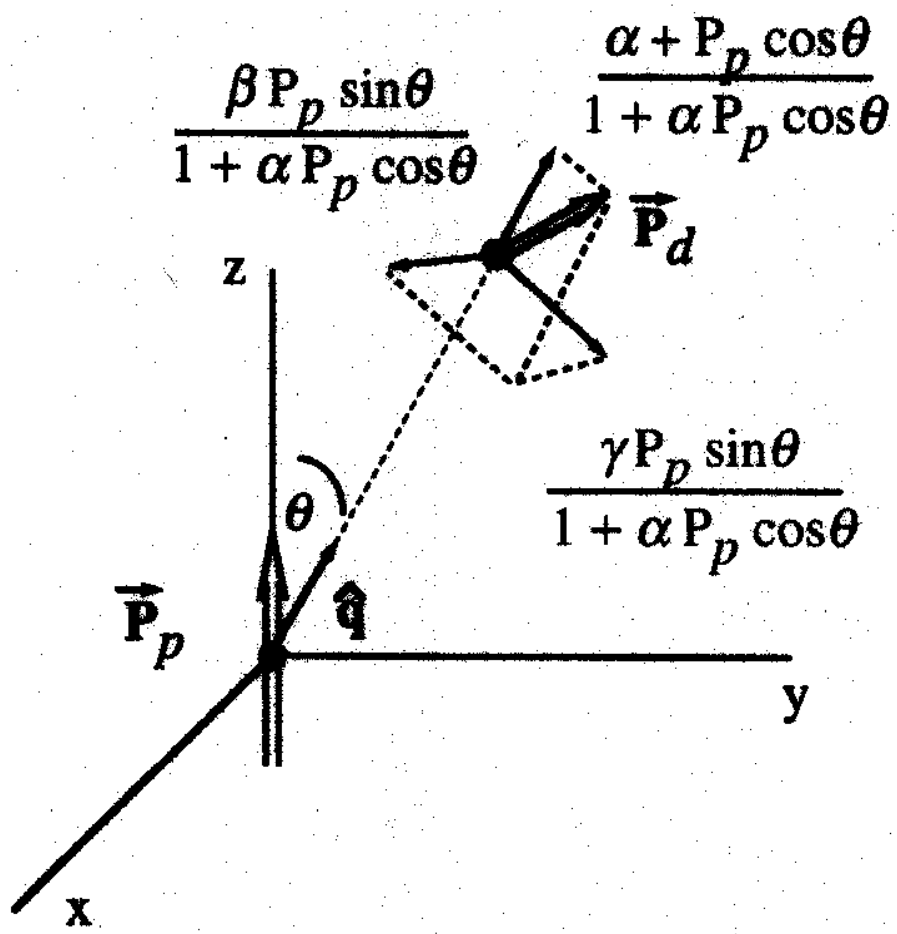
Consider $\Lambda \to p\pi^-$:



In the limit of $\mathcal{CP}$ invariance $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$.

The daughter baryon's polarization is given by;

$$\vec{\mathbf{P}}_d = \frac{(\alpha_p + \vec{\mathbf{P}}_p \cdot \hat{\mathbf{q}})\hat{\mathbf{q}} + \beta_p(\vec{\mathbf{P}}_p \times \hat{\mathbf{q}}) + \gamma_p(\hat{\mathbf{q}} \times (\vec{\mathbf{P}}_p \times \hat{\mathbf{q}}))}{(1 + \alpha_p \vec{\mathbf{P}}_p \cdot \hat{\mathbf{q}})}$$



- If $\vec{\mathbf{P}}_\mathbf{p} = 0$ then $\vec{\mathbf{P}}_\mathbf{d} = \alpha_p \hat{\mathbf{q}}$
- The T–odd transverse polarization is governed by β_p. Due to final state scattering $\beta \neq 0$ in general.

If $\mathcal{CP}$ is conserved then

$$\alpha = -\overline{\alpha}, \quad \beta = -\overline{\beta}, \quad \gamma = \overline{\gamma} \quad \text{and } \Gamma = \overline{\Gamma}.$$

Some $\mathcal{CP}$–odd observables in the comparison of hyperon and anti-hyperon decays are;

$$\Delta = \frac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}} \qquad A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}$$

$$B = \frac{\beta + \overline{\beta}}{\beta - \overline{\beta}} \qquad B' = \frac{\beta + \overline{\beta}}{\alpha - \overline{\alpha}}$$

In terms of the isospin amplitudes, final state strong scattering phases δ and $\mathcal{CP}$ violating phases ϕ, the partial waves in the hyperon decay are;

$$S = +\sum_k S_k \exp i(\delta_k^S + \phi_k^S) \quad P = +\sum_k P_k \exp i(\delta_k^P + \phi_k^P)$$

where k runs over all I, ΔI.

The partial waves for the corresponding anti-hyperon decay are;

$$\overline{S} = -\sum_k S_k \exp i(\delta_k^S - \phi_k^S) \quad \overline{P} = +\sum_k P_k \exp i(\delta_k^P - \phi_k^P)$$

For $\Lambda \to p\pi$

$$\begin{aligned}
\Delta_\Lambda &\approx \sqrt{2}\frac{S_3}{S_1}\sin(\delta_3^S - \delta_1^S)\sin(\phi_3^S - \phi_1^S) \\
A_\Lambda &\approx \tan(\delta_1^P - \delta_1^S)\sin(\phi_1^S - \phi_1^P) \\
B_\Lambda &\approx \cot(\delta_1^P - \delta_1^S)\sin(\phi_1^P - \phi_1^S) \\
B'_\Lambda &\approx \sin(\phi_1^S - \phi_1^P)
\end{aligned}$$

where the strong scattering phase shifts have been measured to be

$$\delta_1^P = -1.1 \quad \delta_1^S = 6.0 \quad \delta_3^S = -3.8^\circ \quad (\text{all } \sim \pm 1^\circ)$$

Hierarchy: $\quad 0.1\mathcal{O}(B) \approx \mathcal{O}(B') \approx 10\,\mathcal{O}(A) \approx 100\,\mathcal{O}(\Delta)$

For charged $\Xi \to \Lambda\pi$

$$\begin{aligned}
\Delta_\Xi &\equiv 0 \\
A_\Xi &\approx \tan(\delta_2^P - \delta_2^S)\sin(\phi_1^S - \phi_1^P) \\
B_\Xi &\approx \cot(\delta_2^P - \delta_2^S)\sin(\phi_1^P - \phi_1^S)
\end{aligned}$$

No measurements of $\delta_2^P - \delta_2^S$.

Calculations have ranged from $\sim 17^\circ$ (1965) to $\leq 3^\circ$ (recent)

- Asymmetries B, B' require knowlege of both parent and daughter polarizations.
- Δ requires precise knowlege of normalization

Some predictions of A for $\Lambda \to p\pi$ and charged $\Xi \to \Lambda\pi$ decays.

$\Lambda \to p\pi$

	A_Λ
CKM	$\approx +5 \times 10^{-5}$
Weinberg	$\approx -2.5 \times 10^{-5}$
Left-Right(isoconjugate)	$\approx -1.1 \times 10^{-5}$
Left-Right(with mixing)	$\leq 6 \times 10^{4}$

Charged $\Xi \to \Lambda\pi$

	A_Ξ
CKM	$\approx -4 \times 10^{-6}$
Weinberg	$\approx -3.2 \times 10^{-4}$
Left-Right(isoconjugate)	$\approx 2.5 \times 10^{-5}$
Left-Right(with mixing)	$\leq 1 \times 10^{-5}$

Requirements for a High Sensitivity Measurement

1. Hyperons and anti-hyperons having *precisely* known polarization
   - polarization through production
   - polarization through decay

2. A large data sample; *e.g.* $\mathcal{O}(10^9)$ events for $\delta A \sim 10^{-4}$

$$\delta_A = \frac{1}{\alpha|P|}\sqrt{\frac{3}{N} + \frac{3}{\overline{N}}}$$

3. Control of systematics
   - acceptance differences
   - magnetic field matching
   - differences in interaction cross sections with material of apparatus
   - different backgrounds under the mass peak

Previous Measurements

- only A_Λ was measured
- $\mathcal{CP}$ test was "sideline" topic
- sensitivity was limited by statistics

Mode	events	Limit	Experiment
$pp \to \Lambda X, \bar{p}p \to \overline{\Lambda} X$	9553	-0.02 ± 0.14	R608
$e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$	1847	0.01 ± 0.10	DM2
$p\bar{p} \to \Lambda\overline{\Lambda}$	95832	0.013 ± 0.022	PS185

Earlier tests of $\mathcal{T}$–conservation using only hyperons :

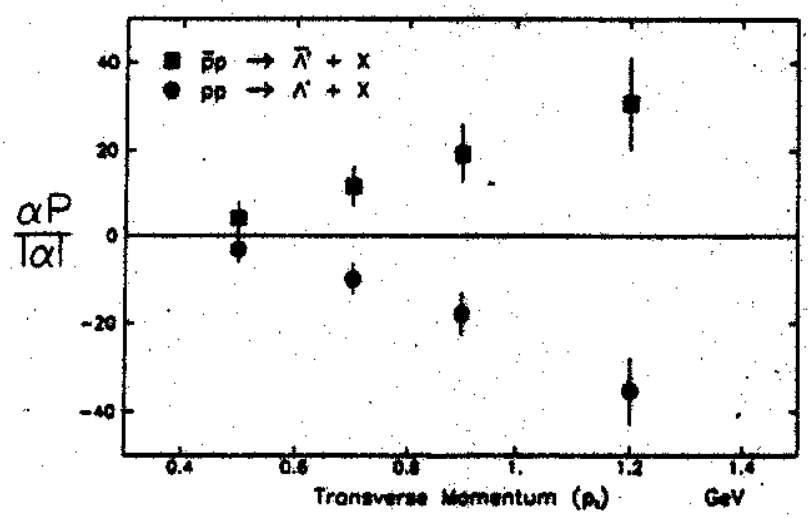
$\Lambda \to p\pi^-$ **decay:** $\frac{\beta}{\alpha} \approx \tan(\delta_1^P - \delta_1^S)$

Ξ^- / Ξ° **decay:** $\frac{\beta^-}{\alpha^-} = \frac{\beta^\circ}{\alpha^\circ}$

R806 at the CERN ISR: $pp \to \Lambda + X$ and $p\bar{p} \to \bar{\Lambda} + X$

At the level of sensitivity of this measurement C invariance is assumed in the production process; $P_\Lambda = P_{\bar{\Lambda}}$.

Extract $\alpha_\Lambda P_\Lambda$ and $\alpha_{\bar{\Lambda}} P_{\bar{\Lambda}}$ from $\frac{dN}{d\cos\theta_p} \propto (1 + \alpha P \cos\theta_p)$



Based on 9553 $\bar{\Lambda}$'s and 17028 Λ's, assuming $P_\Lambda = P_{\bar{\Lambda}}$,

$$\alpha_\Lambda/\alpha_{\bar{\Lambda}} = -1.04 \pm 0.29$$

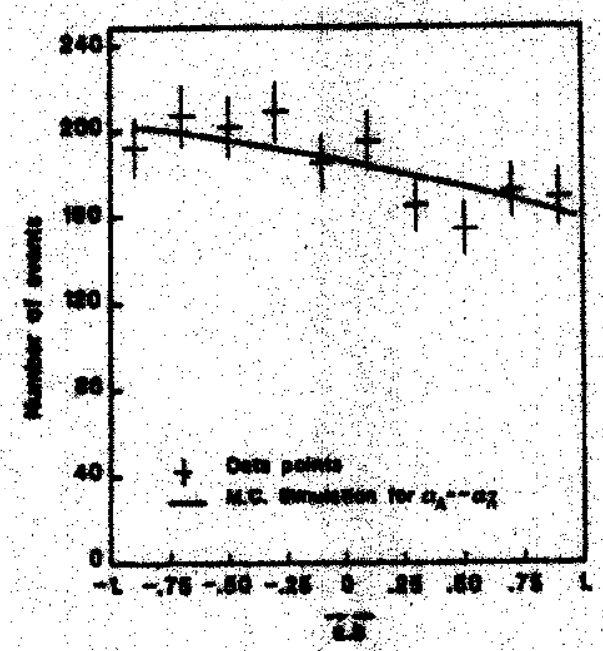
$$A_\Lambda = -0.02 \pm 0.14$$

DM2 at Orsay DCI : unpolarized $e^+e^- \to J/\psi$

1847 $\Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$ from 8.6×10^6 unpolarized $e^+e^- \to J/\psi$

No explicit assumption about Λ and $\bar{\Lambda}$ polarizations needed.

The $\mathcal{CP}$ violating signal appears in the product $\alpha_\Lambda \alpha_{\bar{\Lambda}}\, \mathbf{a} \cdot \mathbf{b}$, where $\mathbf{a}$ and $\mathbf{b}$ are the p and $\bar{p}$ unit vectors in the Λ and $\bar{\Lambda}$ rest frames.

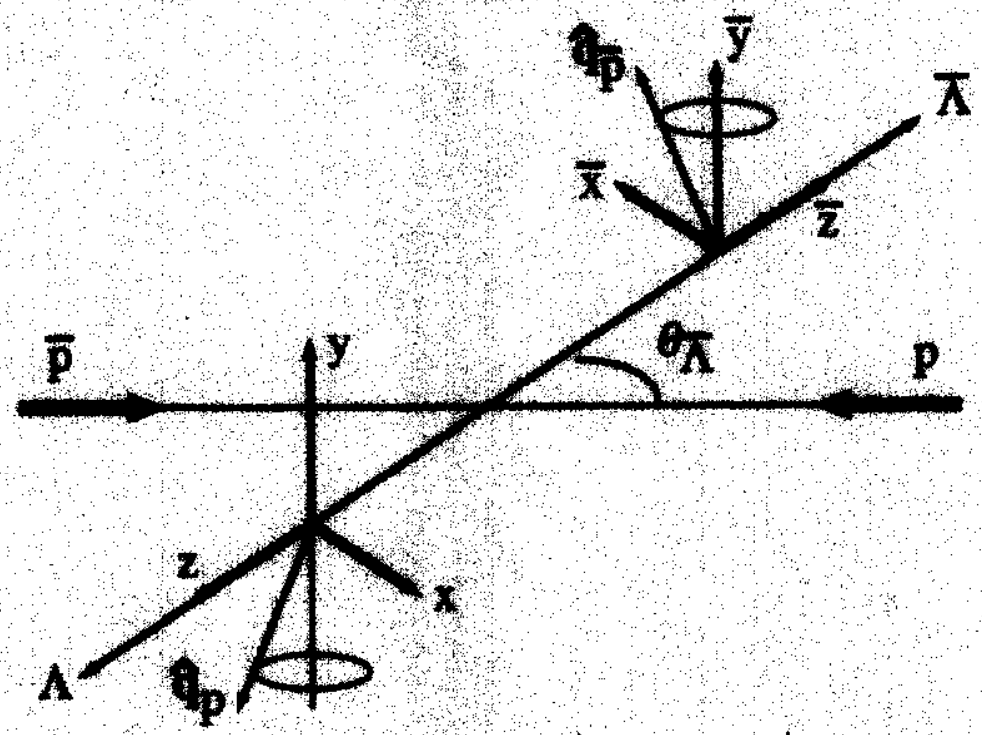


Fixing $\alpha_\Lambda = 0.642$ and varying $\alpha_{\bar{\Lambda}}$ in MC generation of $\mathbf{a} \cdot \mathbf{b}$;

$$A = 0.01 \pm 0.10$$

PS185 at LEAR: $p\bar{p} \to \Lambda\bar{\Lambda}$

Assuming C invariance in the production $\quad P_{y\Lambda} = P_{y\bar{\Lambda}}$



Extraction of αP; $\quad \alpha P = \dfrac{\sum_i \cos\theta_y^{(i)}}{\sum_i \cos^2\theta_y^{(i)}} \quad$ requires $\eta(\theta_y) = \eta(\pi - \theta_y)$

From a combined total sample of 95832 events

$$A_\Lambda \approx \frac{\alpha_\Lambda P_\Lambda + \alpha_{\bar{\Lambda}} P_{\bar{\Lambda}}}{\alpha_\Lambda P_\Lambda - \alpha_{\bar{\Lambda}} P_{\bar{\Lambda}}} = 0.013 \pm 0.022$$

The *HyperCP* Experiment at Fermilab

Obtain Ξ^- and $\overline{\Xi}^+$ hyperons having $\vec{\mathbf{P}}_{\Xi(\overline{\Xi})} = 0$ by selecting production at 0° in 800 GeV pN collisions.

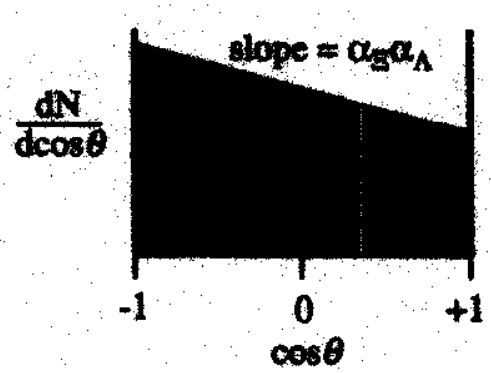
Subsequent $\Xi^- \to \Lambda\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$ yield Λ and $\overline{\Lambda}$ samples having polarization absolutely determined by the Ξ^- and $\overline{\Xi}^+$ decay parameters

$$\vec{\mathbf{P}}_\Lambda = \alpha_\Xi \hat{\mathbf{q}}_\Lambda \quad \vec{\mathbf{P}}_{\overline{\Lambda}} = \alpha_{\overline{\Xi}} \hat{\mathbf{q}}_{\overline{\Lambda}}$$

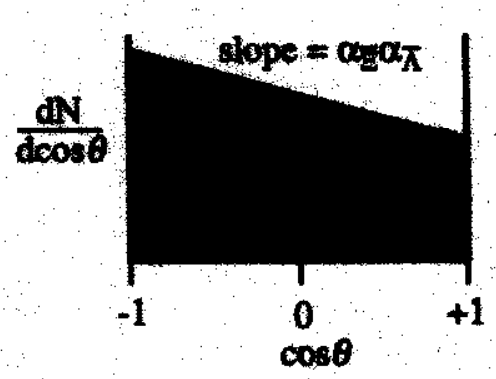
In the Λ and $\overline{\Lambda}$ helicity frames

$$\frac{dN_p}{d\cos\theta_{p\Lambda}} = 1 + \alpha_\Xi \alpha_\Lambda \cos\theta_{p\Lambda} \qquad \frac{dN_{\overline{p}}}{d\cos\theta_{\overline{p}\overline{\Lambda}}} = 1 + \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}} \cos\theta_{\overline{p}\overline{\Lambda}}$$

$\Xi^- \Rightarrow \Lambda\pi^- \quad \Lambda \Rightarrow p\pi^-$



$\overline{\Xi}^+ \Rightarrow \overline{\Lambda}\pi^+ \quad \overline{\Lambda} \Rightarrow \overline{p}\pi^+$



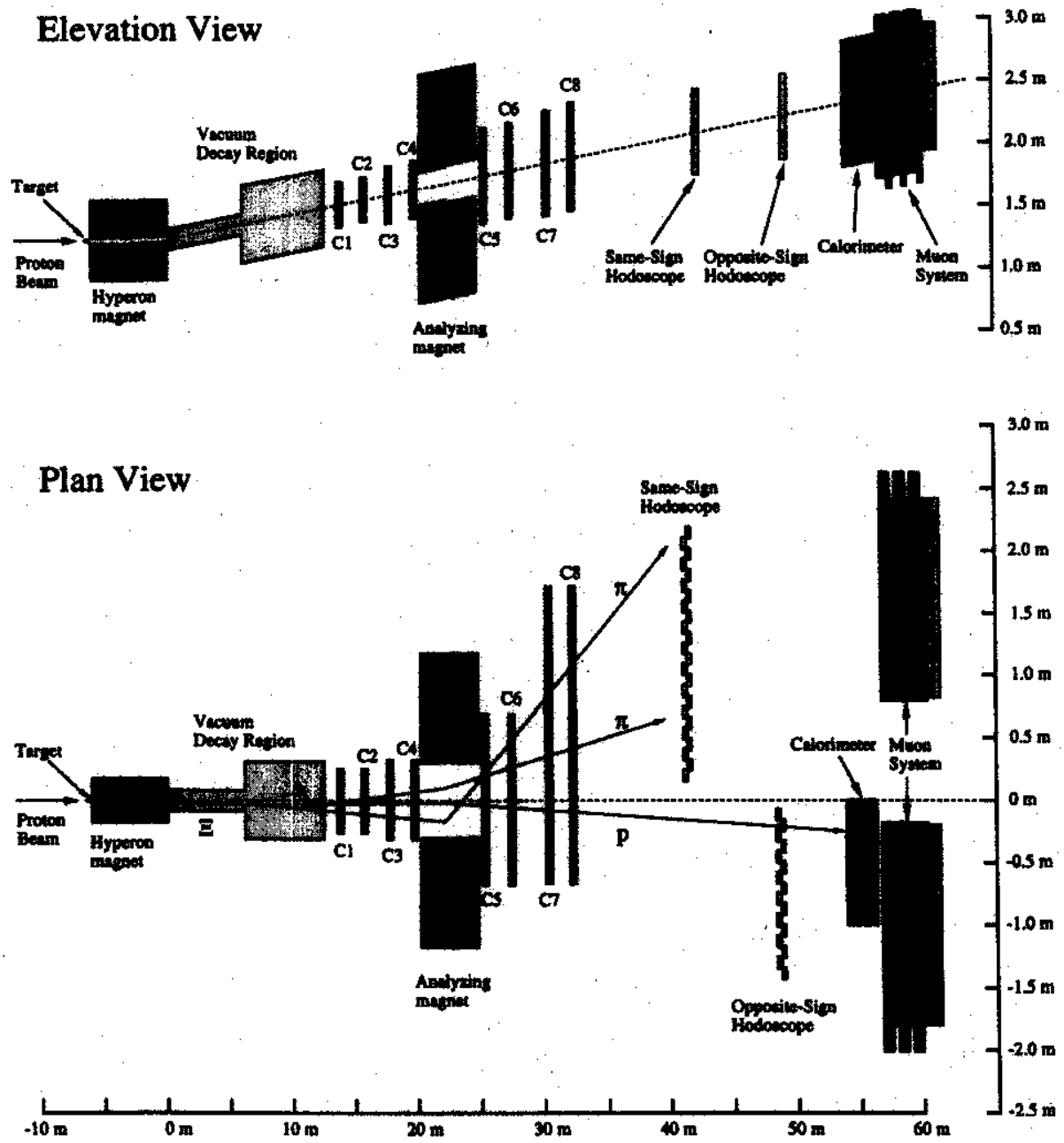
A signal of $\mathcal{CP}$ non-conservation is $\alpha_\Xi \alpha_\Lambda \neq \alpha_{\bar{\Xi}} \alpha_{\bar{\Lambda}}$

The asymmetry measured is

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

- *Hyper*$\mathcal{CP}$ is sensitive to $\mathcal{CP}$-odd effects in both the Ξ and Λ decays.
- Theoretical expectation that $|A_\Xi| << |A_\Lambda|$ makes accidental cancellation unlikely.
- A measurement of β_Ξ can be used to put a limit on the contribution from A_Ξ.

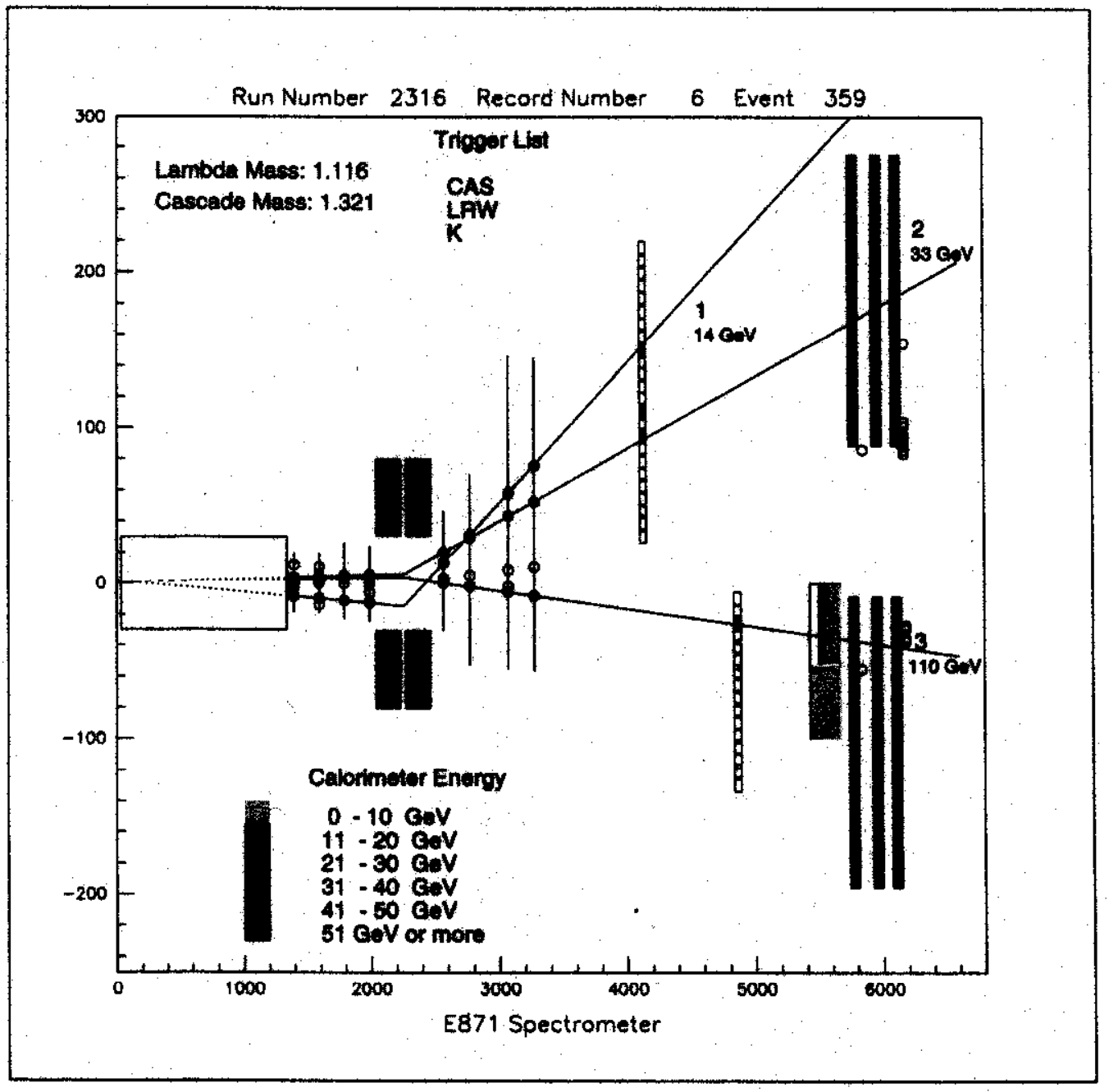
The HyperCP Spectrometer



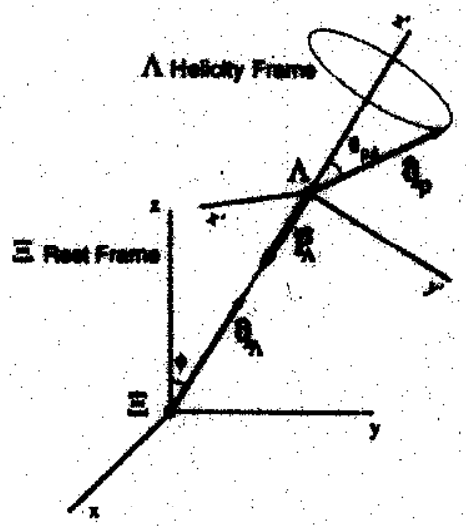
Secondary beam momentum $\approx 160\,\mathrm{GeV}/c$

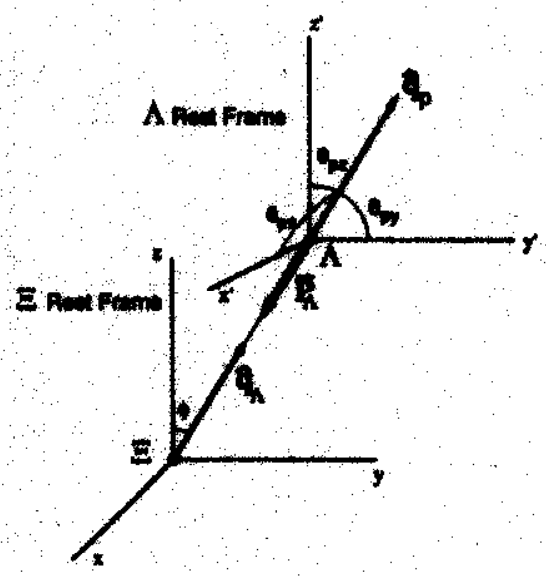
Flip both $\vec{\mathbf{B}}$ fields $\Longrightarrow$ nearly symmetric acceptance.

A TYPICAL EVENT DISPLAY



The orientation of the helicity frame is not fixed in space but changes from event to event.



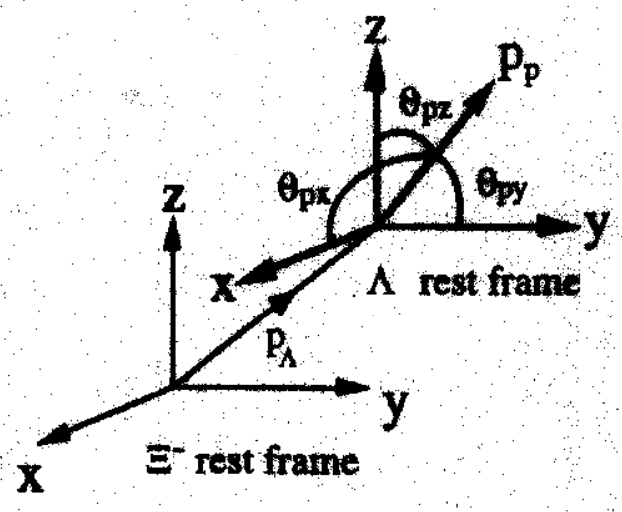


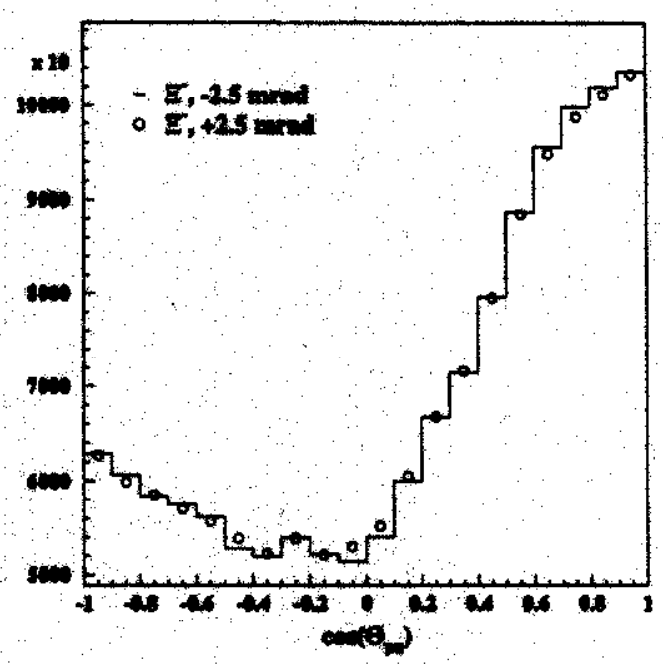
As a result systematic biases that are localized in space are diluted.

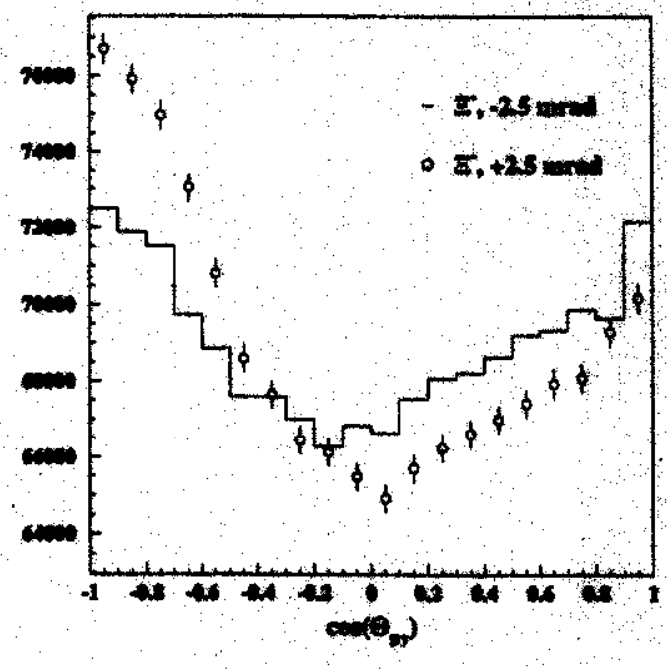
An example: Comparison of two polarized Ξ^- samples having

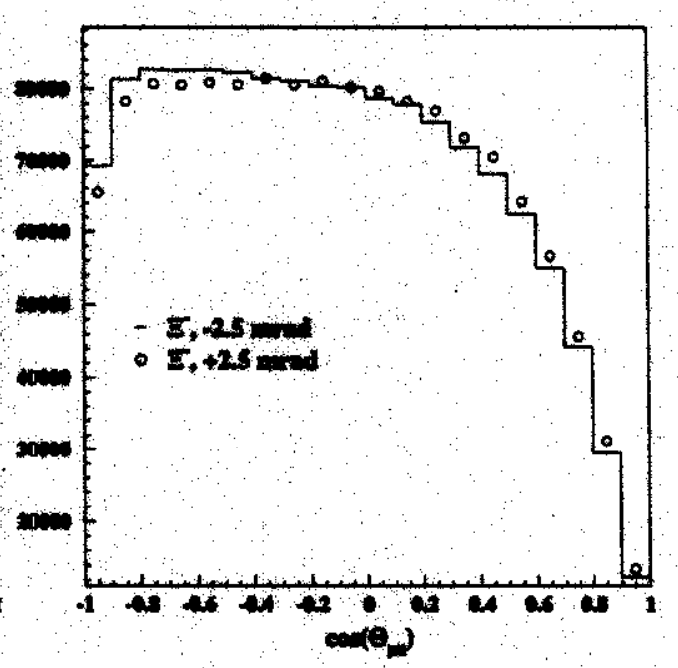
$$\vec{\mathbf{P}} = \pm P\,\hat{\mathbf{y}}$$

obtained from horizontal production angles of $\pm 2.5\,\mathrm{mrad}$.



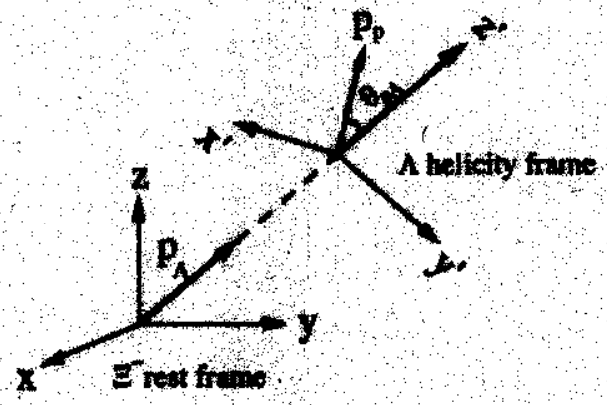


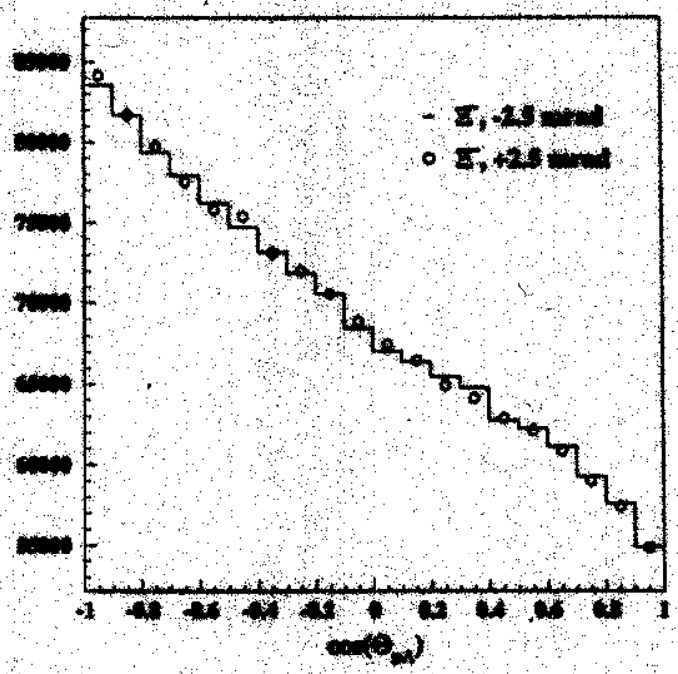




- **The effect of the small polarization is clearly seen in the $cos(\theta_{py})$ distribution in the Λ rest frame**

Ξ^- (-2.5 mrad) vs Ξ^- (+2.5 mrad)





- In the Λ helicity frame the effect of the small polarization on the $cos(\theta_{p\Lambda})$ distribution disappears

Expected Number of Reconstructed Events from '97 Run

	Channeled beam polarity		
	+	−	Total
$\Xi \to \Lambda\pi$	245×10^6	969×10^6	1.21×10^9
$K \to 3\pi$	204×10^6	75×10^6	279×10^6

Statistical sensitivity: $\delta A_{\Xi\Lambda} \approx 2 \times 10^{-4}$.

The *HyperCP* goal is to collect $\sim 4\times$ more events in 1999.

Conclusions

The search for Hyperon CP violation was suggested almost a decade before the discovery of $K_L \to \pi\pi$. Yet progress in the strange baryon sector has lagged behind the K.

Current experimental limits are only at the 10^{-2} level

- So far results have been limited by statistics.
- Until recently there was no dedicated experiment.

The outcome of *Hyper*CP could play an important role in defining the future of CP studies in hyperon decays.