Search for CP Violation in Hyperon Decays with the *HyperCP* Spectrometer at Fermilab

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Why Search for *CP* Violation in Hyperon Decays?

- After 40 years of intense experimental effort — and many beautiful experiments — we still know little about *CP* violation: the origin of *CP* violation remains unknown and there is little hard evidence that it is explained by the Standard Model.
- The asymmetry can be relatively large: up to 1×10^{-2}.
- The price is modest:
  - No new accelerators needed.
  - Apparatus is modest in scope and cost.
- Hyperons are sensitive to sources of *CP* violation that, for example, kaons are not.
- *CP* violation is too important, and experimental evidence is too meagre, not to examine every possible manifestation of the effect.

"We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of CP violation will reveal the presence of New Physics."

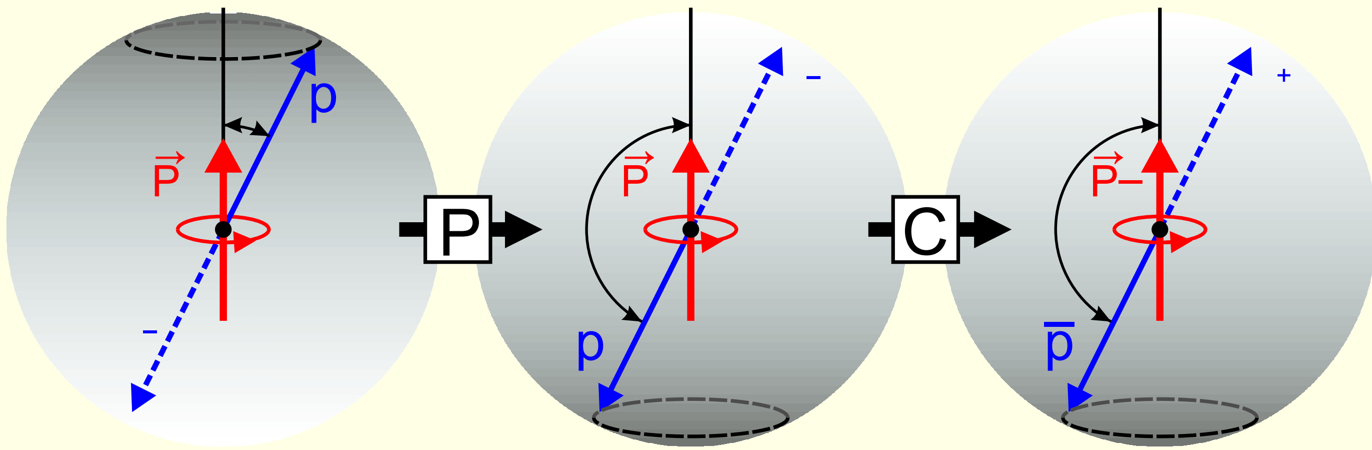
Bigi and Sanda, CP Violation

How to Search for *CP* Violation in Λ Decays

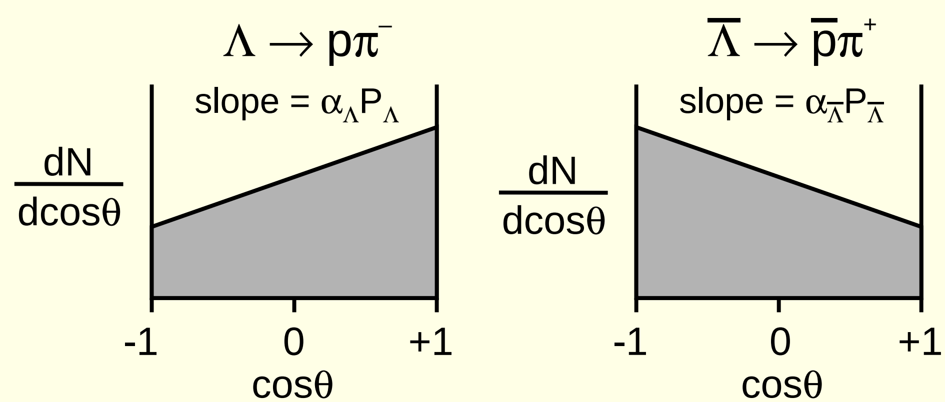
Due to parity violation the proton likes to go in the direction of the Λ spin:

$\Lambda \longrightarrow p\pi^-$: $\quad \dfrac{d\mathrm{N(p)}}{d\cos\theta} = \dfrac{\mathrm{N}_0}{2}(1+\alpha_\Lambda P_\Lambda \cos\theta) \quad \alpha = \dfrac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2}$

Under CP the antiproton likes to go in the direction opposite to the $\overline{\Lambda}$ spin:



$$\alpha_\Lambda \xrightarrow{CP} \overline{\alpha}_\Lambda = -\alpha_\Lambda$$



Problem: Producing Λ's of Known Polarization

$\Lambda/\overline{\Lambda}$'s of known polarization can be produced through the decay of **unpolarized** $\Xi^-/\overline{\Xi}^+$'s:

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

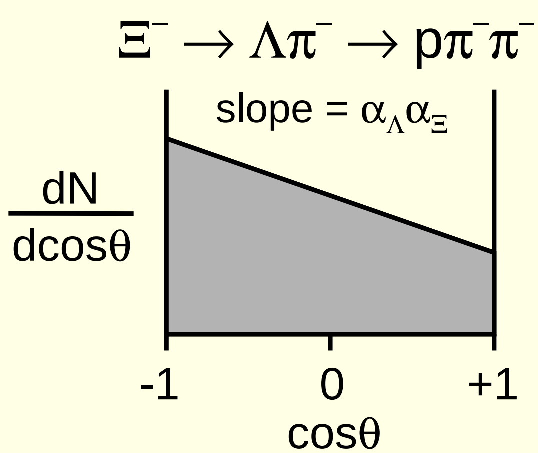
If the Ξ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the Λ is found in a helicity state:

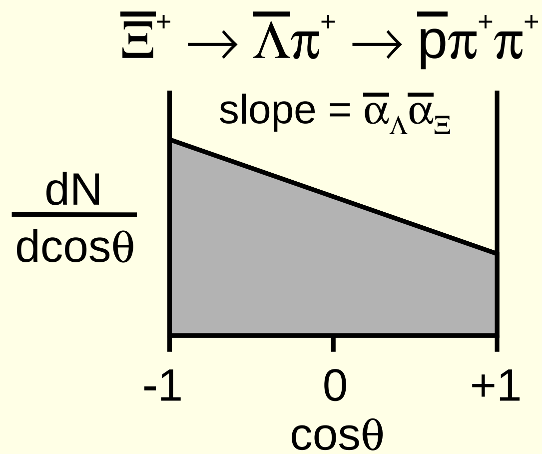
$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad \vec{P}_{\overline{\Lambda}} = \overline{\alpha}_\Xi \hat{p}_{\overline{\Lambda}}$$

$$\frac{d\mathrm{N}(\mathrm{p})}{d\cos\theta} = \frac{\mathrm{N}_0}{2}(1 + \alpha_\Lambda\alpha_\Xi\cos\theta) \qquad \frac{d\mathrm{N}(\bar{\mathrm{p}})}{d\cos\theta} = \frac{\mathrm{N}_0}{2}(1 + \overline{\alpha}_\Lambda\overline{\alpha}_\Xi\cos\theta)$$

If CP is good, the slopes of the proton and antiproton $\cos\theta$ distributions are identical, and:

$$\alpha_\Xi\alpha_\Lambda = \overline{\alpha}_\Xi\overline{\alpha}_\Lambda$$



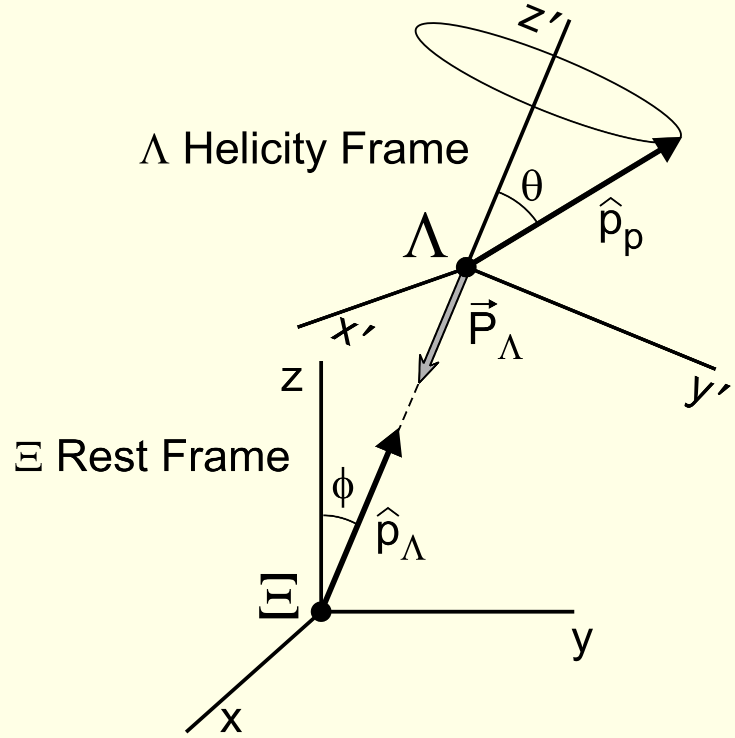


We are sensitive to both Ξ and Λ CP violation

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

where: $A_\Xi = \frac{\alpha_\Xi + \overline{\alpha}_\Xi}{\alpha_\Xi - \overline{\alpha}_\Xi}$ and $A_\Lambda = \frac{\alpha_\Lambda + \overline{\alpha}_\Lambda}{\alpha_\Lambda - \overline{\alpha}_\Lambda}$

What we experimentally measure is the slope of the proton (antiproton) $\cos(\theta)$ distribution in the special Λ rest frame where the Λ momentum direction in the Ξ rest frame defines the polar axis: the Lambda Helicity Frame.



Phenomenology of CP Violation in Ξ and Λ Decay

- CP violation in Ξ and Λ decays is manifestly direct with $\Delta S = 1$.
- Three ingredients are needed to get a non-zero asymmetry:
  1. At least two channels in the final state: the S-and P-wave amplitudes.
  2. The CP violating weak phases must be different in the two channels.
  3. There must be unequal final-state scattering phase shifts in the two channels.

$$A_\Lambda = (\alpha_\Lambda + \alpha_{\overline{\Lambda}})/(\alpha_\Lambda - \alpha_{\overline{\Lambda}}) \cong -\tan(\delta_P - \delta_S)\sin(\phi_P - \phi_S),$$
$$A_\Xi = (\alpha_\Xi + \alpha_{\overline{\Xi}})/(\alpha_\Xi - \alpha_{\overline{\Xi}}) \cong -\tan\underbrace{(\delta_P - \delta_S)}_{\text{strong phases}}\sin\underbrace{(\phi_P - \phi_S)}_{\text{weak phases}}.$$

- Asymmetry greatly reduced by the small strong phase shifts.
  - The $p\pi$ phase shifts have been measured to a precison of about one degree:

$$\Lambda\begin{cases}\delta_P = -1.1 \pm 1.0^\circ\\ \delta_S = 6.0 \pm 1.0^\circ\end{cases}$$

  - The $\Lambda\pi$ phase shifts can't be measured, and theoretical predictions disagree.

$$\Xi^-\left\{\begin{array}{ll}\delta_P = & -2.7^\circ\\ \delta_S = & -18.7^\circ\end{array}\right\}1965 \qquad \left.\begin{array}{l}= -1^\circ\\ = 0^\circ\end{array}\right\}\text{recent}\,\chi PT$$

HyperCP has measured the $\Lambda\pi$ phase shift: $(4.6 \pm 1.4 \pm 1.8)^\circ$

What do we Expect: Theoretical Predictions

- Standard Model predictions range from about $10^{-4} - 10^{-5}$. Beware

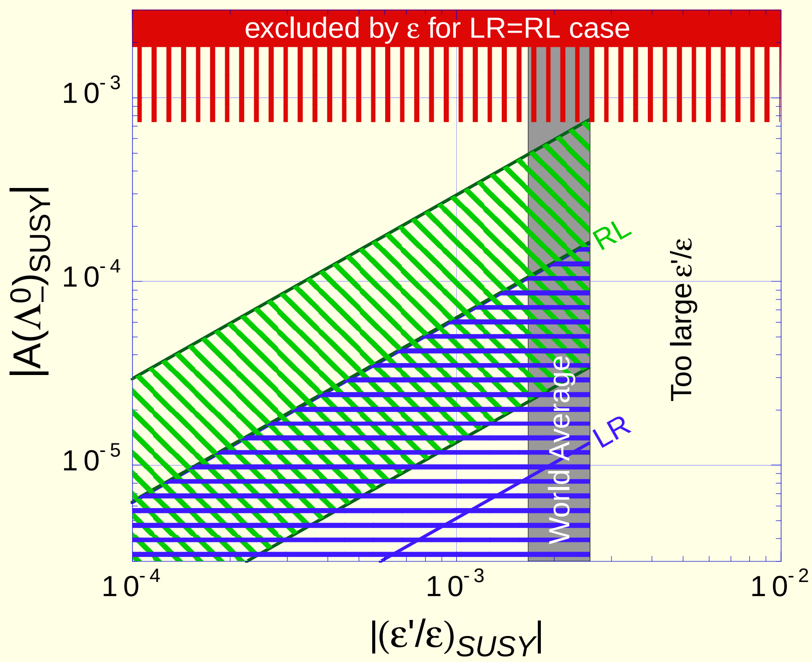
  "Given our crude estimate of the hadronic matrix elements involved, all our numerical results should be viewed with caution."

  He and Valencia, PRD52 (1995) 5257.

- Beyond-the-standard-model predictions larger, and not well contrained by kaon CP measurements: hyperon CP violation probes both parity conserving and parity violating amplitudes.

  Recent preprint by Tandean (hep-ph/0311036) shows that the upper bound on $A_{\Xi\Lambda}$ is $\sim 100 \times 10^{-4}$.

- For example, some supersymmetric models that do not generate ϵ'/ϵ can lead to A_Λ of $O(10^{-3})$.



He et al., PRD 61 (2000) 071701(R).

What is the experimental situation?

- There are no limits on A_Ξ.
- A_Λ has been measured to $2{\times}10^{-2}$.

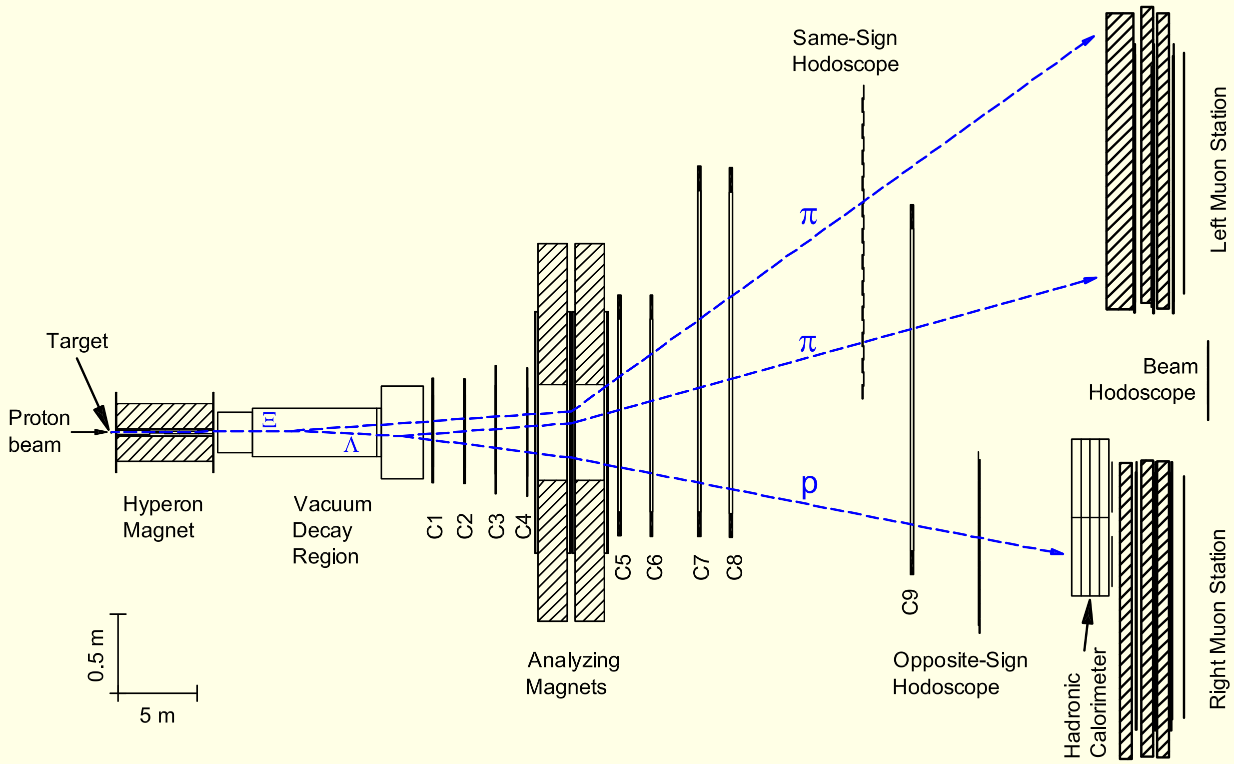
Mode	Method	Limit	Exp	Date
A_Λ	$p\overline{p} \rightarrow \Lambda X,\ p\overline{p} \rightarrow \overline{\Lambda} X$	-0.02 ± 0.14	R608	1985
A_Λ	$e^+e^- \rightarrow \mathrm{J}/\psi \rightarrow \Lambda\overline{\Lambda}$	0.01 ± 0.10	DM2	1988
A_Λ	$p\overline{p} \rightarrow \Lambda\overline{\Lambda}$	0.010 ± 0.022	PS185	1998

- There is a recent measurement of $A_{\Xi\Lambda}$, based on the *HyperCP* technique.

Mode	Method	Limit	Exp	Date
$A_{\Xi\Lambda}$	pN $\rightarrow \Xi\pi \rightarrow \Lambda\pi \rightarrow p\pi\pi$	0.012 ± 0.014	E756	2000

- This measurement of $A_{\Xi\Lambda}$ can be used with measurements of A_Λ to infer a limit on A_Ξ.
- None of these measurements is in the regime of testing theory.
- ***HyperCP* is pushing two orders of magnitude beyond the best limit, to $\sim 10^{-4}$.**

New High-Rate Spectrometer Built



- 800 GeV/c incident proton beam.
- 10–15 MHz, 167 GeV/c secondary beam.
- Low-mass, high-rate, narrow-pitch wire chambers.
- Very high-rate DAQ:
  - ⇒ 50-80 KHz evts/spill-s to tape.
  - ⇒ 27 MB/s on 27 Exabyte 8705 tape drives.
- Simple, low-bias trigger using hodoscopes and calorimeter.

  SS(≥1 hit)·OS(≥1 hit)·Cal(≥40 G eV)
- Muon system for rare and forbidden hyperon and kaon decays.

HyperCP Yields

- In 12 months of data taking we recorded one the largest data samples ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.

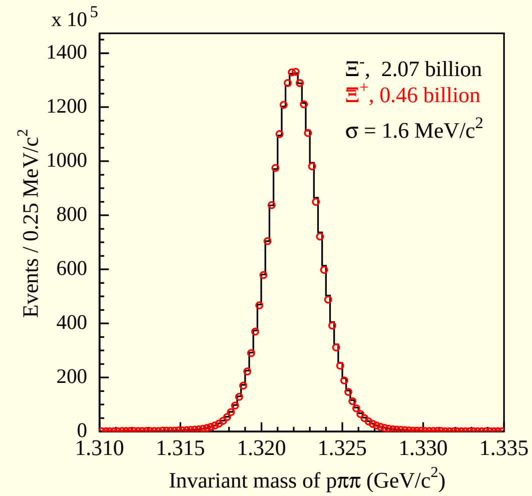
Events

	Year		
Trigger	1997	1999	Total
Cascade	39×10^9	81×10^9	120×10^9
All	58×10^9	173×10^9	231×10^9

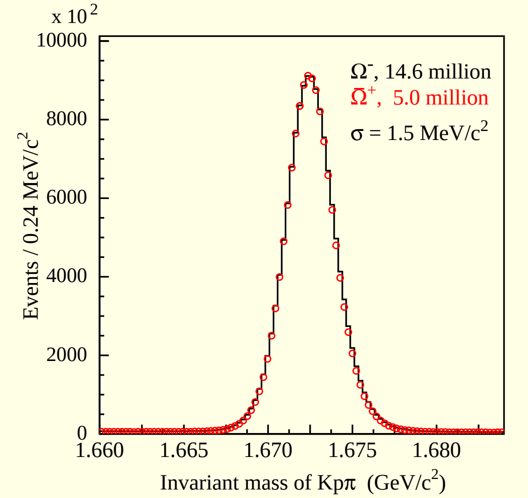
Reconstructed Events

	Channeled beam polarity		
Type	$+$	$-$	Total
$\Xi \to \Lambda\pi$	458×10^6	$2\,032 \times 10^6$	$2\,490 \times 10^6$
$K \to \pi\pi\pi$	391×10^6	164×10^6	555×10^6
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6

$\Xi^\pm \to \Lambda\pi^\pm$

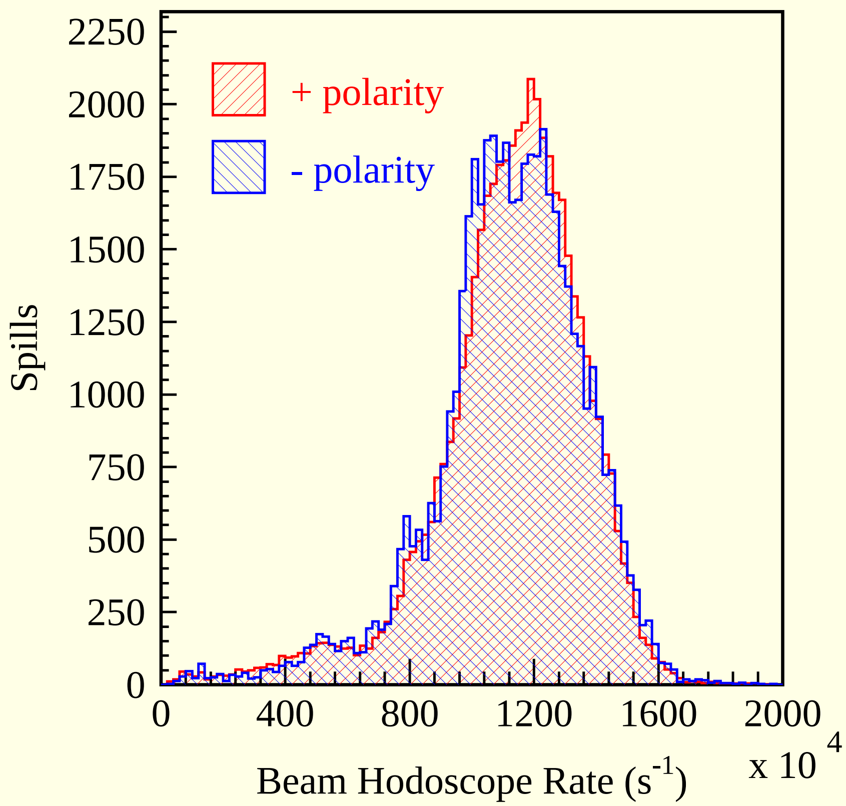


$\Omega^\pm \to \Lambda K^\pm$

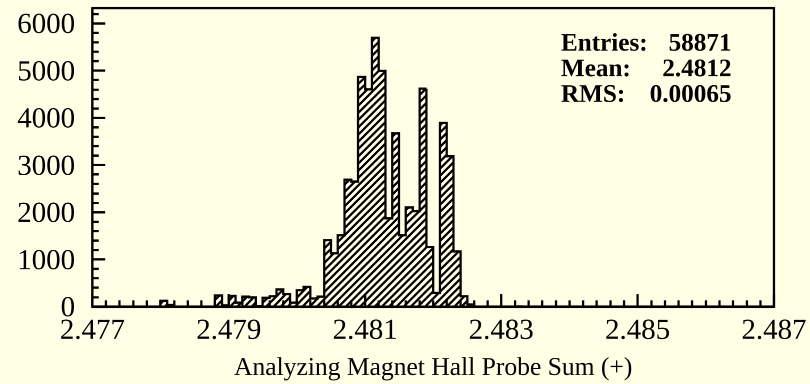


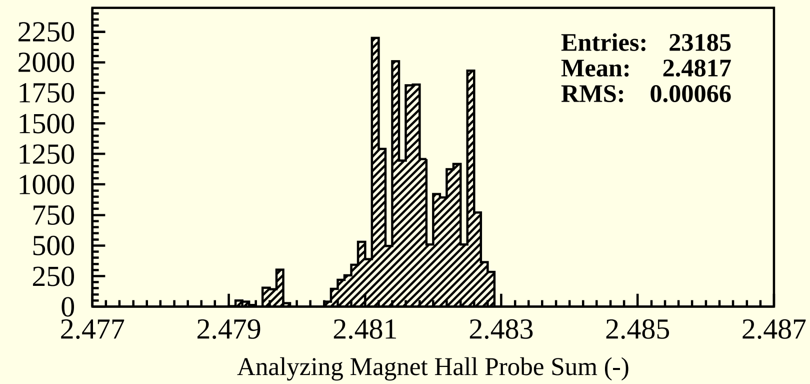
Care Taken to Mimimize Differences in + and − Running

- Target length changed to equalize channeled beam rates.
  - + polarity: 2.0 cm Cu
  - − polarity: 6.0 cm Cu



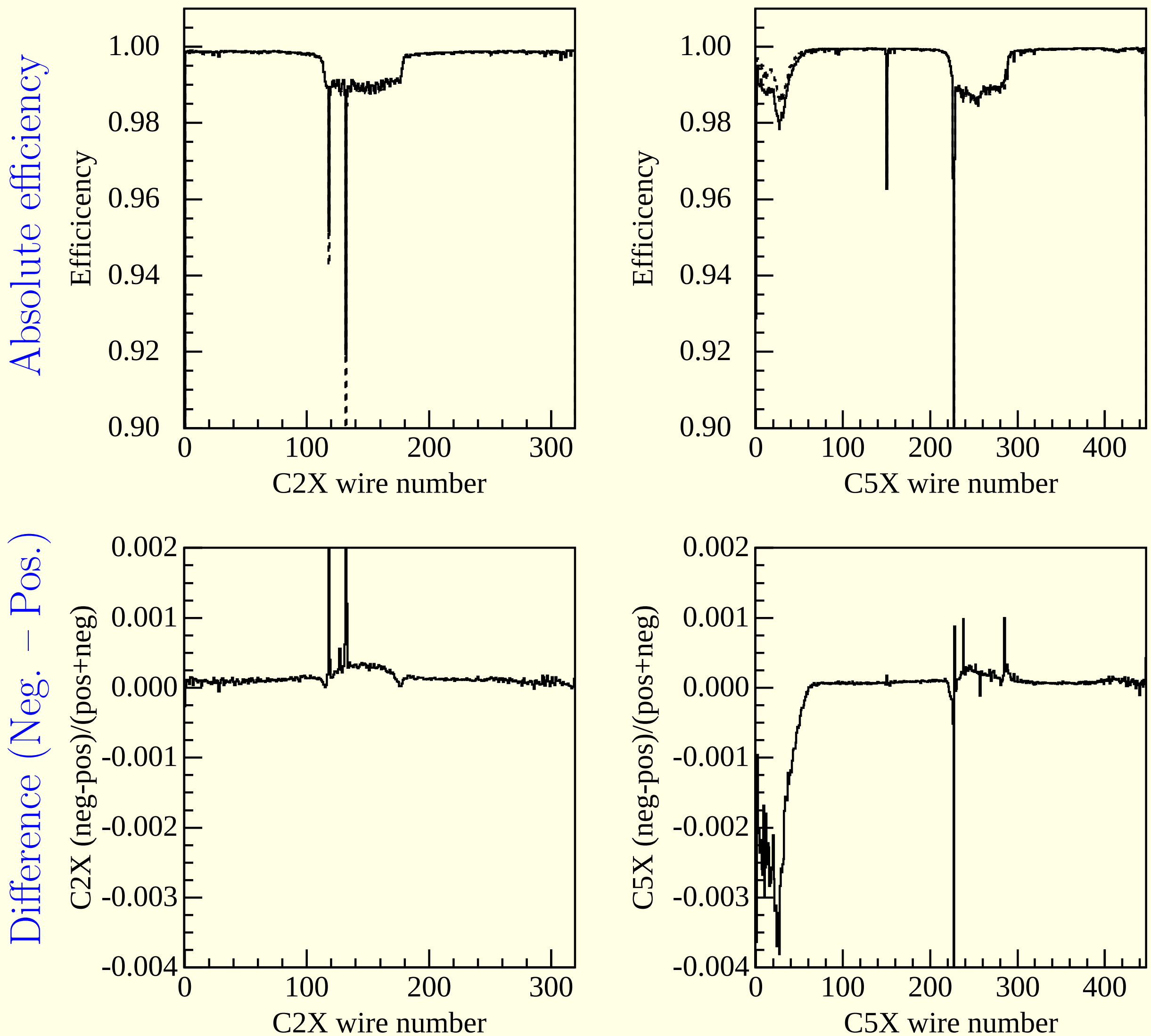
- When flipping polarity, field magnitude kept within $\sim 2\times10^{-4}$.
- This corresponds to a ∼0.3 mm deflection difference at 10 m for the lowest momentum (∼10 GeV/c pions).





Little Difference in PWC Efficiencies from + and − Running

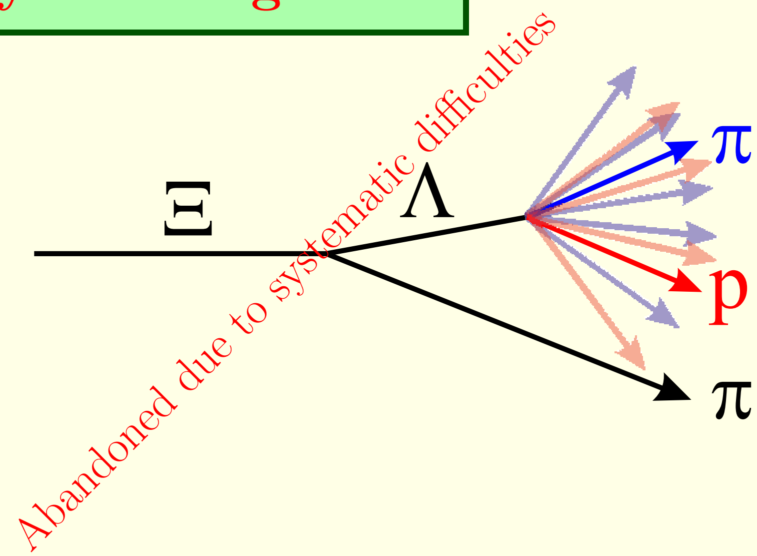
- − data: solid line
- + data: dashed line



Two Different CP Analyses Being Done

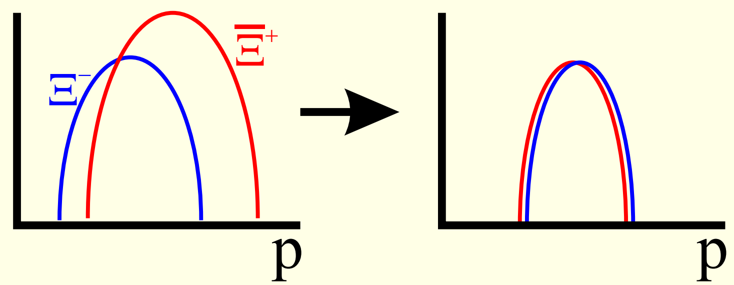
West Coast (LBL): Hybrid Monte Carlo Method

- Compare corrected $\cos\theta$ distributions.
- Take a real $\Xi \rightarrow \Lambda\pi$, $\Lambda \rightarrow p\pi$ event, discard proton and pion, generate 10 new unpolarized Λ decays.
- Advantage: Absolute measurement of $\alpha_\Lambda\alpha_\Xi$.
- Disadvantage: Monte Carlo must be very, very good, and fast: $\sim$20 billion events needed.



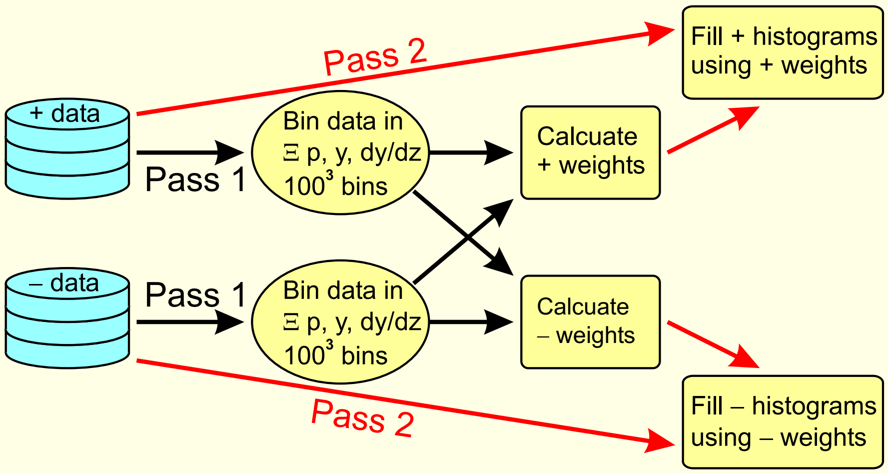
East Coast (UVa): Weighting Method

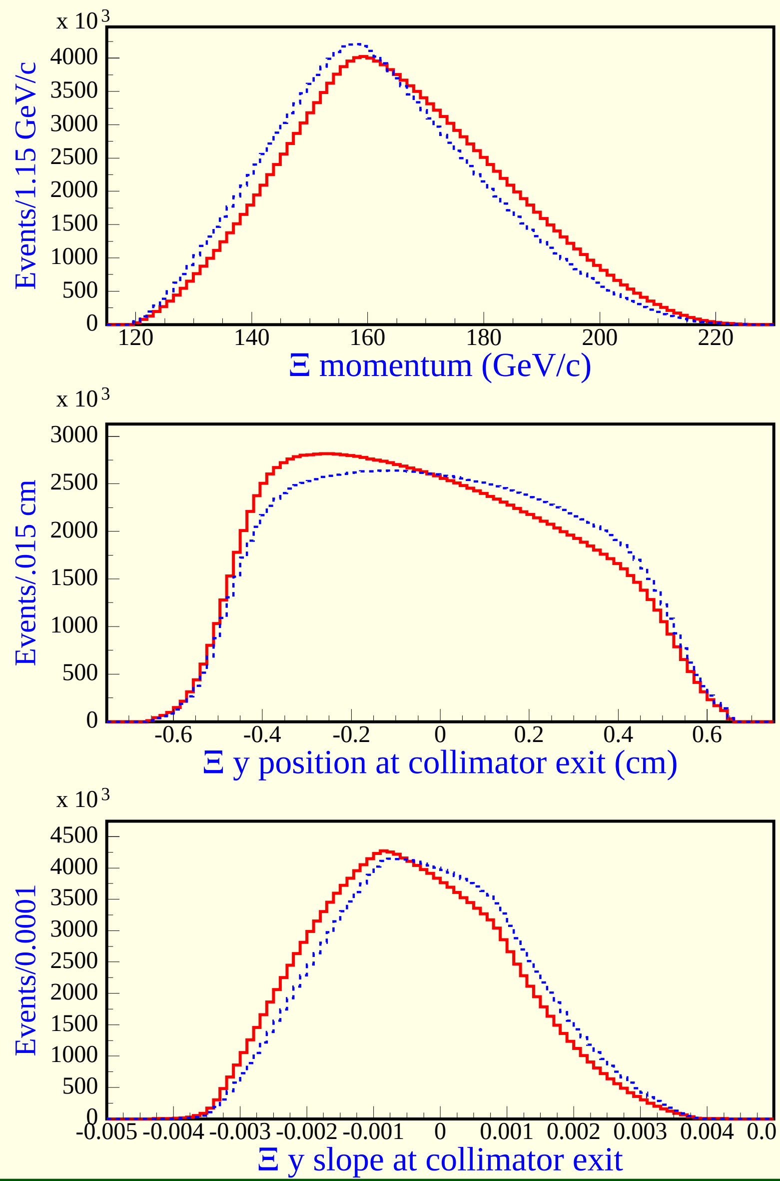
- Compare uncorrected $\cos(\theta)$ distributions.
- Force the Ξ^- and $\overline{\Xi}^+$ events to have similar momentum and spatial distributions by appropriate weighting.
- Advantage: No Monte Carlo needed to measure apparatus acceptance, smaller statistical error.
- Disadvantage: inflexible, event-size dependent analysis.



Weighting Technique

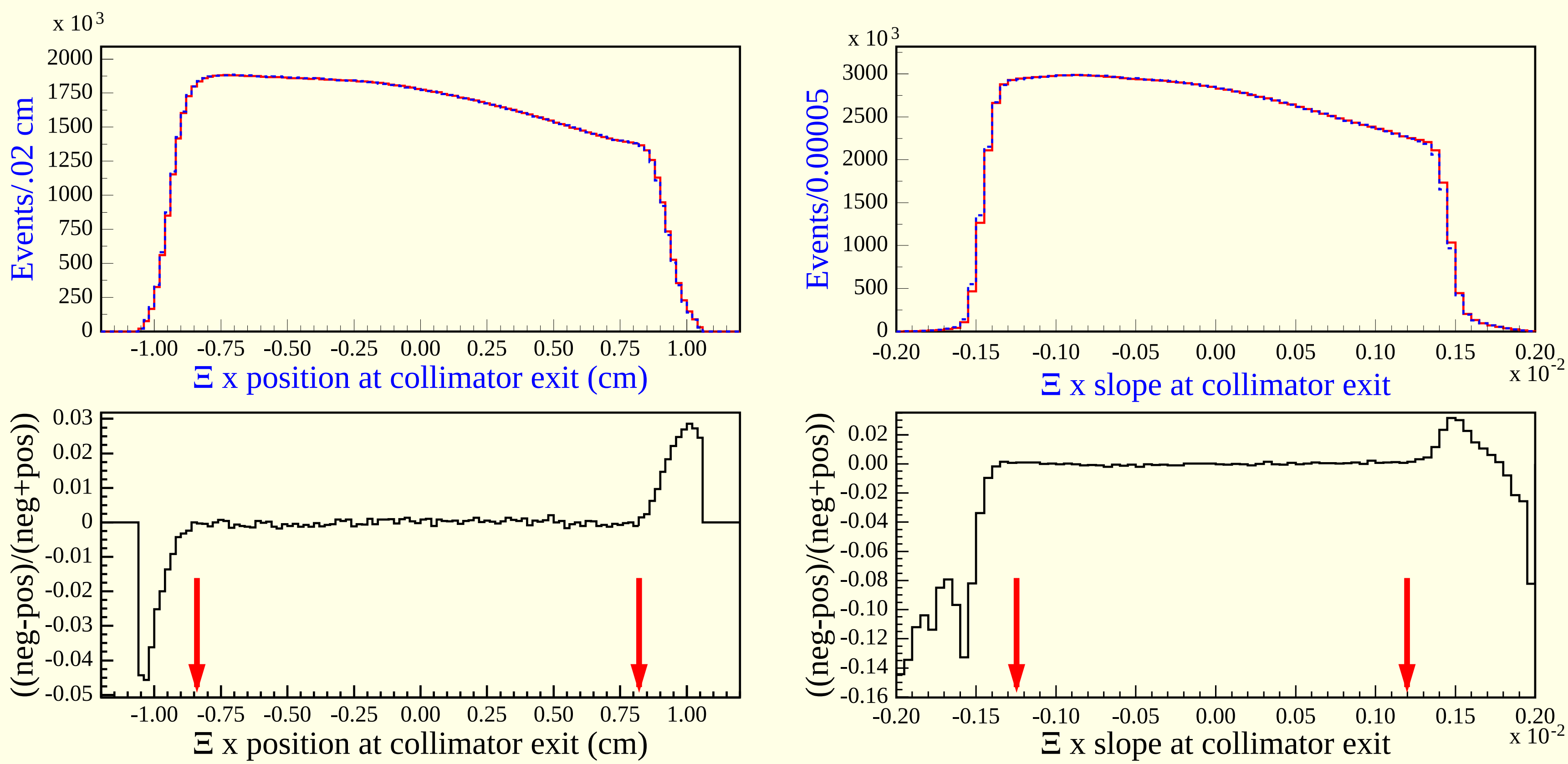
- Problem: Geometical acceptance identical for Ξ^- and $\overline{\Xi}^+$ decay products only if parent Ξ^- and $\overline{\Xi}^+$ have same momentum and inhabit the same phase space exiting the collimator.
- Solution: Weight the Ξ^- and $\overline{\Xi}^+$ events to force the two distributions to be identical.





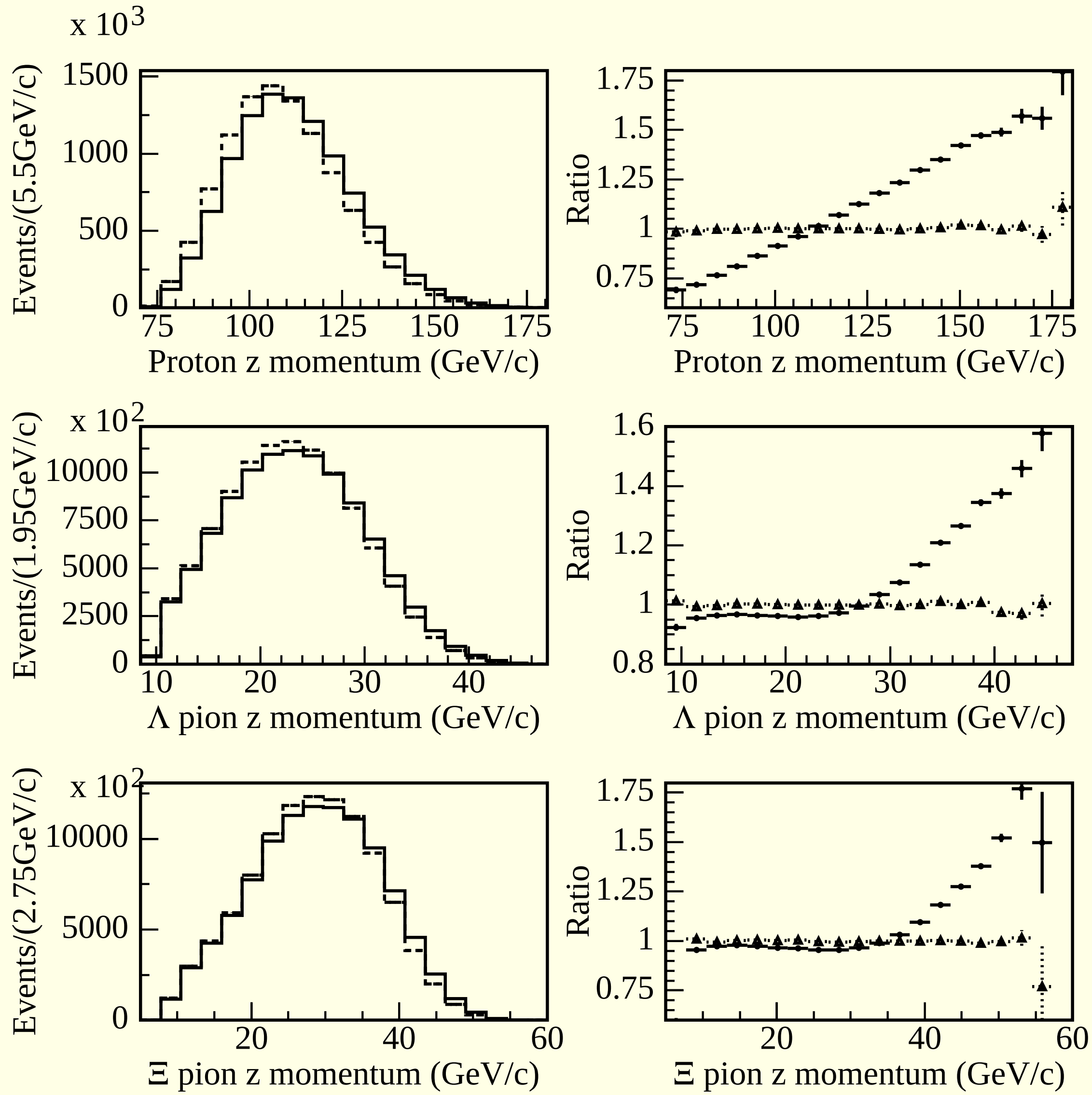
Ξ^- and $\overline{\Xi}^+$ x Slopes and Positions not Weighted

- Distributions almost identical $\Rightarrow$ cut out regions where they are not.
- Ξ^-: Solid lines
- $\overline{\Xi}^+$: Dashed lines



Proton, Λ-pion, Ξ-pion Momenta Before/After Weighting

− Solid lines
+ dashed lines



Ratio

o: before weighting
△ after weighting

Extracting the CP Asymmetry

- Determine weighted proton and weighted antiproton $\cos\theta$ distributions.

$$\frac{dN_-}{d\cos\theta_-} = A_- \frac{N_-}{2}(1+\alpha_\Xi\alpha_\Lambda\cos\theta_-) \qquad \frac{dN_+}{d\cos\theta_+} = A_+ \frac{N_+}{2}(1+\overline{\alpha}_\Xi\overline{\alpha}_\Lambda\cos\theta_+)$$

- Take the ratio of $\cos\theta$ distributions and fit to:

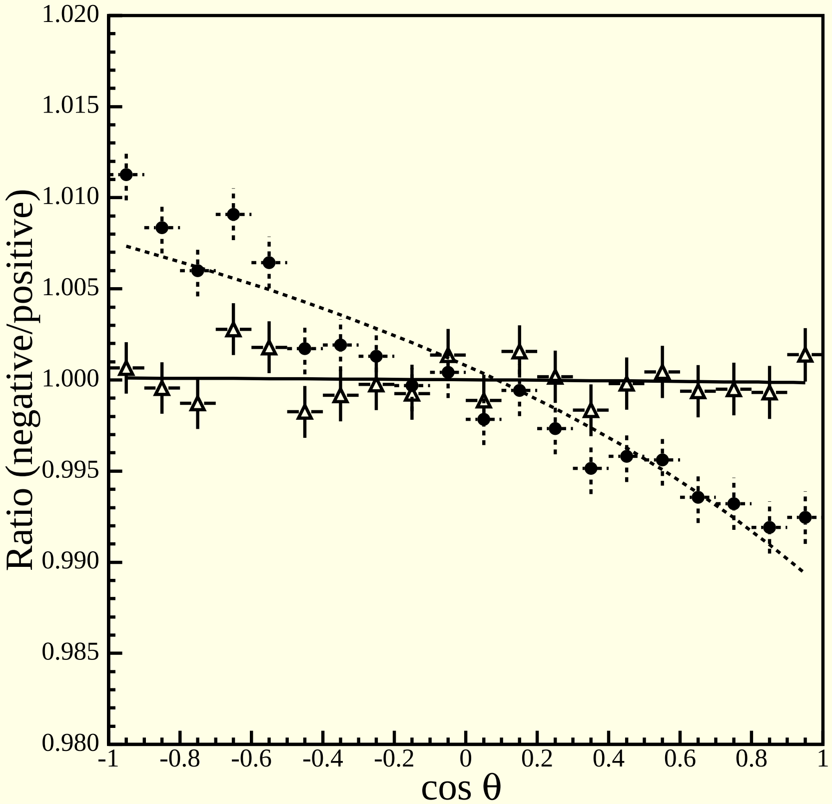
$$R(\theta,\delta) = C\frac{1+\alpha_\Xi\alpha_\Lambda\cos\theta}{1+(\alpha_\Xi\alpha_\Lambda-\delta)\cos\theta}$$

to extract asymmetry δ:

$$\delta = \alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda$$

$$A_{\Xi\Lambda} = \frac{\delta}{\alpha_\Xi\alpha_\Lambda+\overline{\alpha}_\Xi\overline{\alpha}_\Lambda} \approx \frac{\delta}{2\alpha_\Xi\alpha_\Lambda}$$

- Note: acceptances cancel out!



Proton $\cos\theta$ ratio before before (●) and after (△) weighting.

Monte Carlo Tests

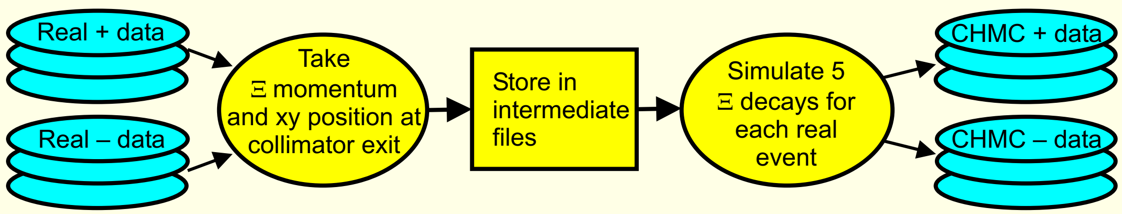
Final result has no Monte Carlo dependence!

Important! Monte Carlo only used to:

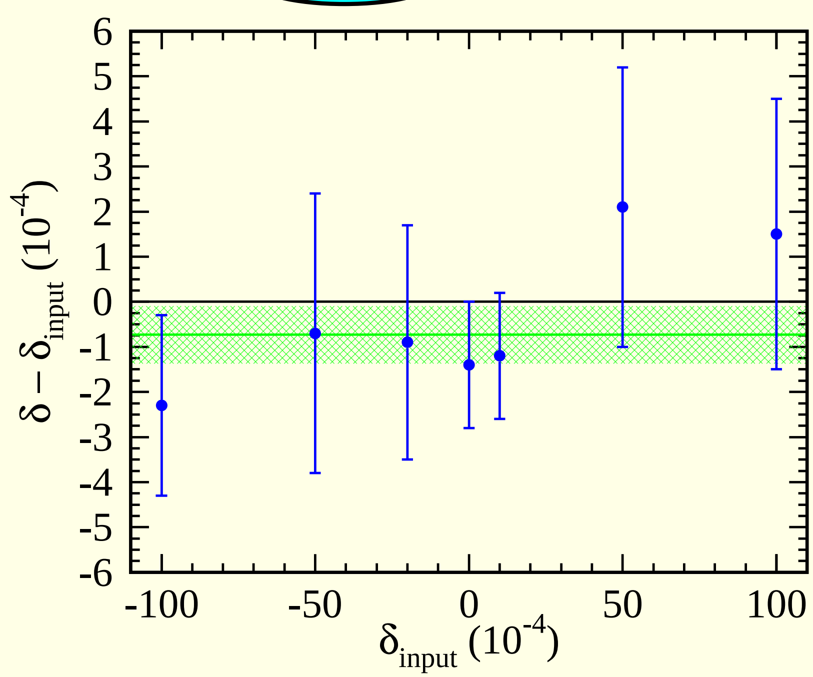
- Verify code and algorithm.
- Study a few systematics.

Problem: How do you generate ∼1 billion MC events?

Solution:



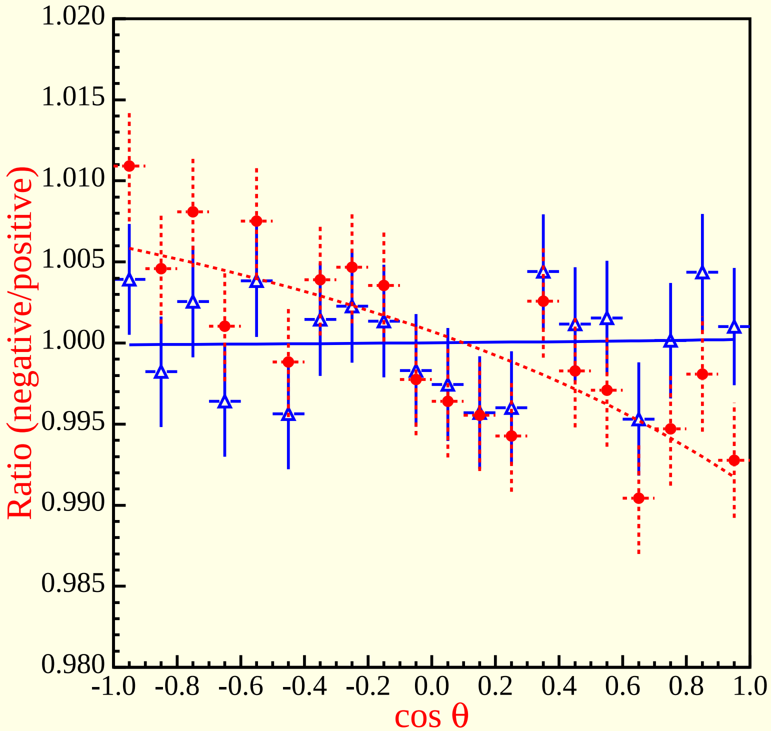
We get the input asymmetry back ⟹



$$\delta = (-0.73 \pm 0.64) \times 10^{-4}$$
$$A_{\Xi\Lambda} = (1.24 \pm 1.09) \times 10^{-4}$$

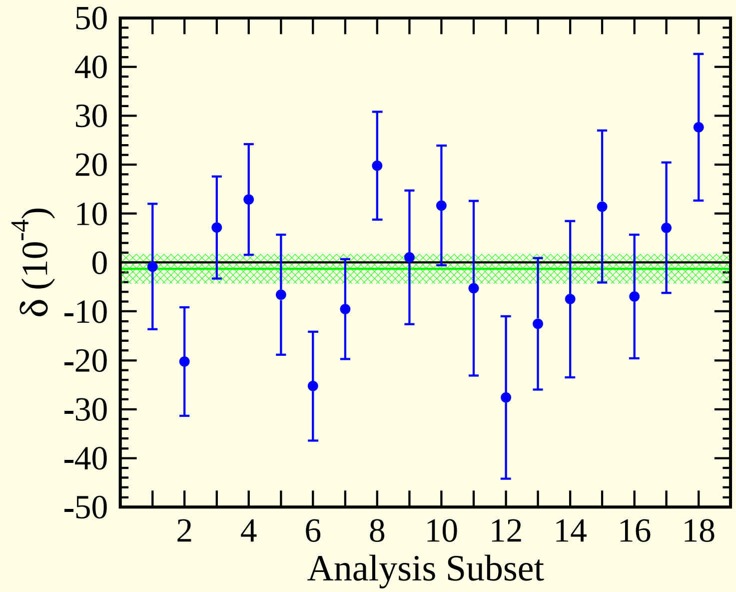
The *CP* Asymmetry $A_{\Xi\Lambda}$ from Weighting Method

- Data broken up into 18 sets of positive and negative data.
- No acceptance corrections.
- No efficiency corrections.
- No background subtraction.



Proton $\cos\theta$ ratio before (●) after (△) weighting, from Analysis Set 1

$$\delta = \alpha_\Xi \alpha_\Lambda - \overline{\alpha}_\Xi \overline{\alpha}_\Lambda$$

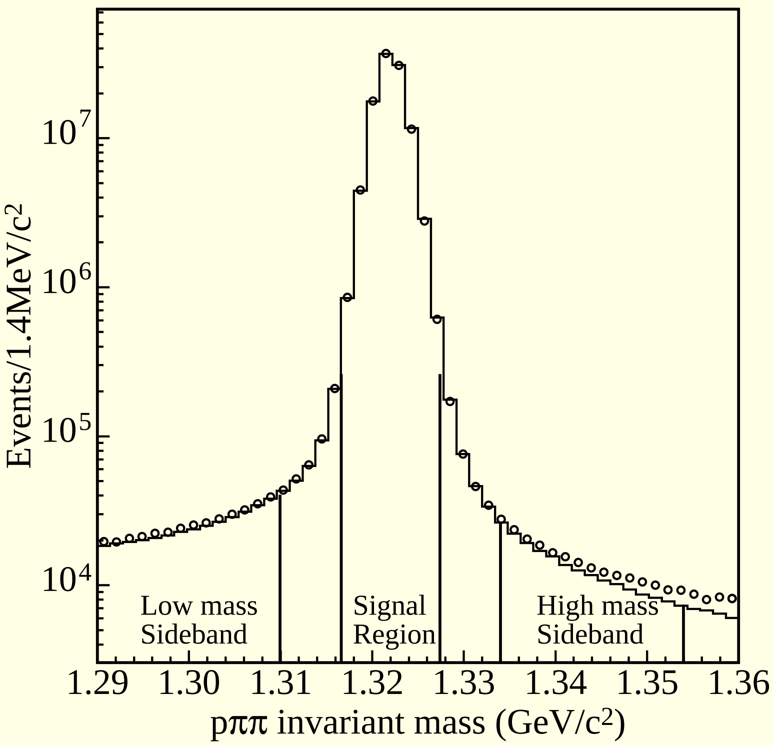


Weighted average of all 18 data sets:

$$\delta = (-1.3 \pm 3.0) \times 10^{-4}$$
$$A_{\Xi\Lambda} = (2.2 \pm 5.1) \times 10^{-4}$$
$$\chi^2 = 24$$

Background Subtraction Has Little Effect

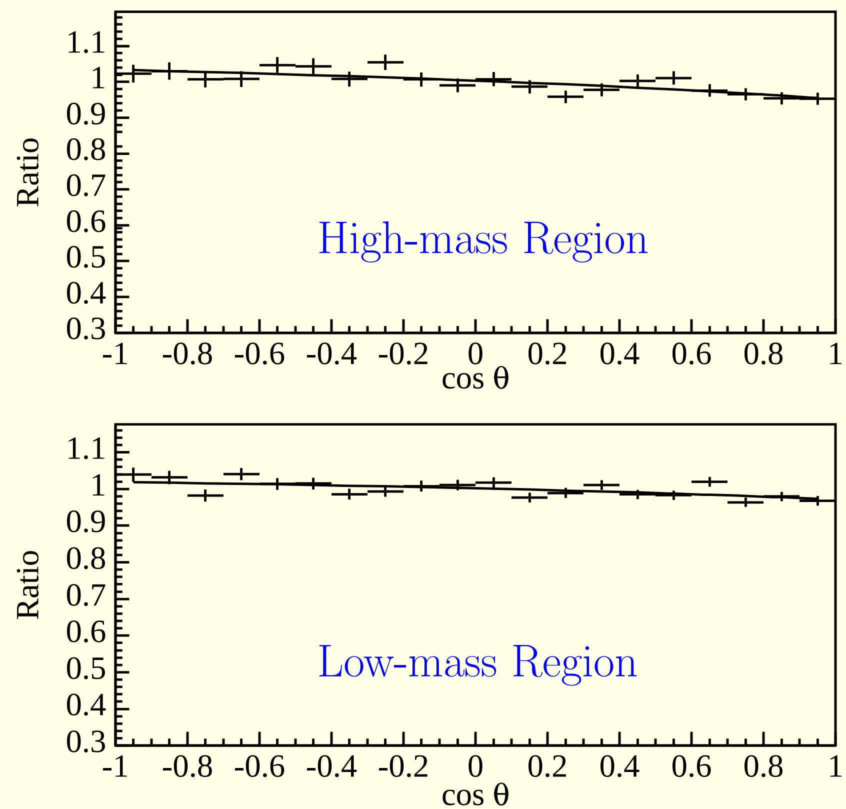
- Triple Gaussian fit with fourth-order polynomial for background.
- Background fraction:
  Ξ^-: 0.43% (lines)
  $\overline{\Xi}^+$: 0.41% (circles)



Low mass: $\delta = (-2.2 \pm 0.5) \times 10^{-2}$
High mass: $\delta = (-3.8 \pm 0.7) \times 10^{-2}$

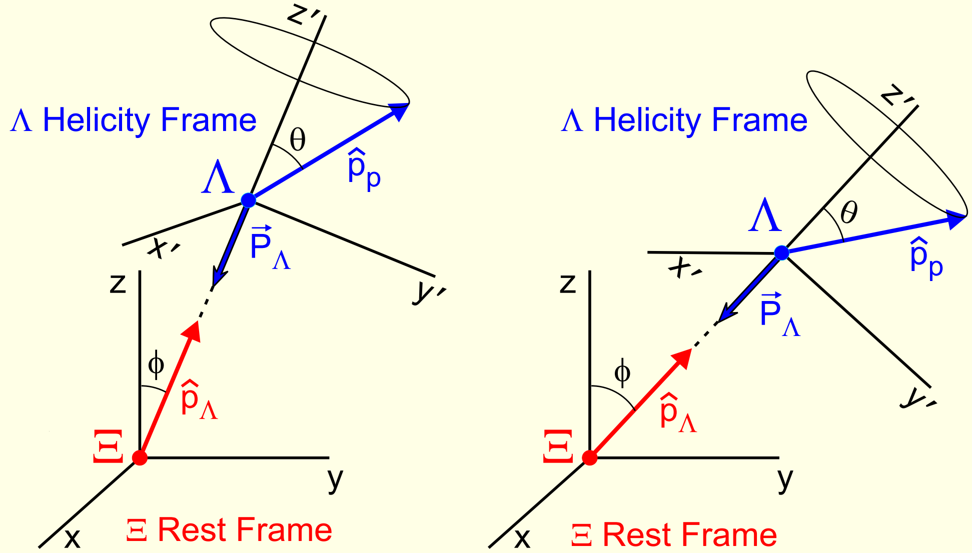
- Weighted background asymmetry:

$$A_{\Xi\Lambda}(bs) = (0.0 \pm 5.1) \times 10^{-4}$$

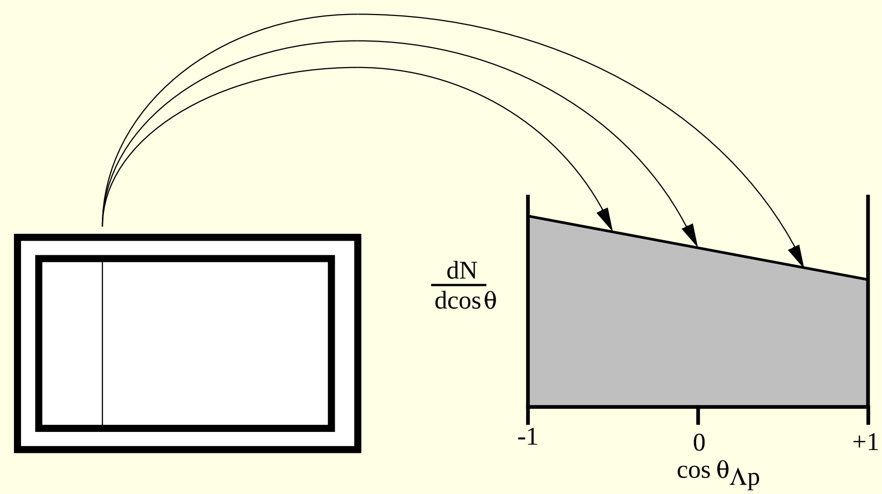


Helicity Frame Analysis Naturally Minimizes Biases

- The helicity frame axes changes from event to event since we always define the polar axis to be the direction of the Λ momentum in the Ξ rest frame.



- Acceptance differences localized in a particular part of the apparatus do **not** map into a particular part of the proton (antiproton) $\cos\theta$ distribution.



Important! Overall acceptance differences do not cause any biases.

Weighted Analysis Bias Error Summary

Systematic	Method	$\delta A_{\Xi\Lambda}(10^{-4})$
Analyzing Magnets field uncertainties	Data	2.8
Calorimeter inefficiency uncertainty	Data	2.1
Validation of analysis code	CHMC	1.9
Collimator exit x slope cut	Data	1.4
Collimator exit x position cut	Data	1.2
PWC inefficiency uncertainty	CHMC	1.0
Hodoscope inefficiency uncertainty	Data	0.3
Particle/antiparitlce interaction differences	MC	0.9
Momentum weights bin size	Data	0.4
Background subtraction uncertainty	Data	0.3
Error on $\alpha\alpha_{PDG}$	Data	0.03
Polarization	MC	negligible
Earth's magnetic field	CHMC	negligible
Total systematic error		4.2

Results from CP Violation Search

Weighting Technique:

- $\sim$10% total data sample
- selected from end of 1999 run
- 118.6 million Ξ^-
- 41.9 million $\overline{\Xi}^+$
- no acceptance or efficiency corrections

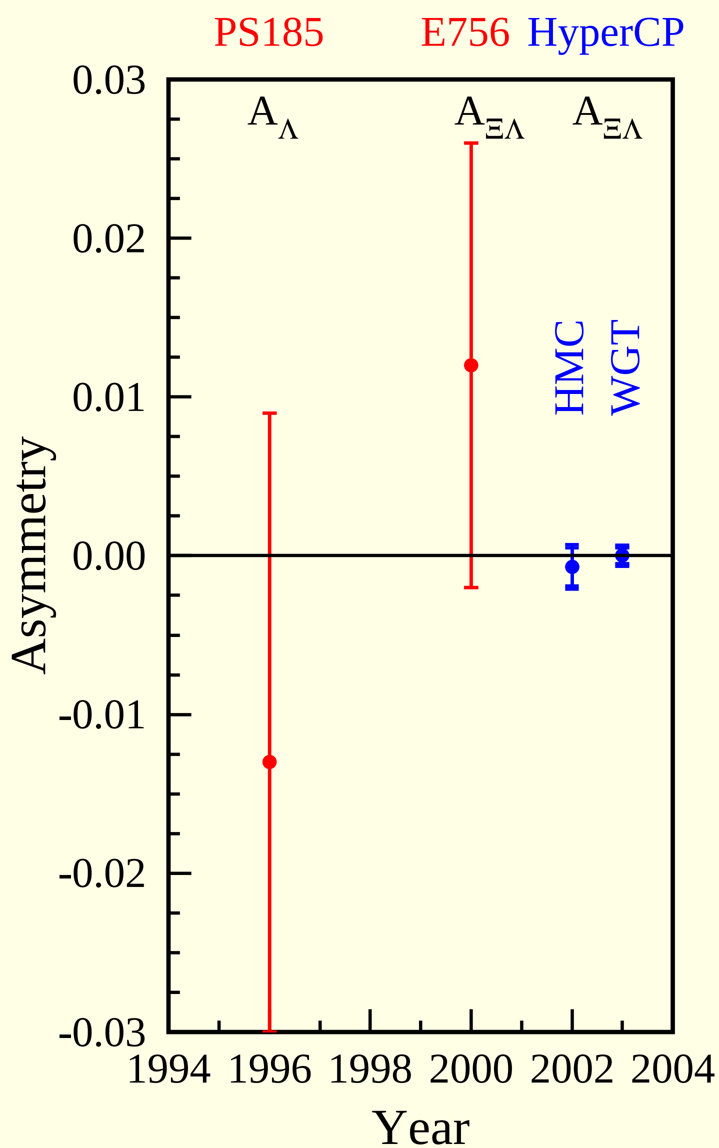
$$A_{\Xi\Lambda} = [0.0 \pm 5.1(\text{stat}) \pm 4.2(\text{syst})] \times 10^{-4}$$

Check with HMC Technique:

- $\sim$ 5% of the total data sample
- prescaled selection of 1997 and 1999
- 15 million Ξ^-
- 30 million $\overline{\Xi}^+$

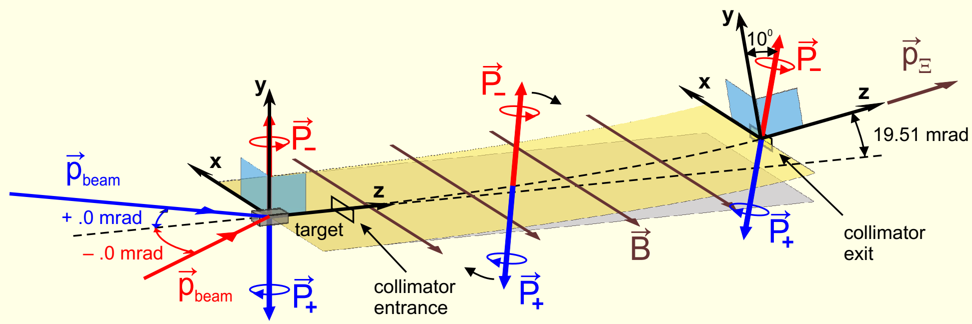
$$A_{\Xi\Lambda} = [-7 \pm 12(\text{stat}) \pm 6.2(\text{syst})] \times 10^{-4}$$

$\Rightarrow$20$\times$ improvement on previous result.

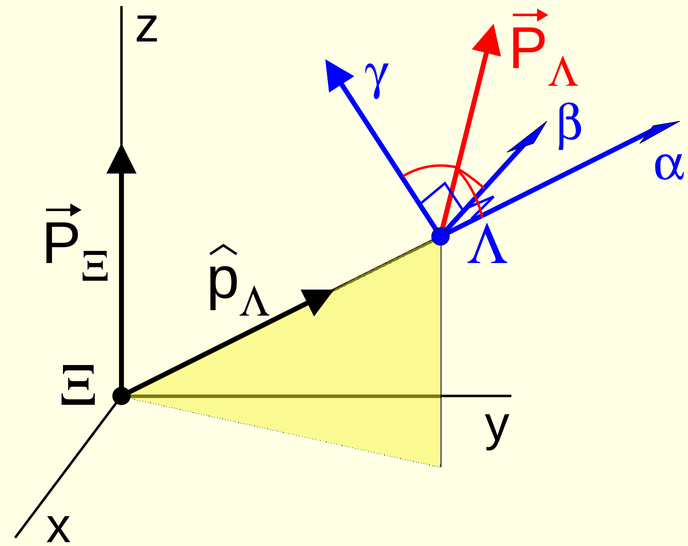


Measuring the Λ-π Strong Phase Shift

- This is done by analyzing the Λ decay distribution from **polarized** Ξ^-'s.
- Polarized Ξ^-'s are produced by targeting at nonzero angles.
- A polarized Ξ^- decay produces a Λ with three components of polarization:



$$\vec{P}_\Lambda = \frac{(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{p}_\Lambda)\hat{p}_\Lambda + \beta_\Xi(\vec{P}_\Xi \times \hat{p}_\Lambda) + \gamma_\Xi(\hat{p}_\Lambda \times (\vec{P}_\Xi \times \hat{p}_\Lambda))}{(1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{p}_\Lambda)}$$



where:

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

- Measuring β_Ξ allows the phase shift to be extracted:

$$\frac{\beta_\Xi}{\alpha_\Xi} = \tan(\delta_P - \delta_S) \approx \delta_P - \delta_S$$

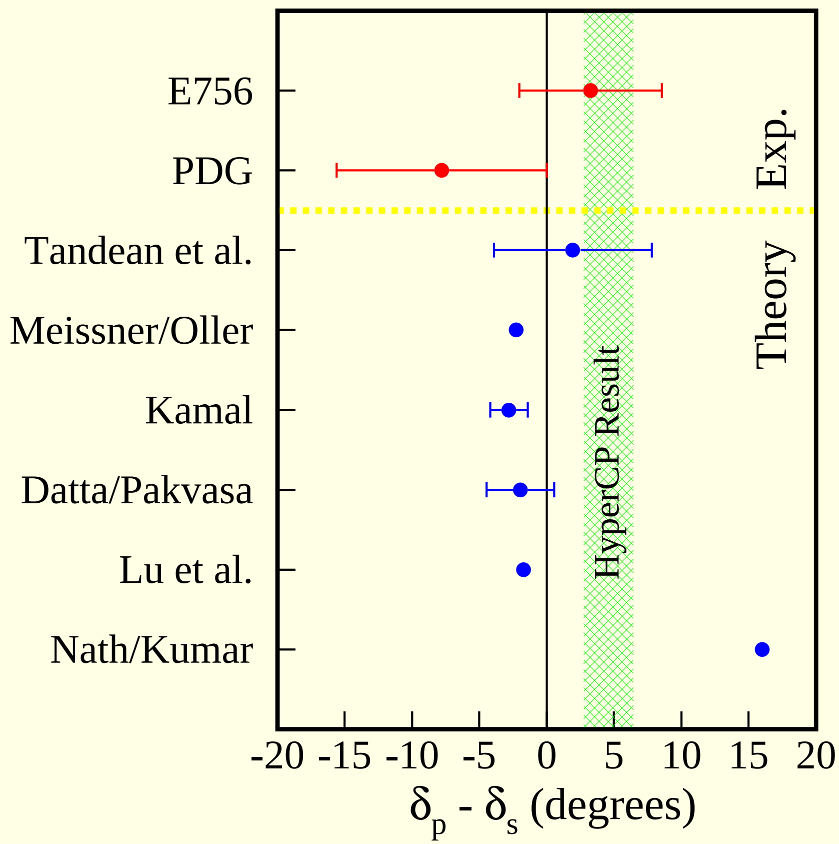
Measurement of the Λ-π Phase Shift

- From 144 million polarized Ξ^- decays:

$$\beta_\Xi = -0.037 \pm 0.011(\text{stat}) \pm 0.010(\text{syst})$$
$$\gamma_\Xi = 0.888 \pm 0.0004(\text{stat}) \pm 0.006(\text{syst})$$

- Using the known value of α_Ξ (-0.456 ± 0.008), the strong phase shift is:

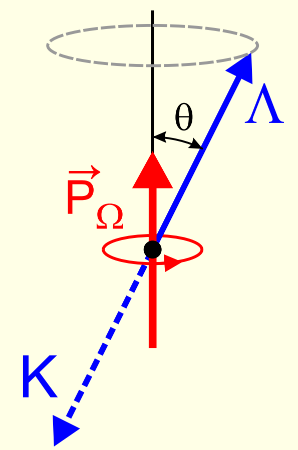
$$\delta_P - \delta_S = \tan^{-1}\left(\frac{\beta_\Xi}{\alpha_\Xi}\right) = (4.6 \pm 1.4 \pm 1.2)^\circ$$



- First non-zero measurement of phaseshift.
- This is about the same magnitude as the p-π phase shift:
  - $\Rightarrow$ CP equally likely to be seen in $\Xi \to \Lambda\pi$ decays.
  - $\Rightarrow$ CP predictions underestimated,
  - $\Rightarrow$ χPT calculations off.

Search for Parity Violation in $\Omega^- \rightarrow \Lambda K^-$ Decays

$$\Omega^- \longrightarrow \Lambda K^- \qquad \Lambda \longrightarrow p\pi^-$$



- Although spin-3/2, $\Omega^- \rightarrow \Lambda K^-$ decay goes much like the other hyperon two-body decays:

$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega P_\Omega \cos\theta)$$

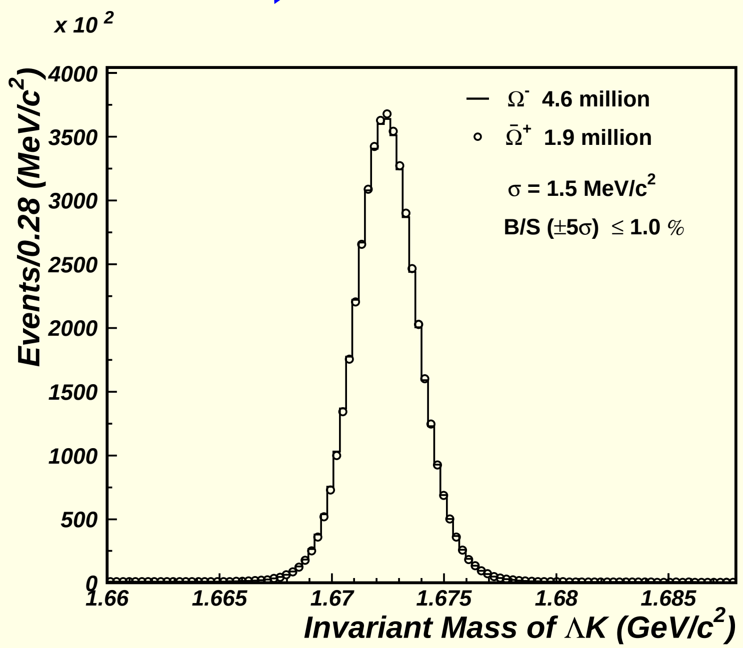
- Here:

$$\alpha_\Omega = \frac{2\mathrm{Re}(P^* D)}{|P|^2 + |D|^2}$$

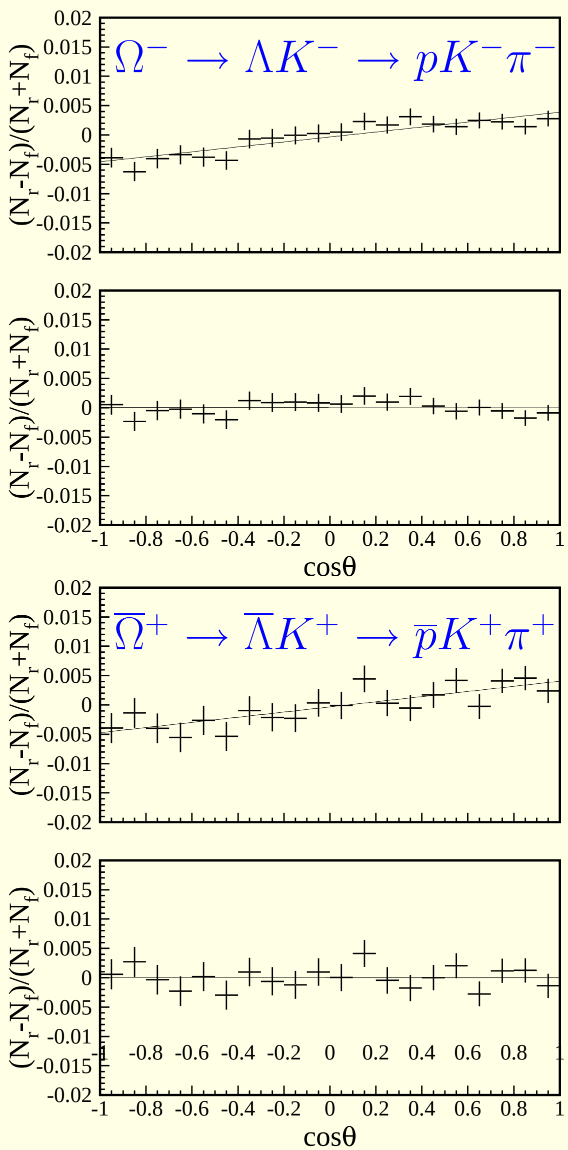
- A non-zero α_Ω indicates parity violation.
- All other hyperons have non-zero α parameters; only the Ω^- has resisted efforts to find an asymmetrical decay distribution.
- *HyperCP* is measuring α_Ω using unpolarized Ω^-'s through the polarization given to the daughter Λ, which is α_Ω:

$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega \alpha_\Lambda \cos\theta)$$

- Large data sample, little background.

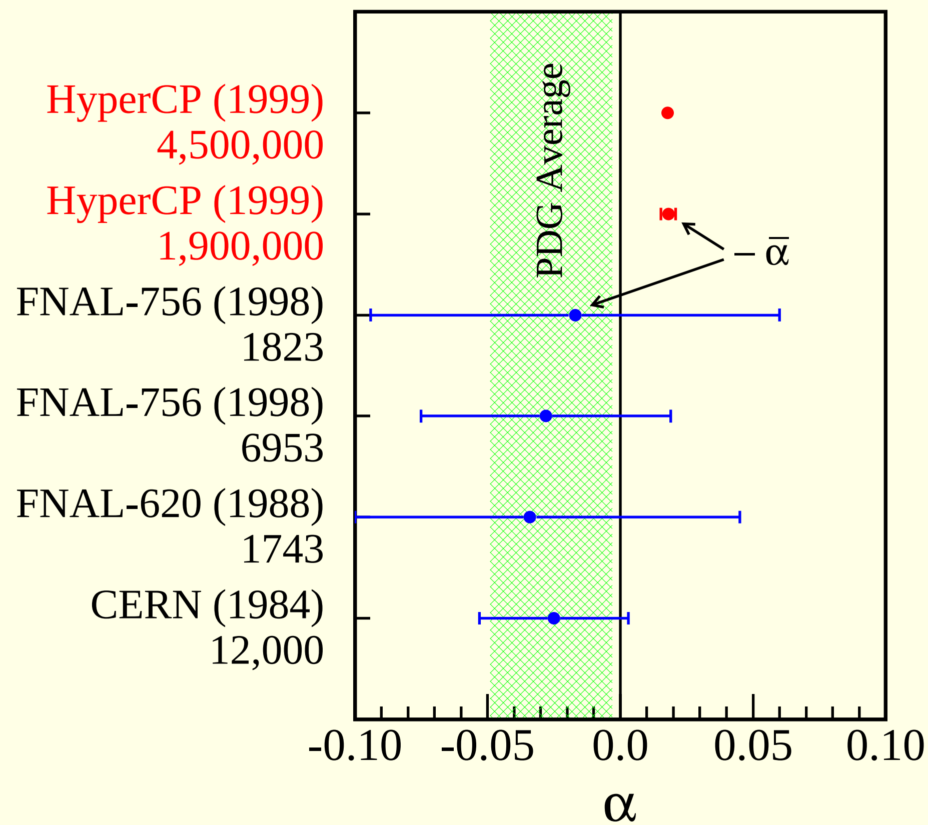


Preliminary Measurement of α_Ω and $\overline{\alpha}_\Omega$ in $\Omega^- \to \Lambda K^-$ Decays



1999 : $\alpha_\Omega = [\ \ 1.78 \pm 0.19(\text{stat}) \pm 0.10(\text{syst})] \times 10^{-2}$

1999 : $\overline{\alpha}_\Omega = [-1.81 \pm 0.28(\text{stat})] \times 10^{-2}$



- First evidence of parity violation in Ω^- decays.
- Can search for CP violation in $\Omega^-/\overline{\Omega}^+$ decays.

Conclusions and Outlook

- Analyzing by far the largest sample of hyperons ever recorded, we have assulted CP violation from a different direction than the kaon and B experiments.
- We find no evidence of CP violation in $\Xi^{\pm}$ and Λ decays:
$$\delta A_{\Xi\Lambda} = (0.0 \pm 5.1 \pm 4.2)\times 10^{-4}$$
- This result is constraining some SUSY models of CP violation.
- Shortly we will push our statistical limit to
$$\delta A_{\Xi\Lambda} \approx 2\times 10^{-4}$$
two orders of magnitude better than the present limit.
- We have the first evidence of parity violation in $\Omega^- \to \Lambda K^-$ decays.
- A preliminary analysis shows no evidence of CP violation in $\Omega^- \to \Lambda K^- \;/\; \overline{\Omega}^+ \to \overline{\Lambda} K^+$ decays.