Search for CP Violation in Hyperon Decays with the *Hyper*CP 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.
- Although CP is expected to be ubiquitous in weak interactions — albeit often vanishingly small — the experimental evidence is still meager.
- Although CP violation is accommodated quite nicely in the standard model, there is little hard evidence that it is the sole province of the standard model.
- Many beyond-the-standard-model theories can produce large new sources of CP violation, none of which have yet been seen.

> **"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

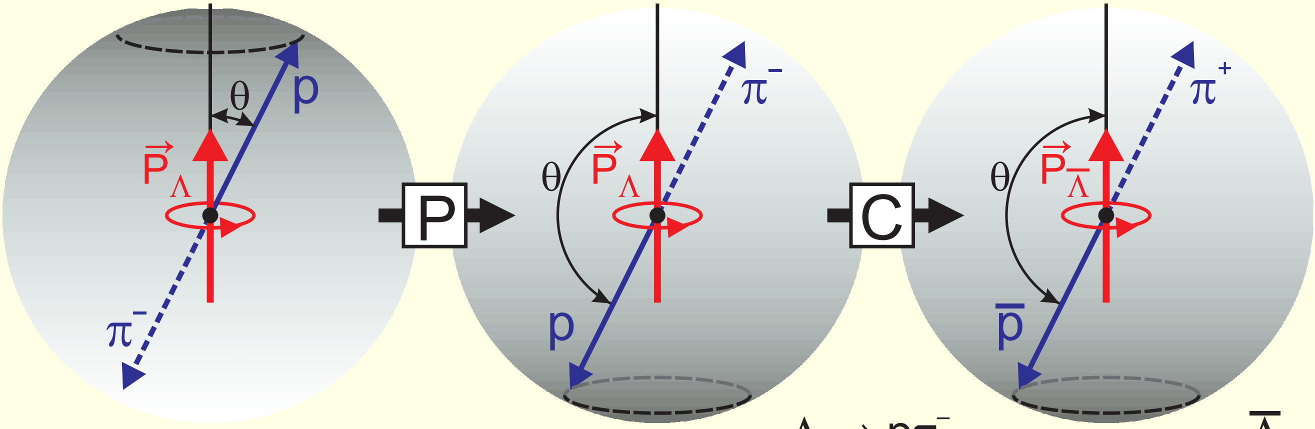
- Hyperons are sensitive to sources of CP violation that are not probed in other systems.
- These sources are experimentally accessible.
- The cost is small:
  - No new accelerators needed.
  - Apparatus is modest in scope and cost.

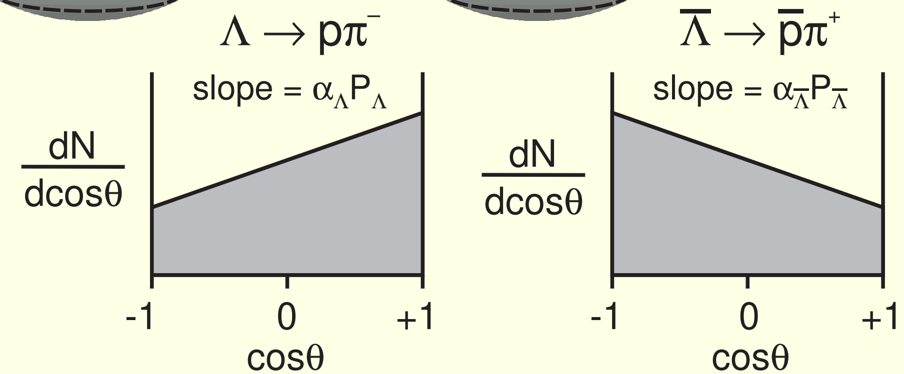
How to Search for *CP* Violation in Λ Decays

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

$$\Lambda \rightarrow p\pi^- : \qquad \frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1+\alpha_\Lambda P_\Lambda \cos\theta) \qquad \alpha = \frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2} = 0.642$$

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





$$\boxed{\alpha_\Lambda \xrightarrow{CP} \alpha_{\overline{\Lambda}} = -\alpha_\Lambda}$$

Problem: The $\Lambda/\overline{\Lambda}$ polarizations have to be precisely known to extract $\alpha_\Lambda/\overline{\alpha}_\Lambda$

Producing Polarized $\Lambda/\overline{\Lambda}$'s : unpolarized Ξ Decays

In this technique, pioneered by *HyperCP*, $\Lambda/\overline{\Lambda}$'s of known polarization are produced from **unpolarized** $\Xi^-/\overline{\Xi}^+$'s:

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

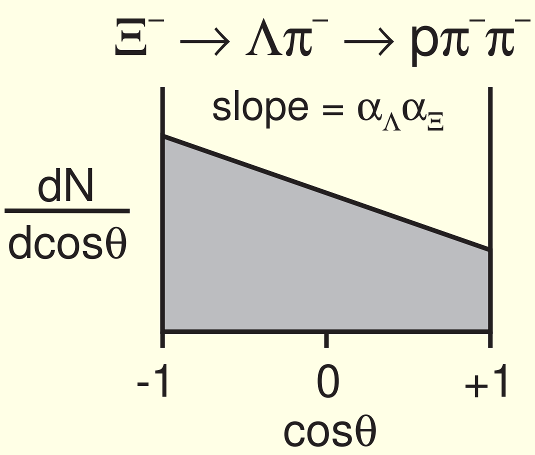
If the Ξ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the Λ is found in a helicity state, with a large polarization ($\alpha_\Xi = -0.458$):

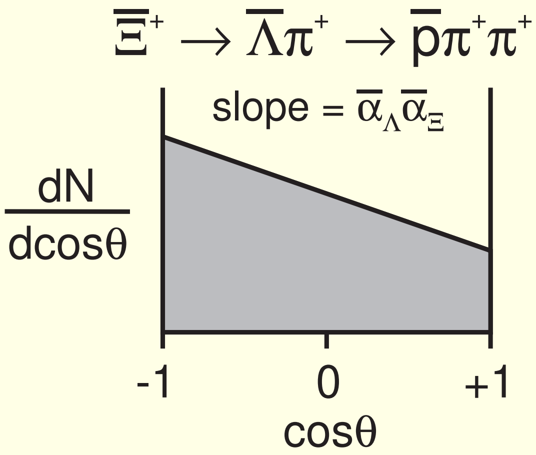
$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad\qquad \vec{P}_{\overline{\Lambda}} = \overline{\alpha}_\Xi \hat{p}_{\overline{\Lambda}}$$

$$\boxed{\frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda\alpha_\Xi\cos\theta)} \qquad \boxed{\frac{dN(\bar{p})}{d\cos\theta} = \frac{N_0}{2}(1 + \overline{\alpha}_\Lambda\overline{\alpha}_\Xi\cos\theta)}$$

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

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



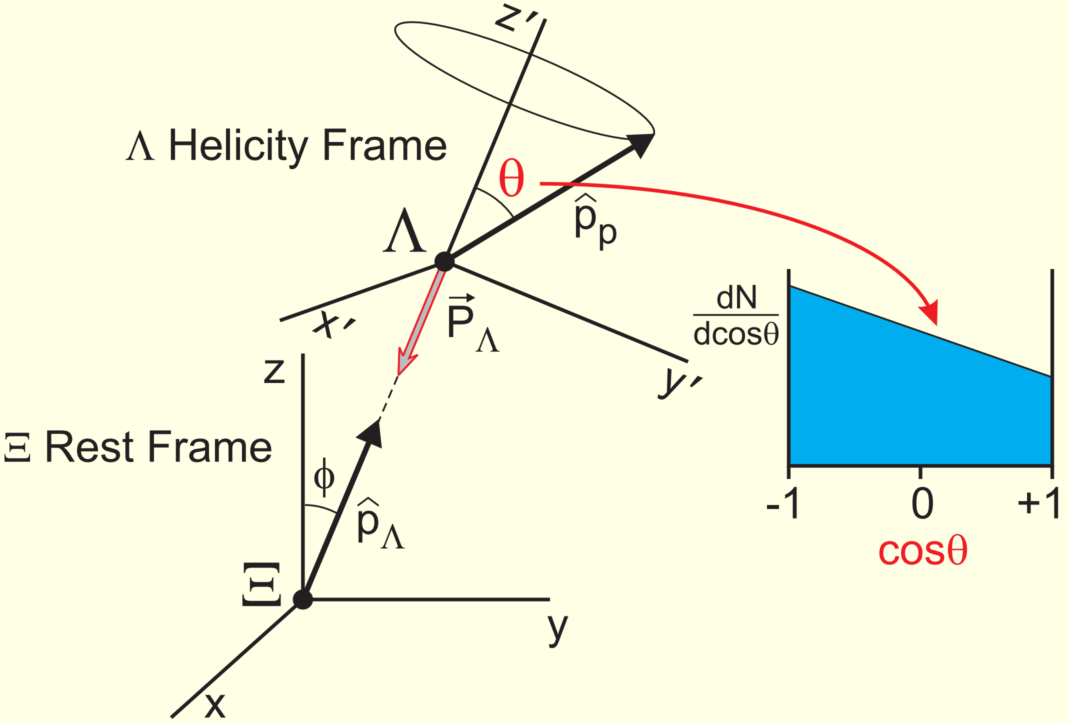


HyperCP technique is sensitive to both Ξ and Λ *CP* violation

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

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

What HyperCP experimentally measures $\Rightarrow$



Important: polar axis changes from event to event.

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.

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

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

$$\Lambda\left\{\begin{aligned} \delta_P &= -1.1 \pm 1.0^\circ \\ \delta_S &= 6.0 \pm 1.0^\circ \end{aligned}\right.$$

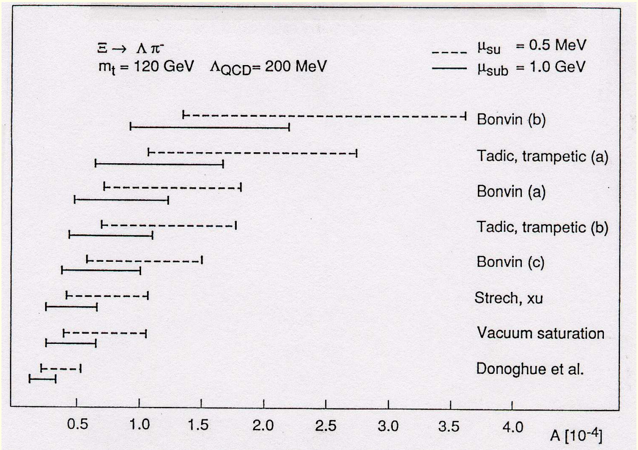
  - The $\Lambda\pi$ phase shifts can't be directly measured, theoretical predictions disagree:

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

***HyperCP* has measured the $\Lambda\pi$ phase shift: $(4.6\pm1.8)^\circ$**

Bad News: Standard Model Theory Predictions Small

- Much enthusiasm a decade ago as Standard Model predictions were relatively large.



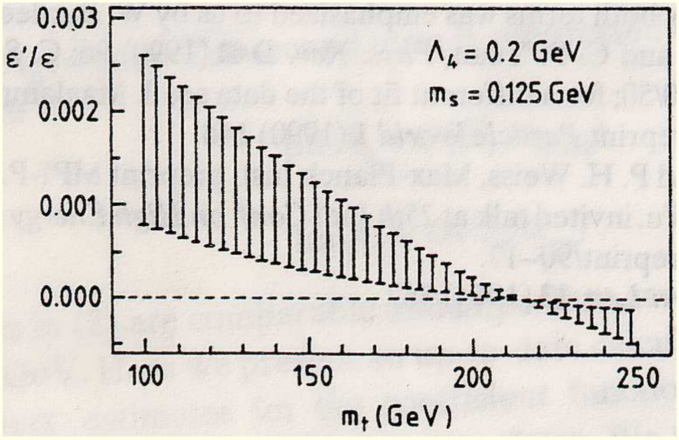
Valencia (1991)

- Standard Model predictions have slowly fallen to:

$$\boxed{-0.5\times10^{-4} < A_{\Xi\Lambda} < +0.5\times10^{-4}}$$

(Tandean & Valencia, 2003)

- At same time there was concern that accidental cancellation in the kaon system would lead to $\epsilon'/\epsilon \approx 0$.



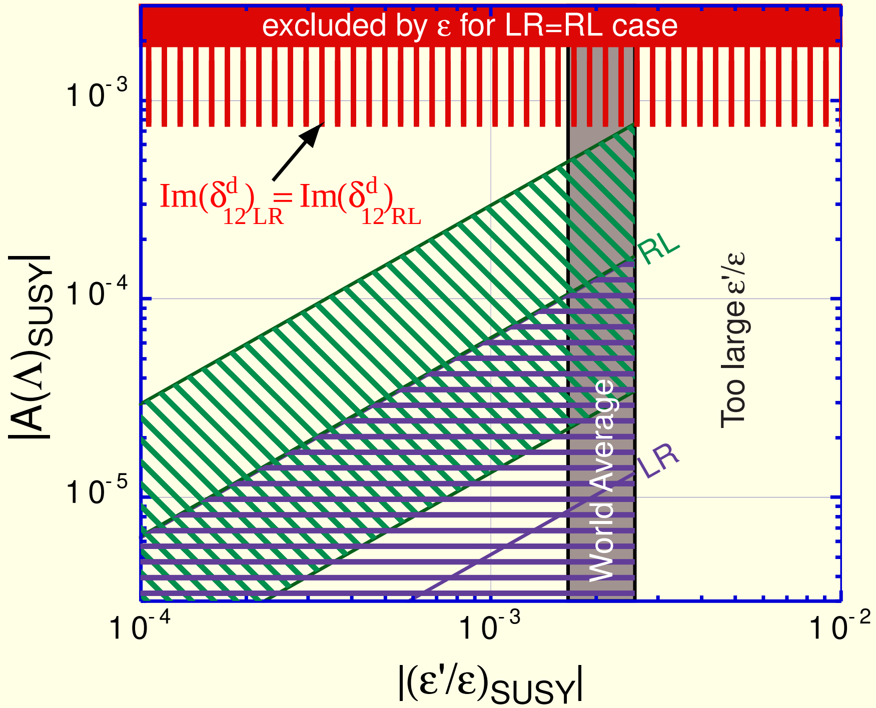
Paschos (1991)

- The expected SM asymmetry is out of reach for any experiment, planned or otherwise.

Important: no unambiguous connection between: $\delta_{\rm CKM} \Leftrightarrow A_\Xi, A_\Lambda$

Good News: Standard Model Theory Predictions Small

- Beyond-the-standard-model predictions larger, and not well constrained by kaon CP measurements: hyperon CP violation probes both parity conserving and parity violating amplitudes.
- Recent paper by Tandean (2004) shows that the upper bound on $A_{\Xi\Lambda}$ from ϵ'/ϵ and ϵ measurements is $\sim 100\times10^{-4}$.
- For example, some supersymmetric models that do not generate ϵ'/ϵ can lead to A_Λ of $O(10^{-3})$.
- Other BSM theories, such as Left-Right mixing models, (Chang, He, Pakvasa (1994)), also have enhanced asymmetries.



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

Any CP-violation signal will almost certainly come from New Physics.

What is the experimental situation?

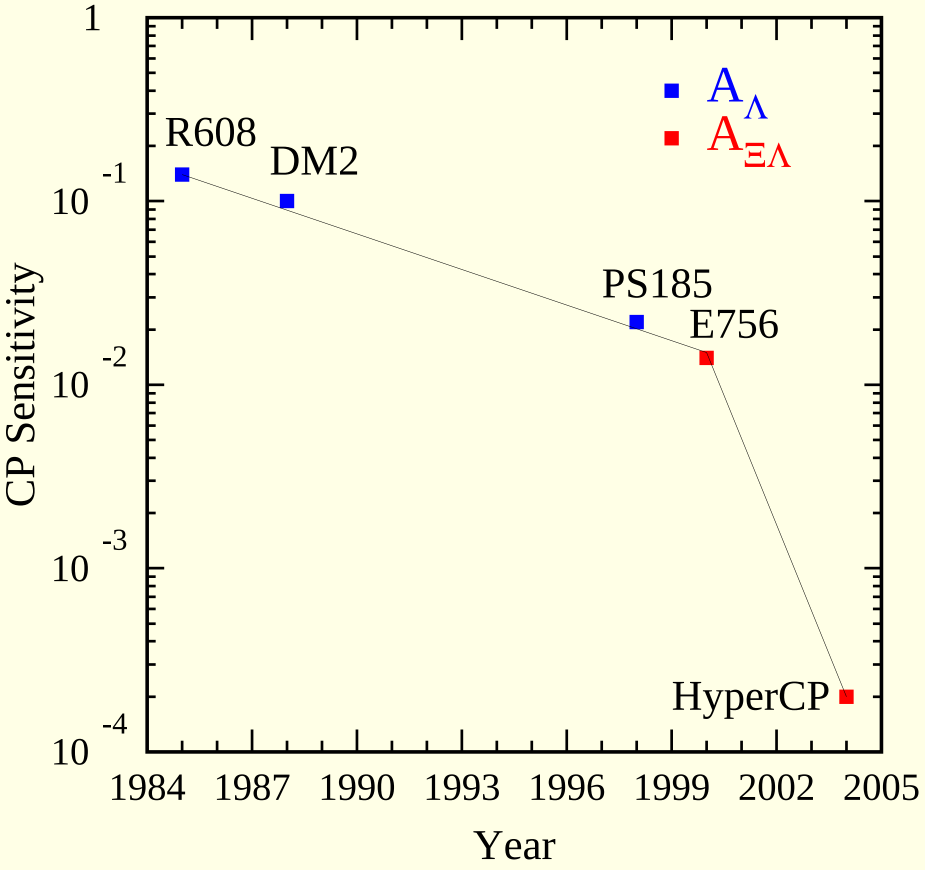
- To date there are only upper limits on the asymmetries.
- A_Λ has been measured to 2×10^{-2}:

Exp	Mode	Method
R608	A_Λ	$p\overline{p} \to \Lambda X$, $p\overline{p} \to \overline{\Lambda} X$
DM2	A_Λ	$e^+e^- \to \mathrm{J}/\psi \to \Lambda\overline{\Lambda}$
PS185	A_Λ	$p\overline{p} \to \Lambda\overline{\Lambda}$

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

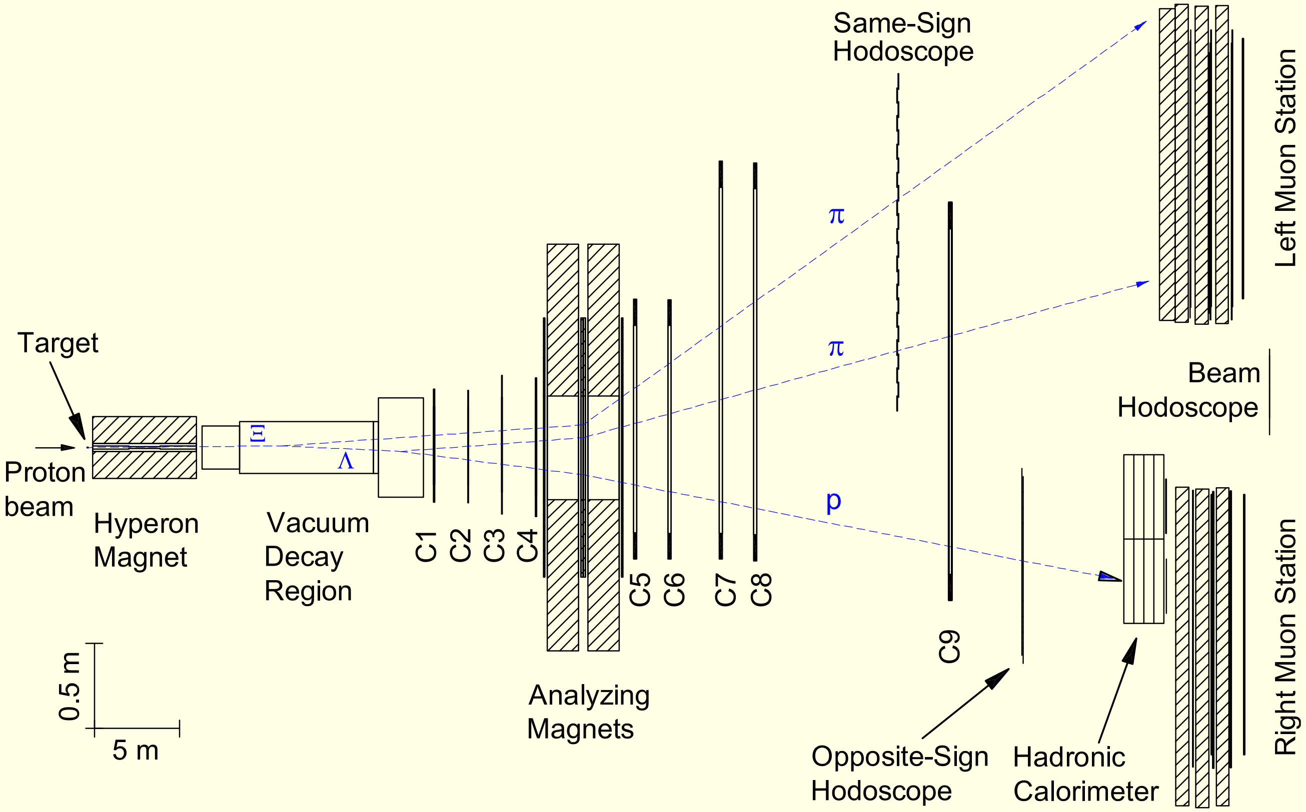
Exp	Mode	Method
E756	$A_{\Xi\Lambda}$	$\mathrm{pN} \to \Xi^\pm X \to \Lambda\pi^\pm$

- 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 $\sim10^{-4}$.**

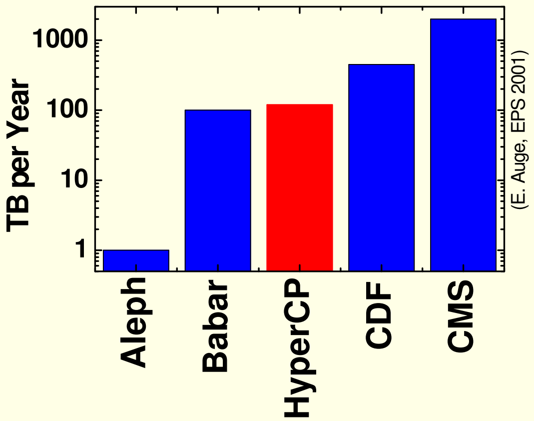
The *HyperCP* Spectrometer

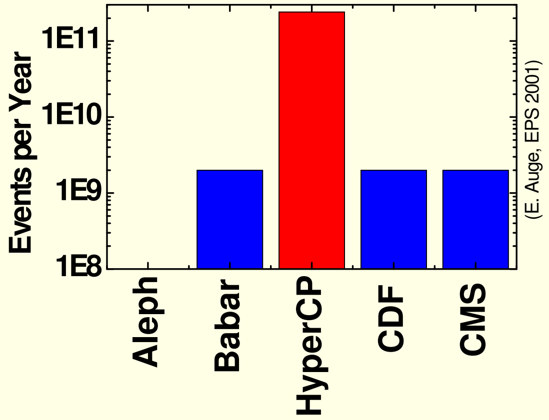


- Alternate + and − running.
- 800 GeV/c incident proton beam.
- 10–15 MHz, 167 GeV/c charged beam.
- High-rate, narrow-pitch wire chambers.
- Muon system for rare/forbidden hyperon and kaon decays.
- Very high-rate DAQ:
  $\rightarrow$ 50-80 KHz evts/spill-s to tape.
  $\rightarrow$ 27 MB/s on 27 Exabyte 8705 tape drives.
- Simple, low-bias trigger using hodoscopes and calorimeter.
  SS($\geq$1 hit)$\cdot$OS($\geq$1 hit)$\cdot$Cal($\geq$40 G eV)

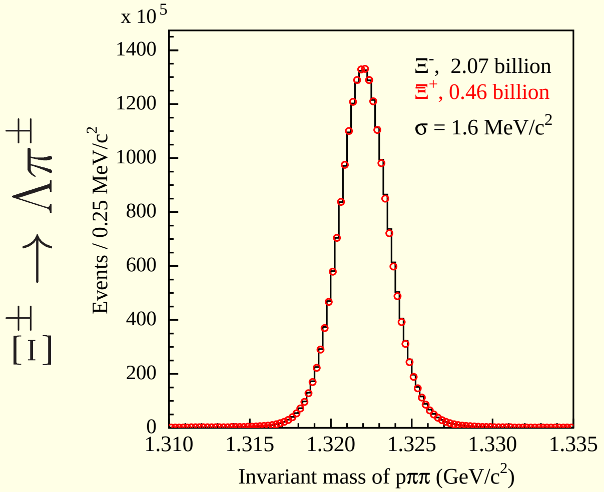
HyperCP Yields

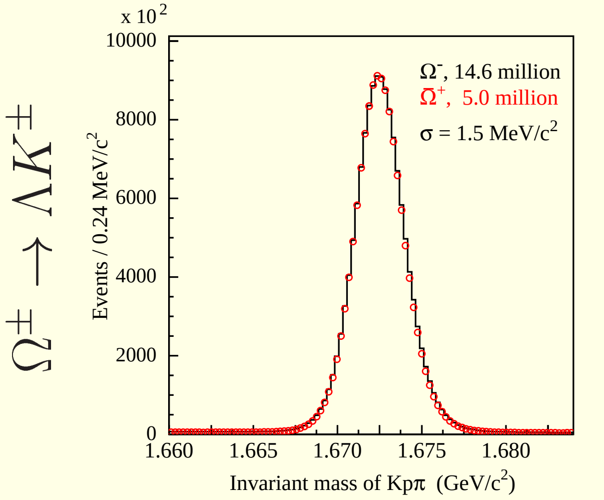
- In 12 months of data taking *HyperCP* recorded one the largest data samples ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.





Entire WWW on 9/11/01 was 5 TB!





Reconstructed Events

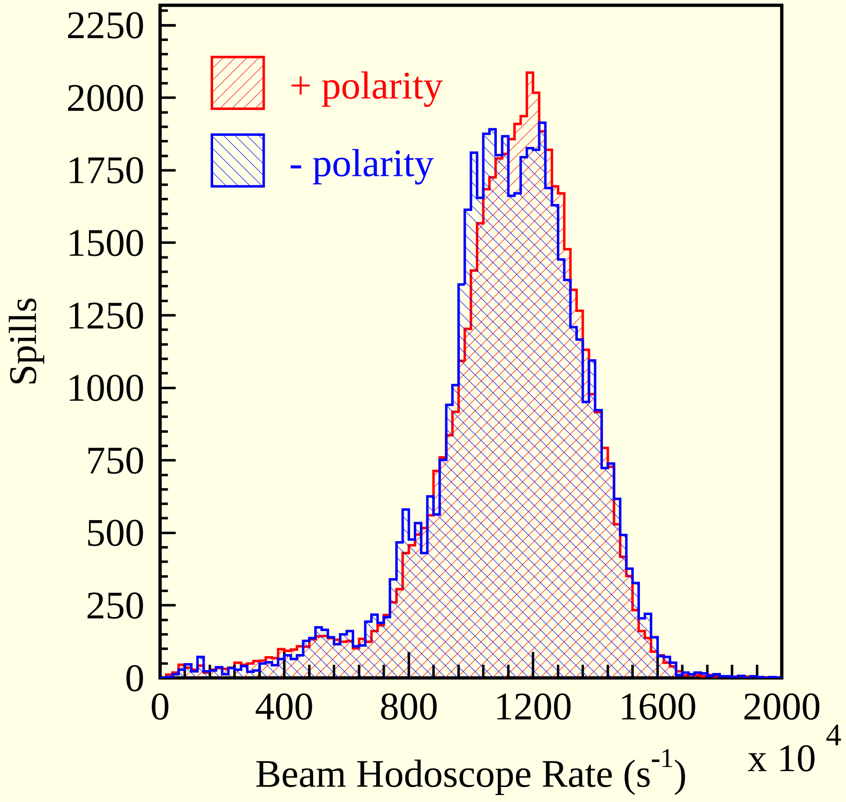
	Channeled beam polarity		
Type	+	−	Total
$\Xi \to \Lambda\pi$	458×10^6	$2\,032 \times 10^6$	$2\,490 \times 10^6$
$K \to \pi\pi\pi$	391×10^6	164×10^6	555×10^6
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6

Care Taken to Minimize Differences in + and − Running

- Targets changed to equalize secondary-beam rates.

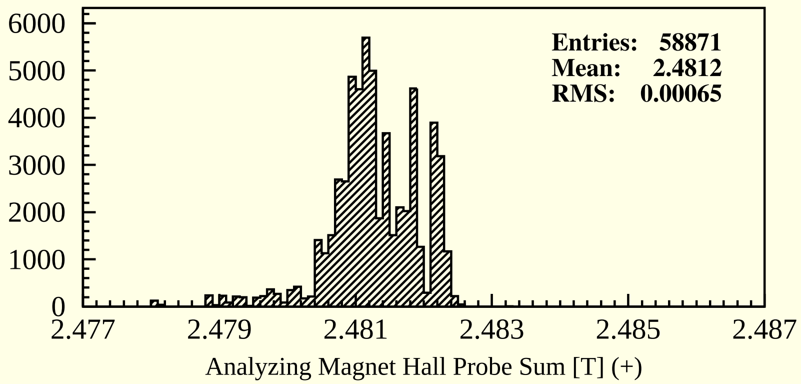
  \+ polarity: 2.0 cm Cu

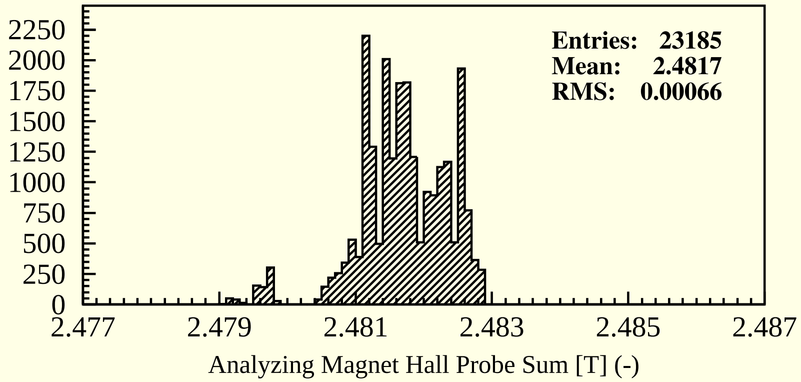
  − polarity: 6.0 cm Cu



- About a 1% difference in rates.

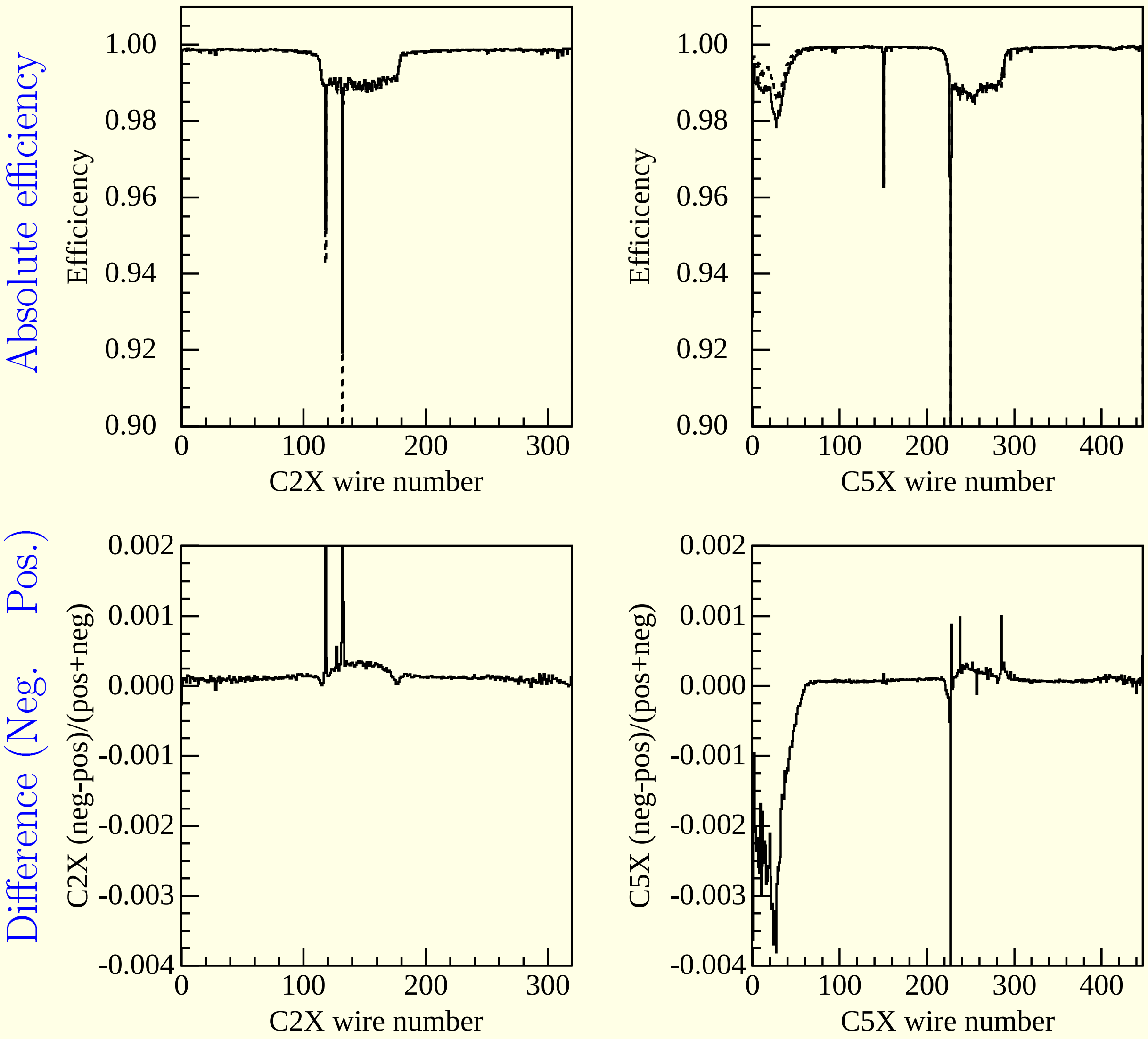
- When flipping polarity, field magnitude kept within $\sim 2\times10^{-4}$.
- This corresponds to a ~0.3 mm deflection difference at 10 m for the lowest momentum (~10 GeV/c pions).





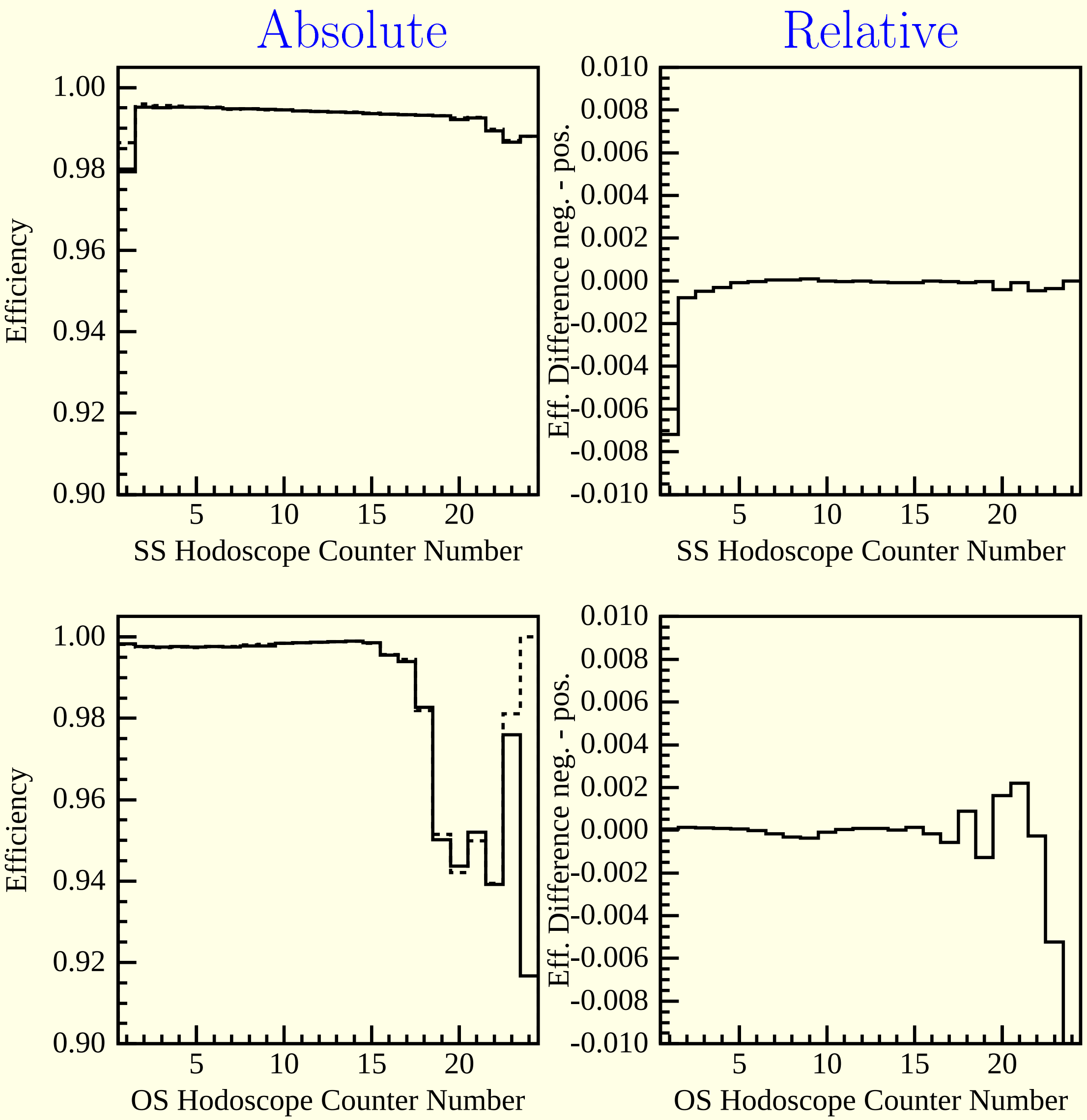
Little Difference in PWC Efficiencies from + and − Running

- − data: solid line
- + data: dashed line
- 32 total planes ⇒ good redundancy



Little Difference in Hodo Efficiencies from + and − Running

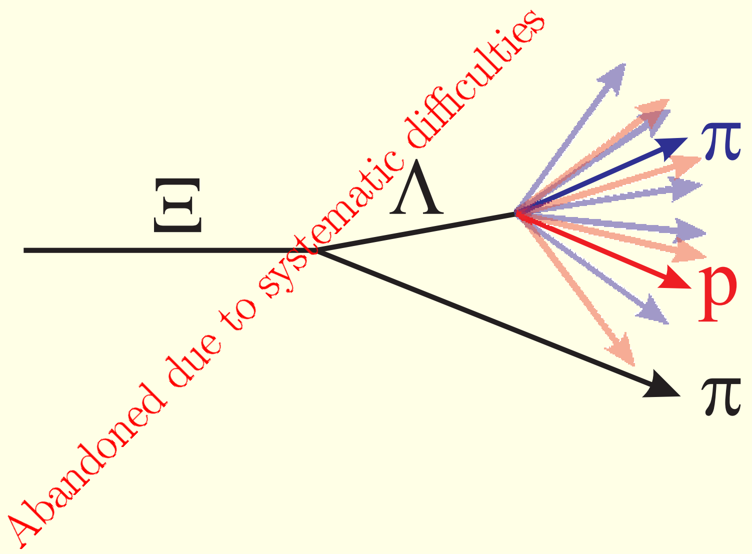
- − data: solid line.
- + data: dashed line.
  - Differences where it matters <0.1%.
  - Redundant counters make real inefficiencies vanishingly small.
  - Two rows on OS side.
  - Two particles on SS side.



Two Different *CP* Analyses Attempted

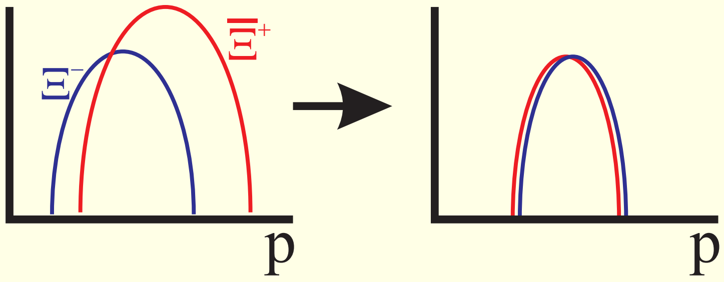
Hybrid Monte Carlo Method:

- Compare corrected $\cos\theta$ distributions.
- Take a real $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$ 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.



Weighting Method:

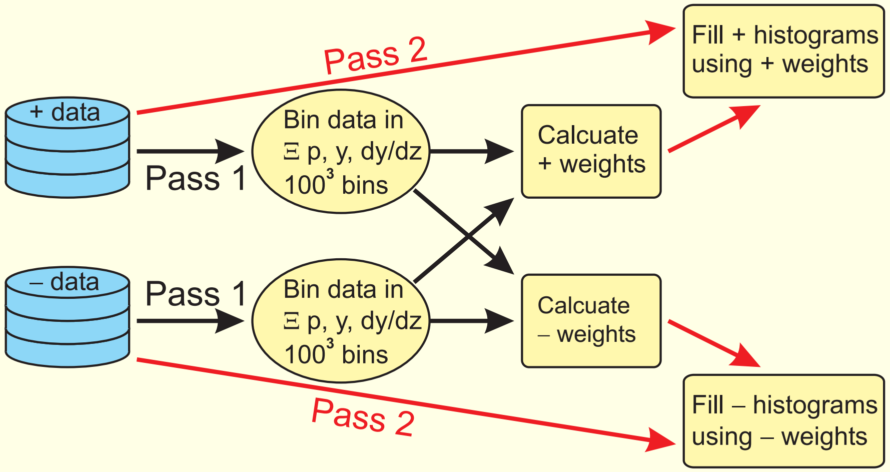
- Compare uncorrected $\cos\theta$ distributions.
- Force the Ξ^- and $\overline{\Xi}^+$ events to have similar momentum and spatial distributions by appropriate weighting.
- Advantage: No Monte Carlo needed to measure apparatus acceptance, smaller statistical error.
- Disadvantage: inflexible, event-size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

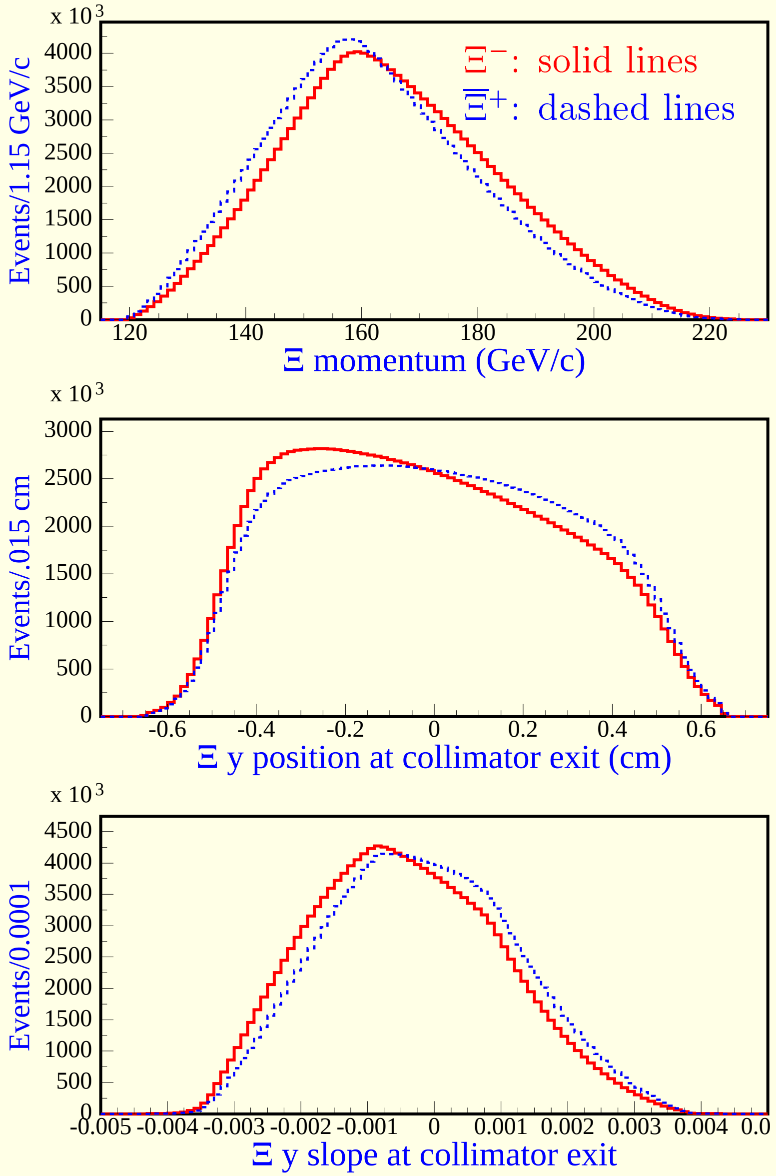


Large data set, $\sim$1 billion events, in both cases makes the analysis difficult.

Weighting Technique

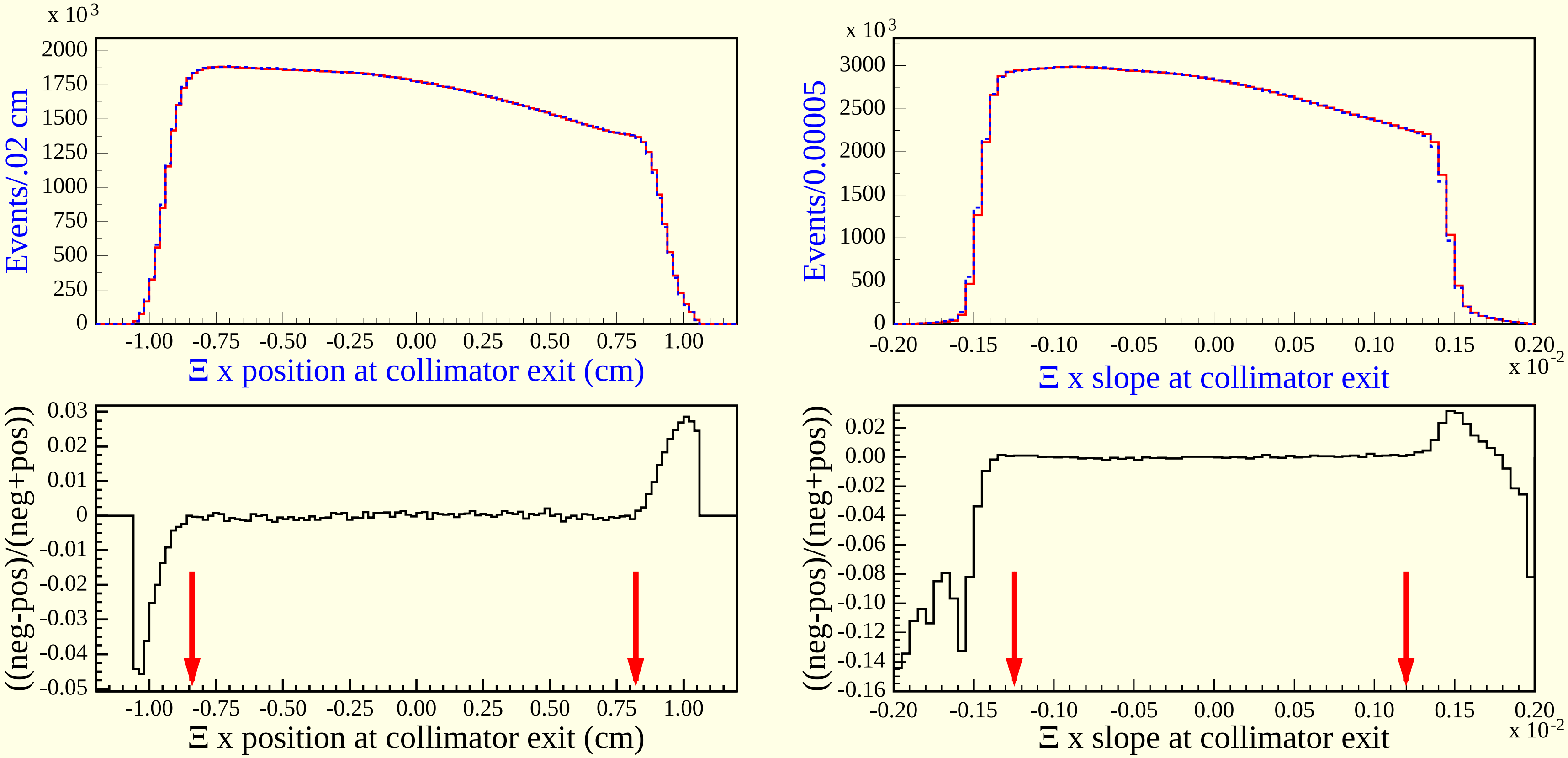
- Problem: Geometical acceptance identical for Ξ^- and $\overline{\Xi}^+$ decay products only if parent Ξ^- and $\overline{\Xi}^+$ have same momentum and inhabit the same phase space exiting the collimator.
- They are not the same due to different production dynamics.
- Solution: Weight the Ξ^- and $\overline{\Xi}^+$ events to force the two distributions to be identical.
- Momentum-dependent parameters of Ξ at collimator exit matched.
- $100 \times 100 \times 100 = 1 \times 10^6$ bins used.



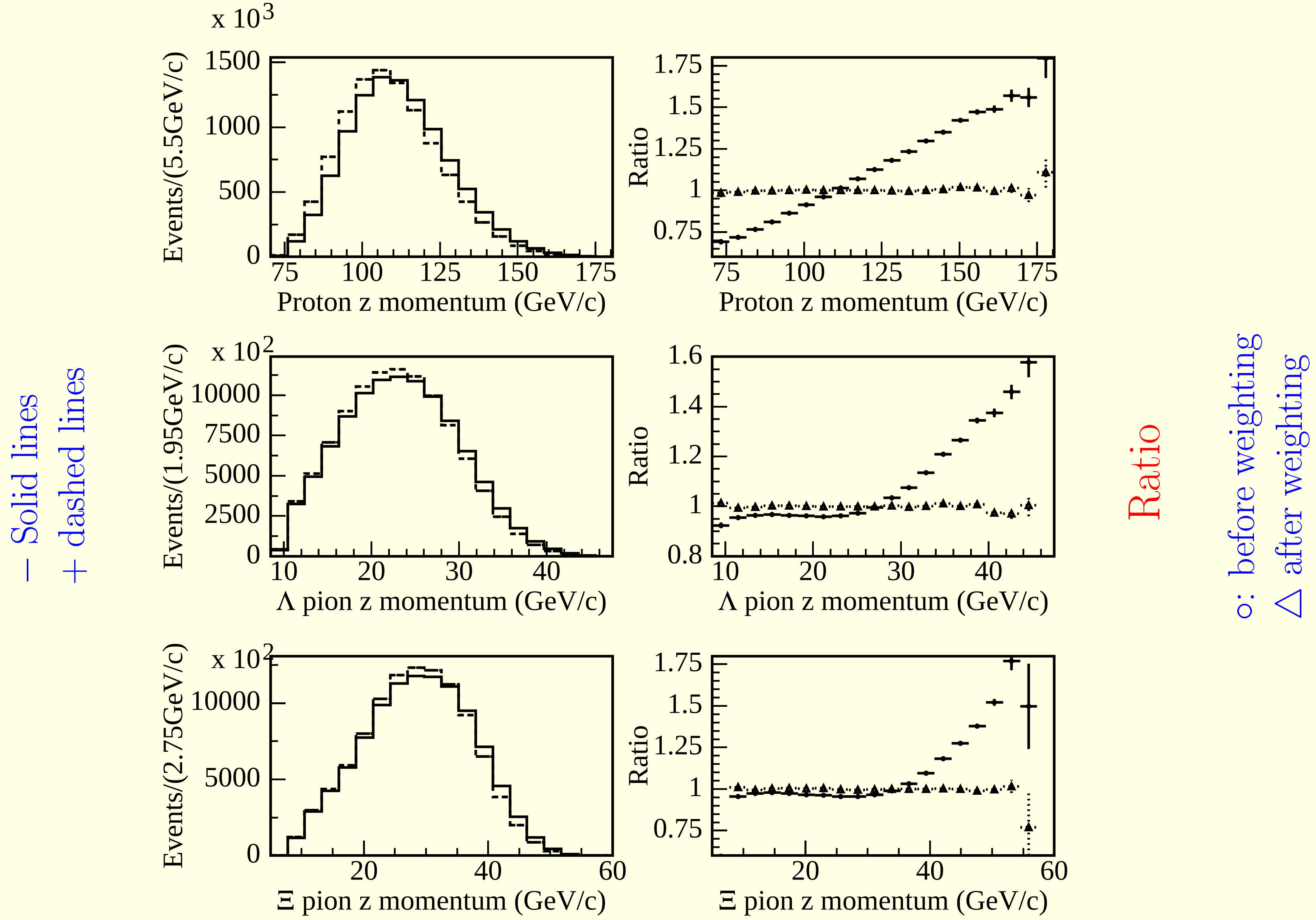


Ξ^- and $\overline{\Xi}^+$ x Slopes and Positions not Weighted

- Not momentum dependent $\Rightarrow$ distributions almost identical
- Cut out regions where they are not.
- Ξ^-: Solid lines
- $\overline{\Xi}^+$: Dashed lines



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



Extracting the CP Asymmetry

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

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

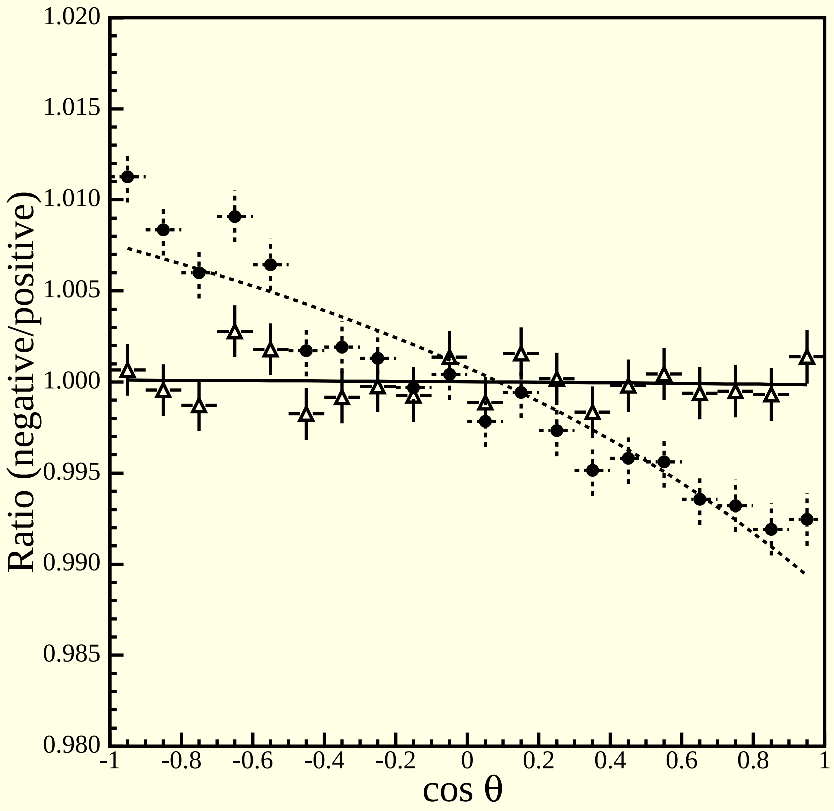
- Assume the acceptances A_- and A_+ have the same $\cos\theta$ dependence.
- Take the ratio of proton and antiproton $\cos\theta$ distributions: a nonzero slope is evidence of CP violation.
- Fit ratios to:

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

to extract asymmetry δ:

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

$$A_{\Xi\Lambda} = \frac{\delta}{\alpha_\Xi\alpha_\Lambda + \overline{\alpha}_\Xi\overline{\alpha}_\Lambda} = \frac{\delta}{2\alpha_\Xi\alpha_\Lambda} = 1.71\,\delta$$



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

Monte Carlo Tests

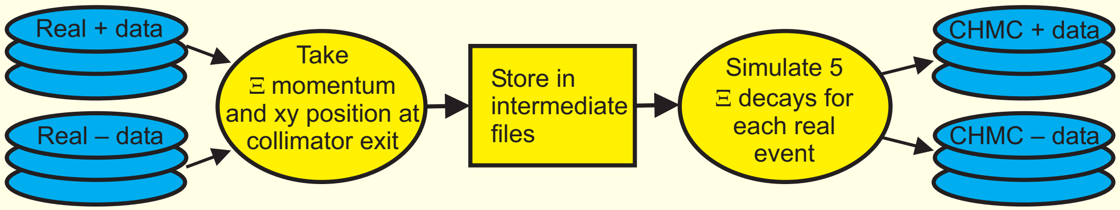
Final result has no Monte Carlo dependence!

Important! Monte Carlo only used to:

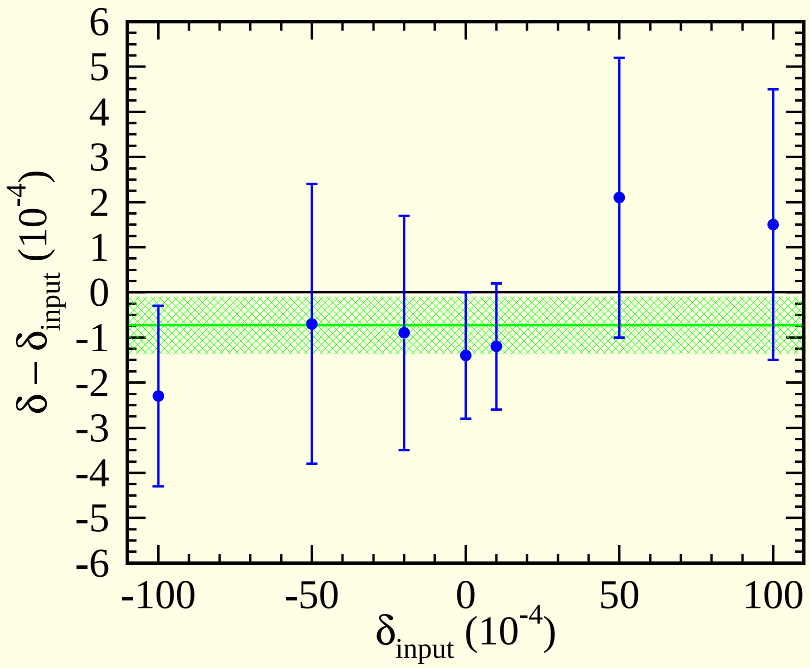
- Verify code and algorithm.
- Study a few systematics.

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

Solution:



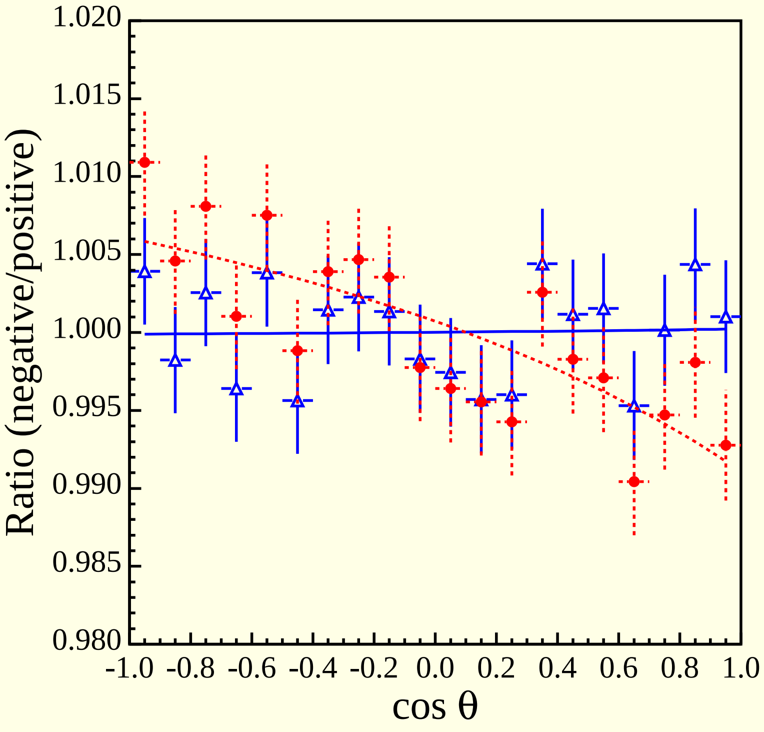
We get the input asymmetry back $\Longrightarrow$



$$
\begin{aligned}
\delta &= (-0.73\pm0.64)\times10^{-4} \\
A_{\Xi\Lambda} &= (1.24\pm1.09)\times10^{-4}
\end{aligned}
$$

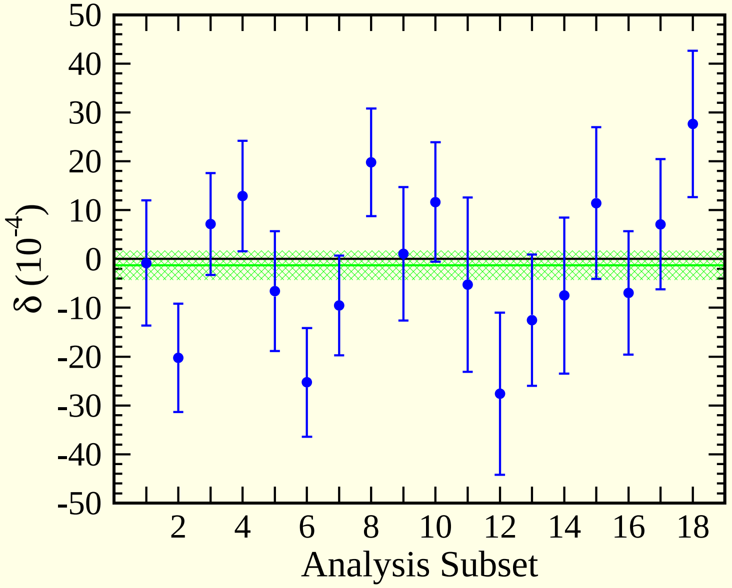
The CP Asymmetry $A_{\Xi\Lambda}$ from Weighting Method

- Data broken up into 18 sets, each with positive and negative events.
- No acceptance corrections.
- No efficiency corrections.
- No background subtraction.



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

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

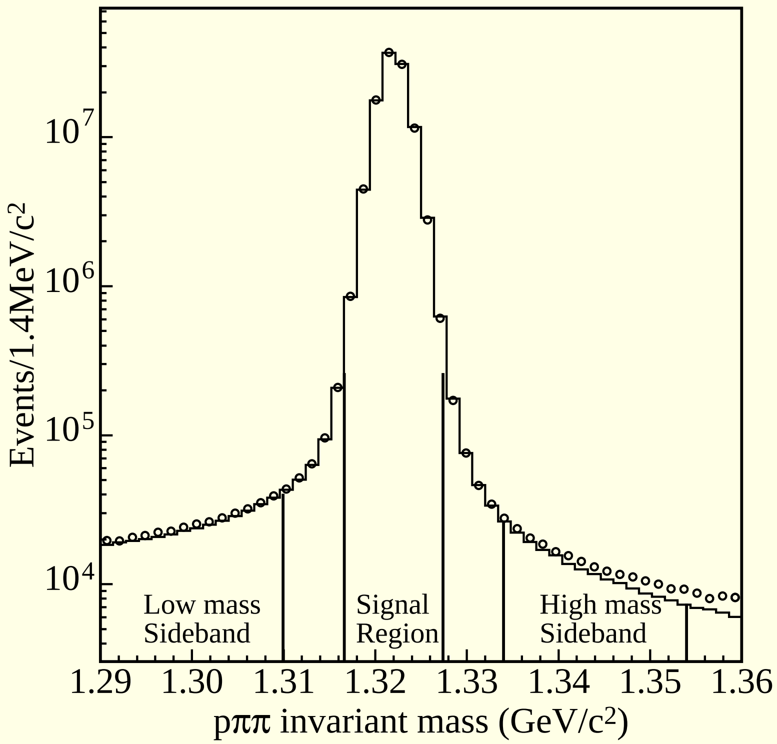


Weighted average of all 18 data sets:

$$\begin{aligned} \delta &= (-1.3\pm3.0)\times10^{-4} \\ A_{\Xi\Lambda} &= (\ 2.2\pm5.1)\times10^{-4} \\ \chi^2 &= 24 \end{aligned}$$

Background Subtraction Has Little Effect

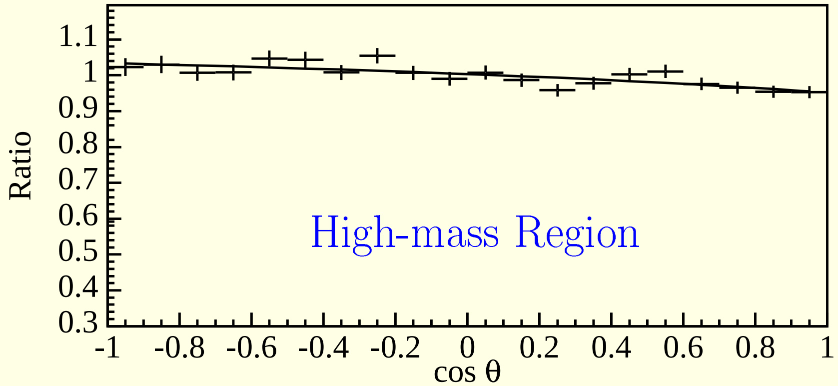
- Triple Gaussian fit with fourth-order polynomial for background.
- Background fraction:
  Ξ^-: 0.43% (lines)
  $\overline{\Xi}^+$: 0.41% (circles)

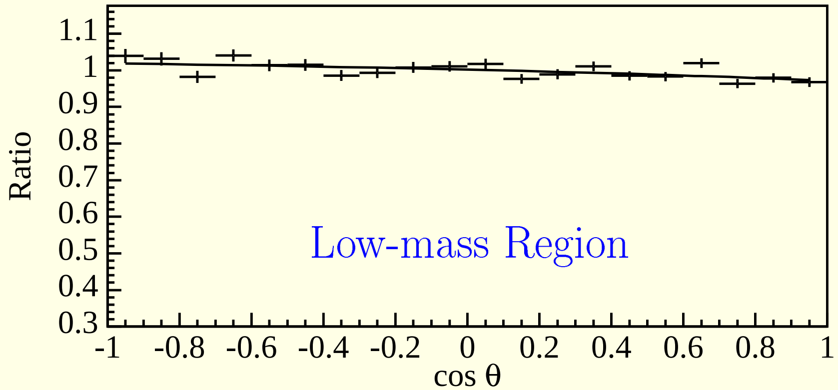


Low mass: $\delta = (-2.2 \pm 0.5) \times 10^{-2}$
High mass: $\delta = (-3.8 \pm 0.7) \times 10^{-2}$

- Weighted background asymmetry:

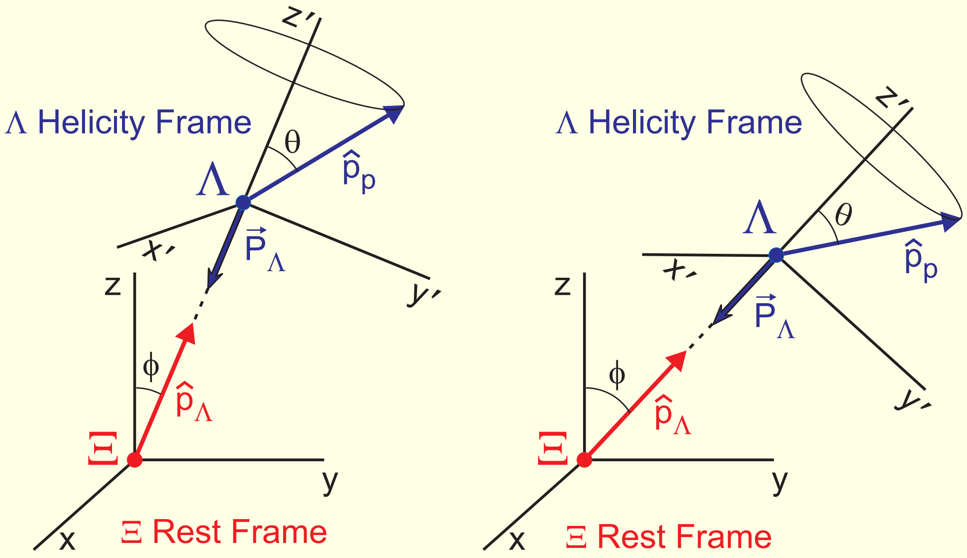
$$A_{\Xi\Lambda}(bs) = (0.0 \pm 5.1) \times 10^{-4}$$



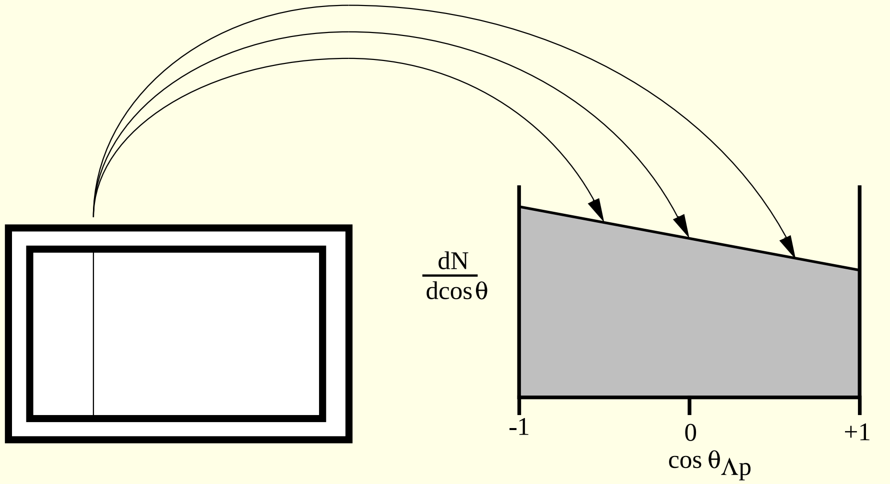


Helicity Frame Analysis Naturally Minimizes Biases

- 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	2.4
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/antiparticle 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		4.4

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

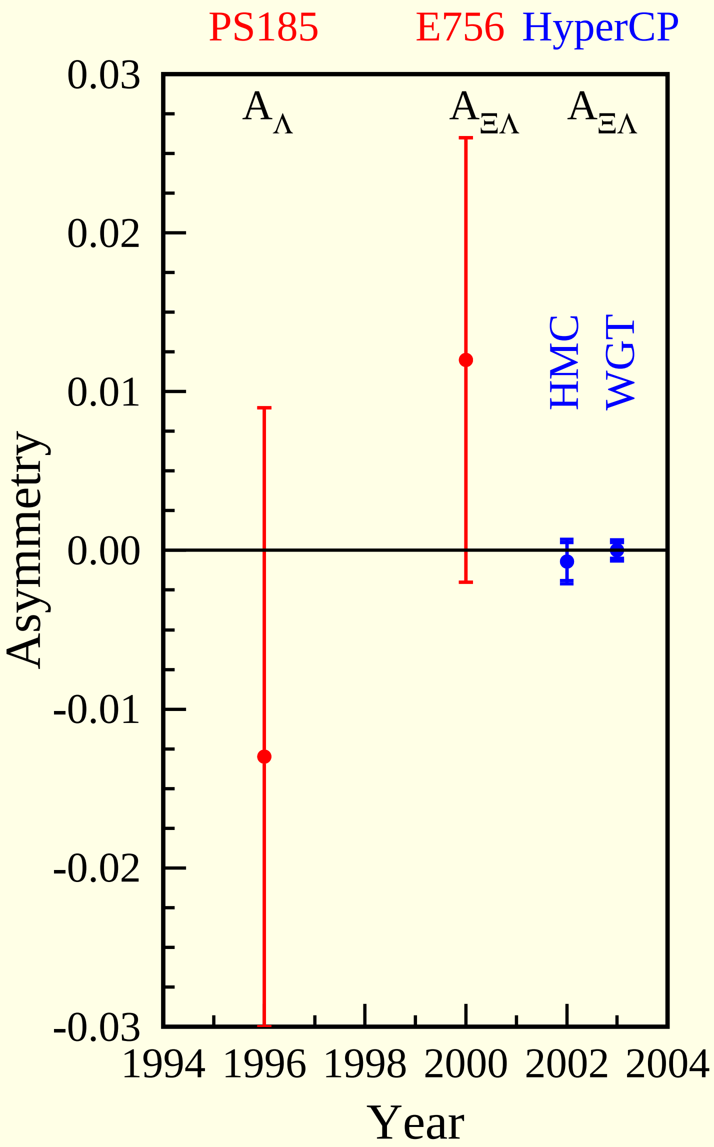
$$A_{\Xi\Lambda} = [0.0 \pm 5.1(\text{stat}) \pm 4.4(\text{syst})] \times 10^{-4}$$

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.



Conclusions and Outlook

- Hyperon *CP* violation measurements probing limits not constrained by Kaon, B, or EDM measurements.

  "...we can then conclude that the available preliminary measurement by HyperCP has already begun to probe the parity-even contributions better than ϵ does."

  Tandean (2004)

- *HyperCP*, in particular, the first dedicated hyperon *CP* violation experiment, has pushed into the region where SUSY models allow an effect.

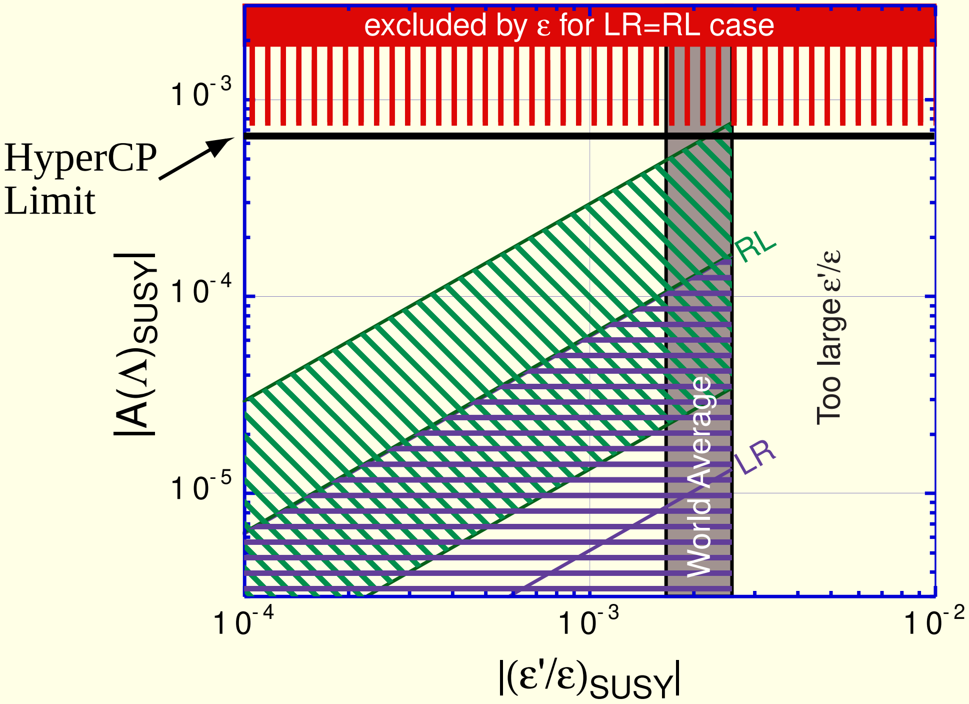
- *HyperCP* finds no evidence of *CP* violation in $\Xi^{\pm}$ and Λ decays:

  $$\delta A_{\Xi\Lambda} = (0.0 \pm 5.1 \pm 4.4)\times 10^{-4}$$

- Shortly we should push our statistical limit to:

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

  two orders of magnitude better than the present limit.

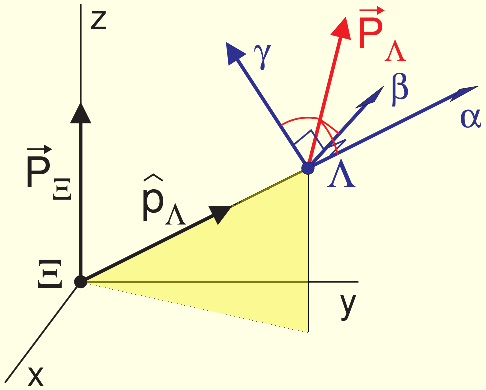


Backup Slides

Measurement of the Λ-π Phase Shift

- This is done by analyzing the Λ decay distribution from 144 million **polarized** Ξ^-'s.
- Λ has three components of polarization:

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

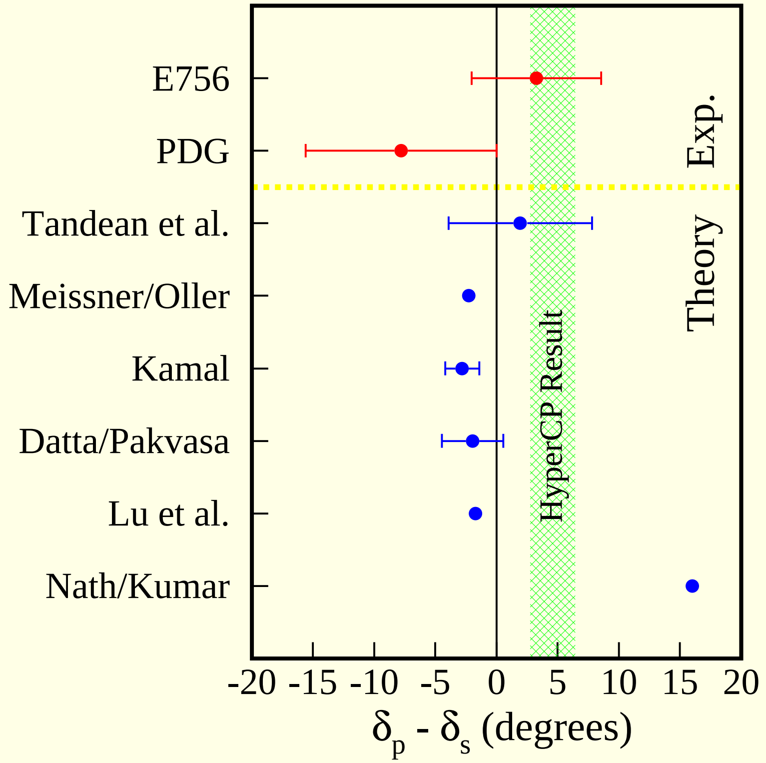


$$\beta_\Xi = -0.037 \pm 0.011(\text{stat}) \pm 0.010(\text{syst})$$
$$\gamma_\Xi = 0.888 \pm 0.0004(\text{stat}) \pm 0.006(\text{syst})$$

- Using the known value of α_Ξ:

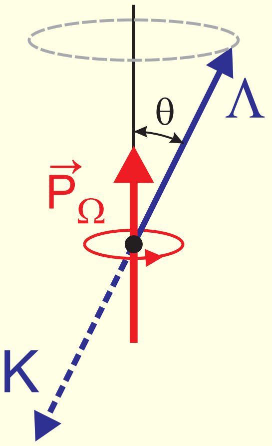
$$\boxed{\delta_P - \delta_S = \tan^{-1}\left(\frac{\beta_\Xi}{\alpha_\Xi}\right) = (4.6 \pm 1.4 \pm 1.2)^\circ}$$

- First non-zero measurement of phaseshift.
- This is about the same magnitude as the p-π phase shift:
  - $\Rightarrow$ CP equally likely in Ξ and Λ decays.
  - $\Rightarrow$ CP predictions underestimated,
  - $\Rightarrow$ χPT calculations off.



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

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



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

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

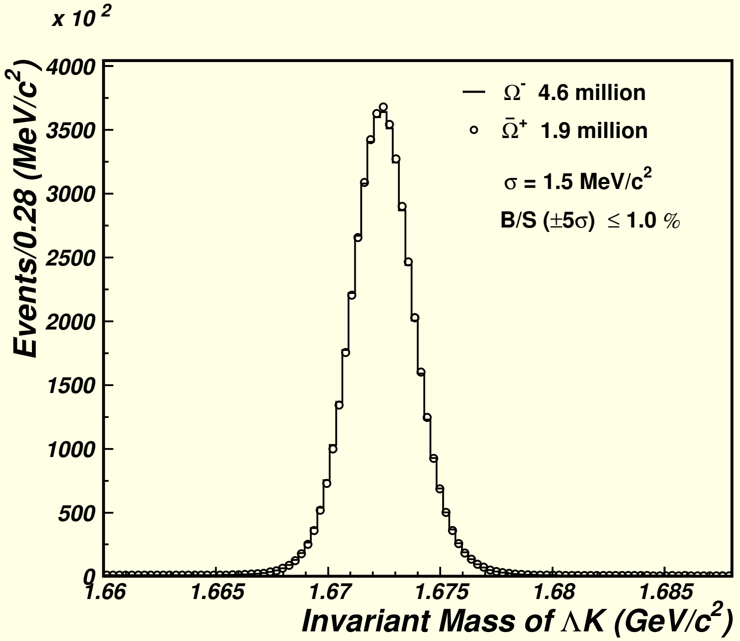
- Here:

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

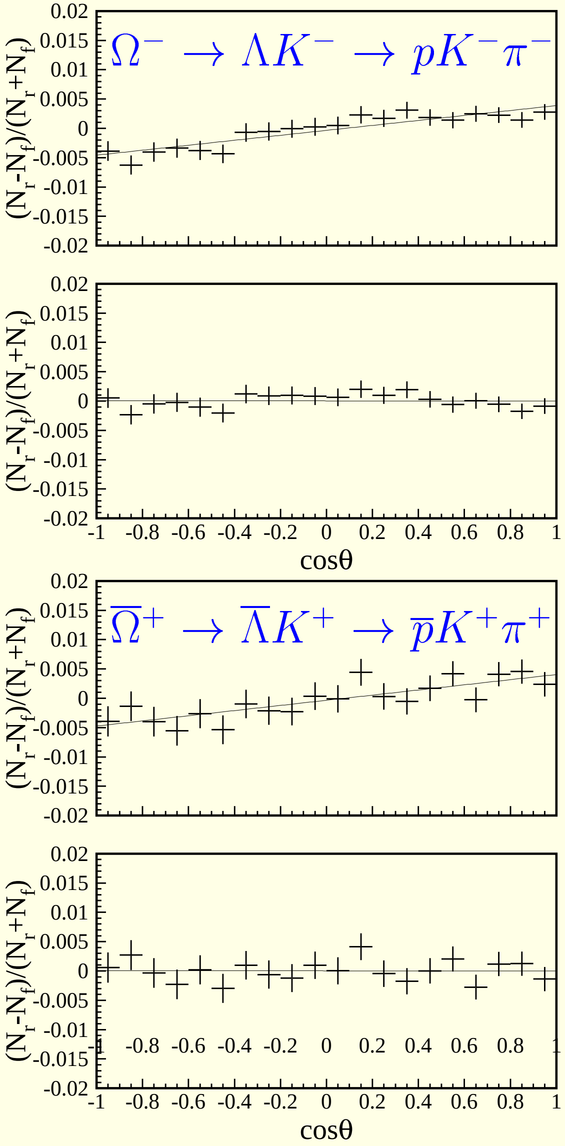
- A non-zero α_Ω indicates parity violation.
- All other hyperons have non-zero α parameters; only the Ω^- has resisted efforts to find an asymmetrical decay distribution.
- *HyperCP* is measuring α_Ω using unpolarized Ω^-'s through the polarization given to the daughter Λ, which is α_Ω:

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

- Large data sample, little background.

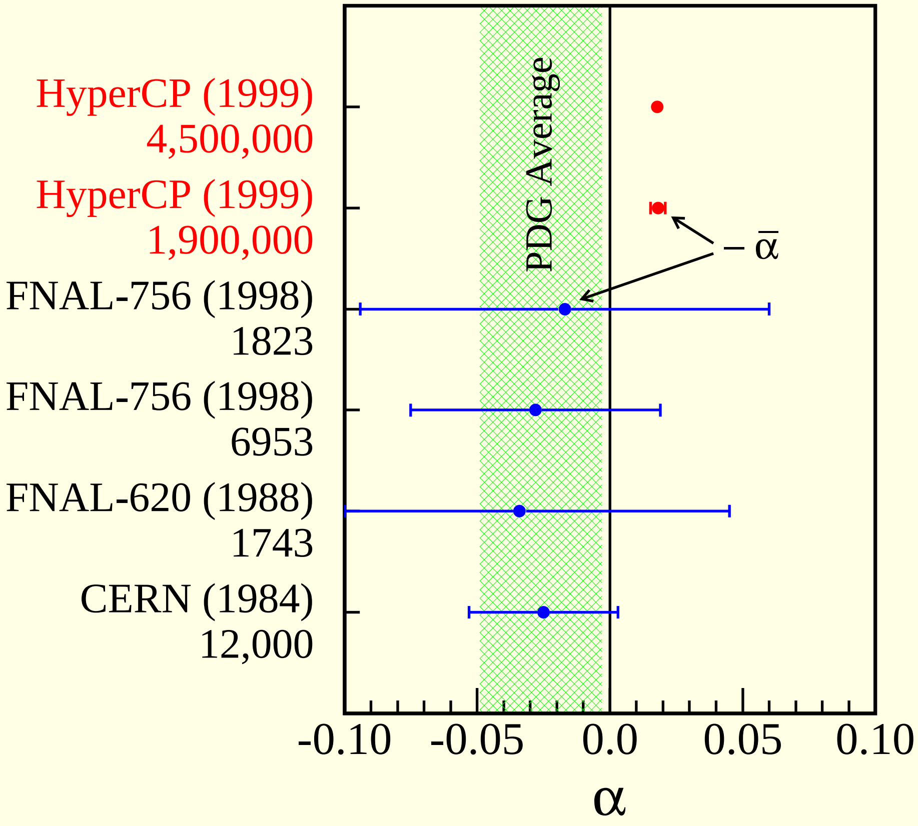


Preliminary Measurement of α_Ω and $\overline{\alpha}_\Omega$ in $\Omega^- \to \Lambda K^-$ Decays



1999 : α_Ω= [1.78±0.19(stat)±0.10(syst)]×10^{-2}

1999 : $\overline{\alpha}_\Omega$= [−1.81±0.28(stat)]×10^{-2}



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