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.
- 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

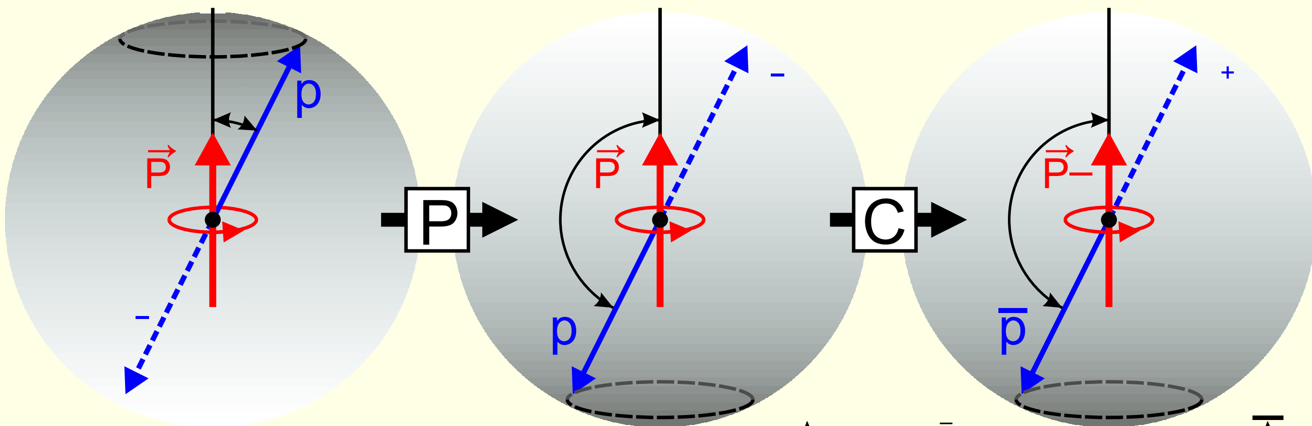
- Hyperons are sensitive to sources of CP violation that are not probed in other systems.
- These sources are experimentally accessible.
- The cost is small:
  - No new accelerators needed.
  - Apparatus is modest in scope and cost.

How to Search for *CP* Violation in Λ Decays

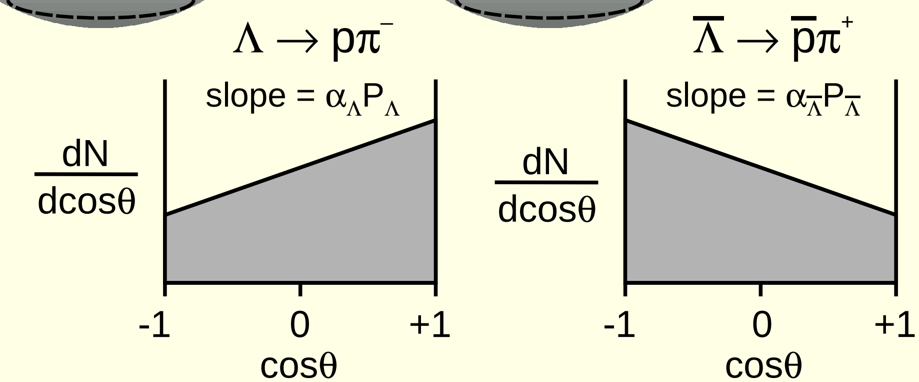
Due to parity violation the proton likes to go in the direction of the Λ spin:

$$\Lambda \longrightarrow p\pi^-: \qquad \frac{d\mathrm{N(p)}}{d\cos\theta} = \frac{\mathrm{N}_0}{2}(1+\alpha_\Lambda P_\Lambda \cos\theta) \qquad \alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2} = 0.642$$

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



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



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:

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

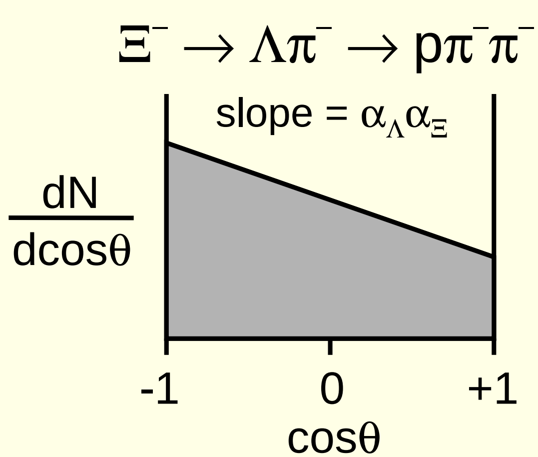
If the Ξ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the Λ is found in a helicity state, with a large polarization ($\alpha_\Xi = -0.458$):

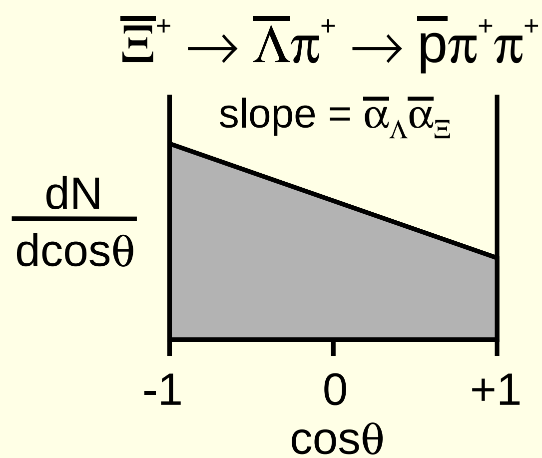
$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad\qquad \vec{P}_{\overline{\Lambda}} = \overline{\alpha}_\Xi \hat{p}_{\overline{\Lambda}}$$

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

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

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





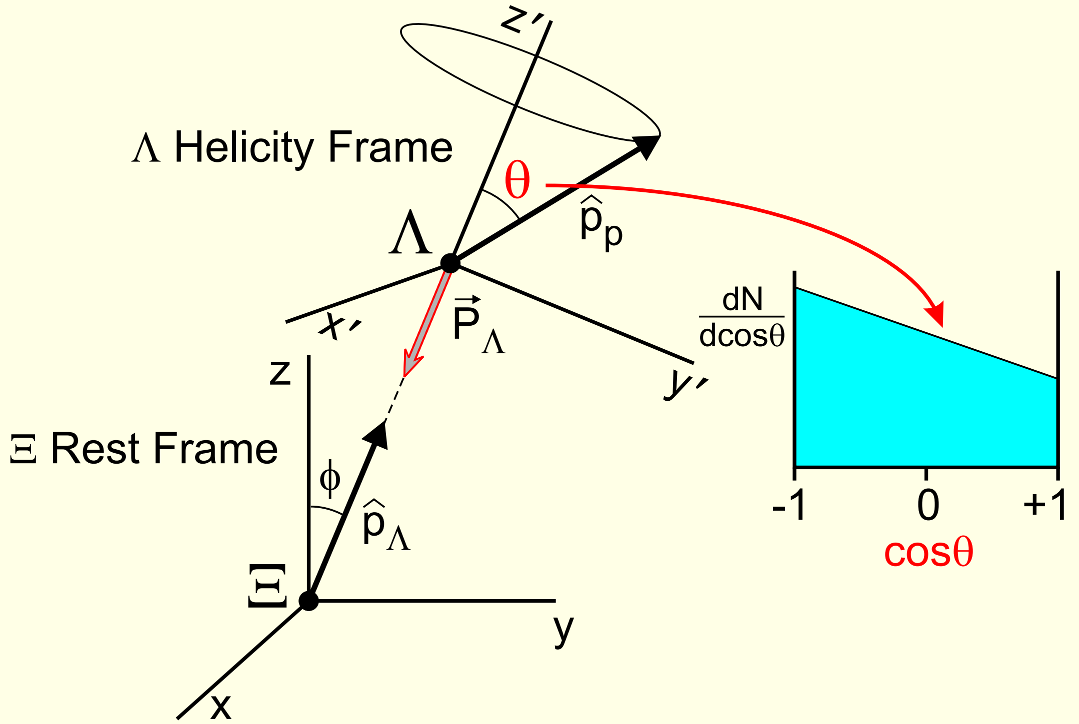
HyperCP technique is sensitive to both Ξ and Λ *CP* violation

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

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

What HyperCP experimentally measures ⇒

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.

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

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

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

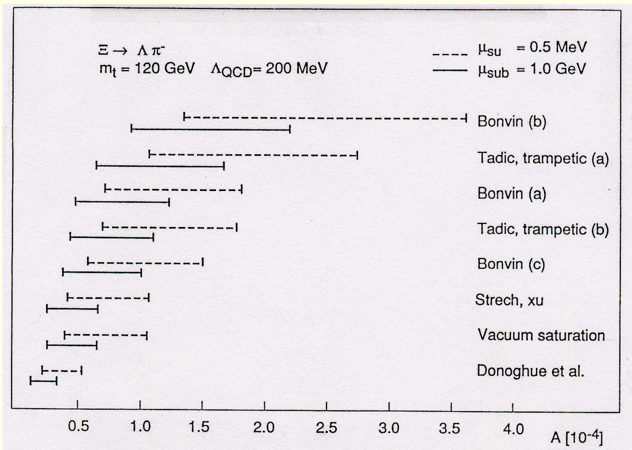
  - The $\Lambda\pi$ phase shifts can't be directly measured, theoretical predictions disagree:

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

HyperCP has measured the $\Lambda\pi$ phase shift: $(4.6 \pm 2.3)^\circ$

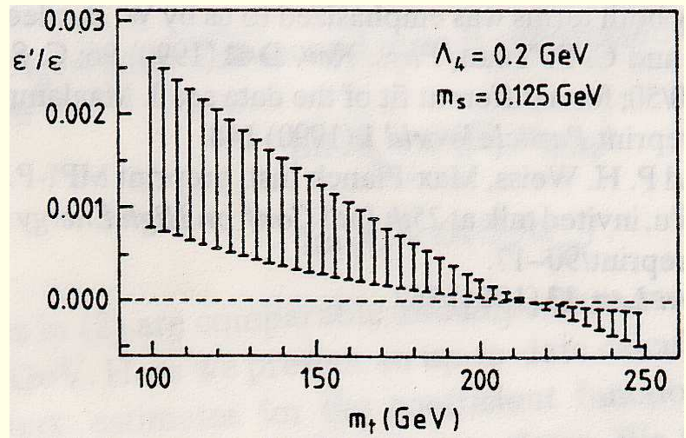
Bad News: Standard Model Theory Predictions Small

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



Valencia (1991)

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



Paschos (1991)

- Standard Model predictions have slowly fallen to:

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

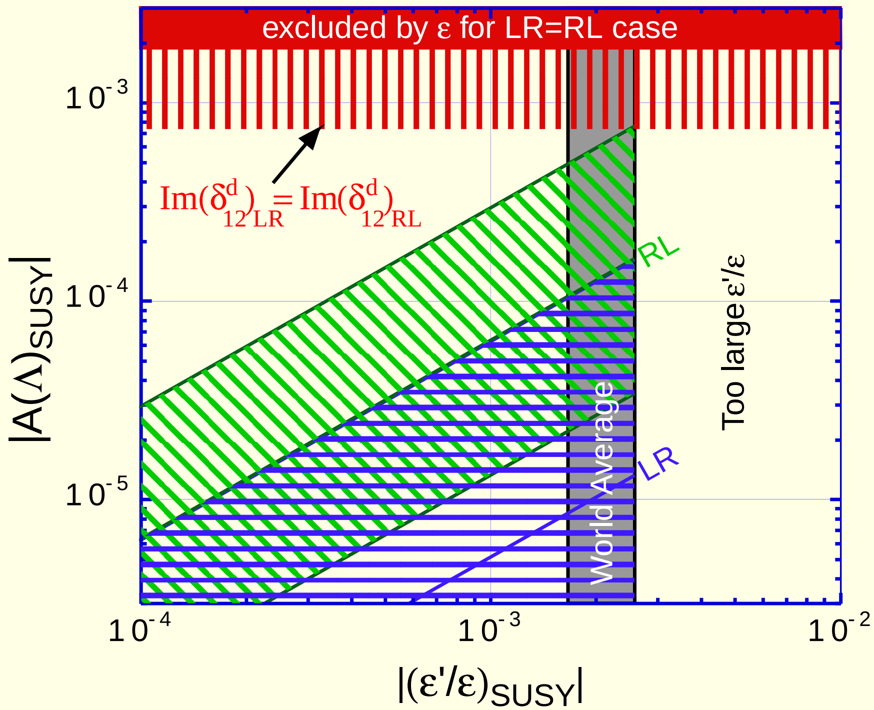
(Tandean & Valencia, 2003)

- 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 $\sim 100\times 10^{-4}$.
- 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?

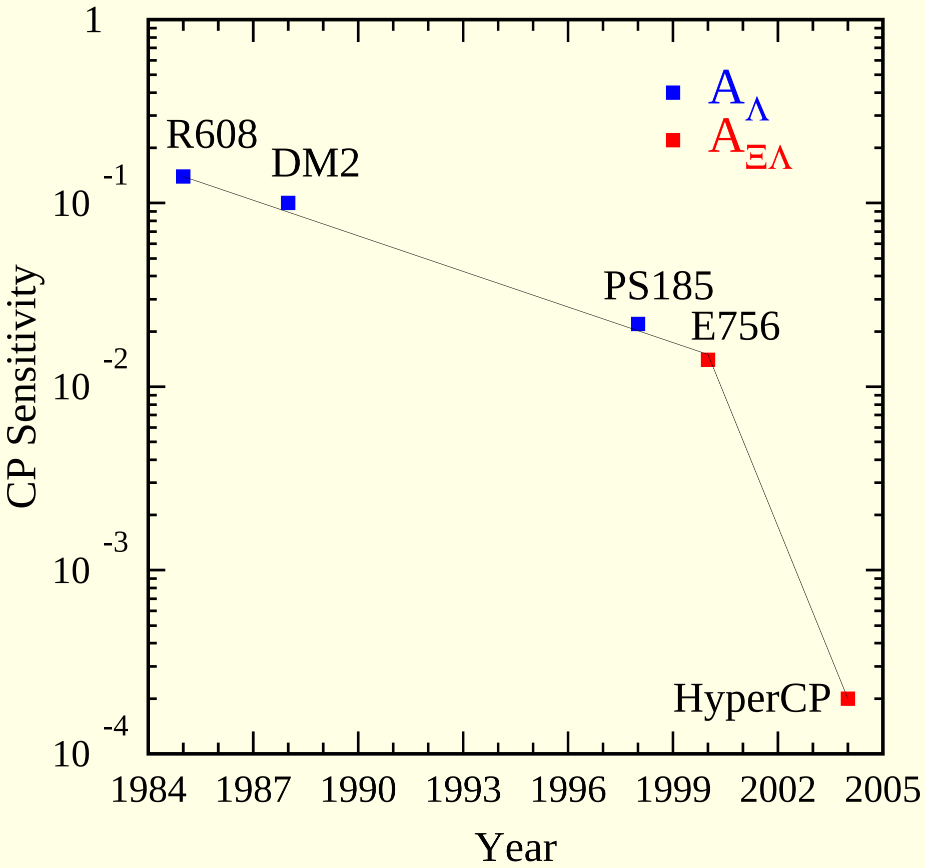
- To date there are only upper limits on the asymmetries.
- A_Λ has been measured to 2×10^{-2}:

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:

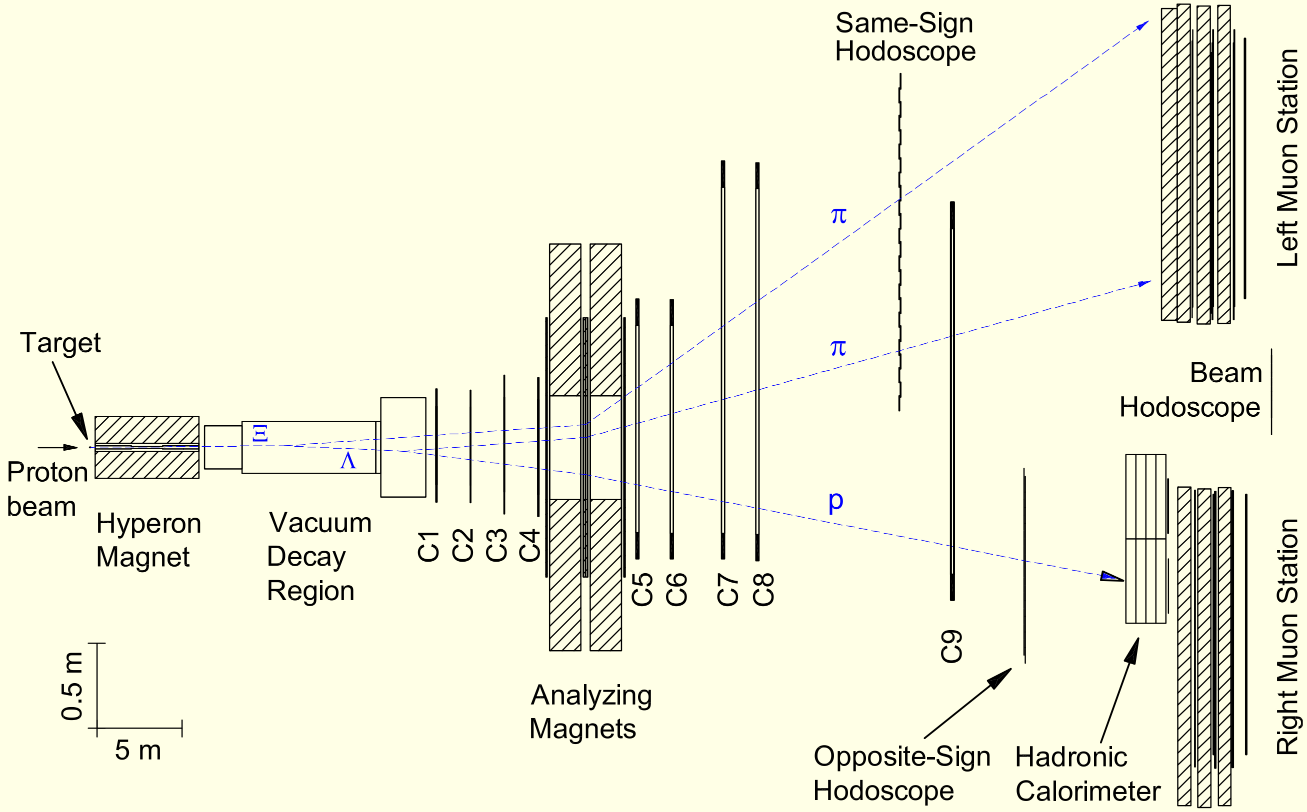
Exp	Mode	Method
E756	$A_{\Xi\Lambda}$	$\mathrm{pN} \to \Xi^\pm X \to \Lambda\pi^\pm$

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

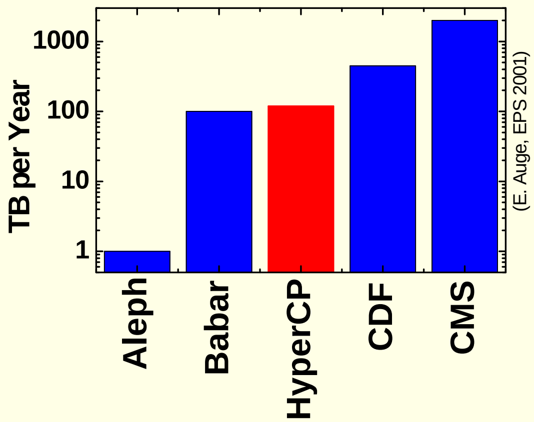
The *HyperCP* Spectrometer

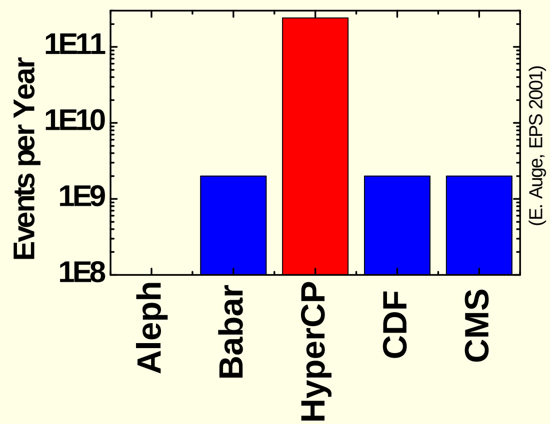


- Alternate + and − running.
- 800 GeV/c incident proton beam.
- 10–15 MHz, 167 GeV/c charged beam.
- High-rate, narrow-pitch wire chambers.
- Muon system for rare/forbidden hyperon and kaon decays.
- Very high-rate DAQ:
  → 50-80 KHz evts/spill-s to tape.
  → 27 MB/s on 27 Exabyte 8705 tape drives.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

HyperCP Yields

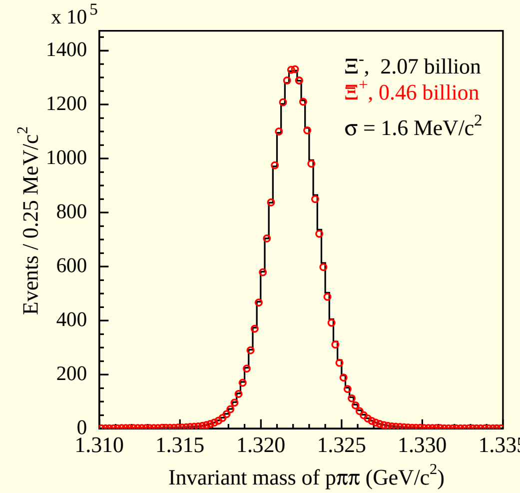
- In 12 months of data taking *HyperCP* recorded one the largest data samples ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.



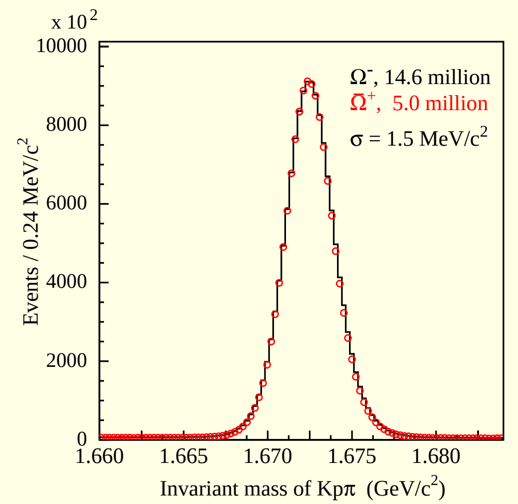


Entire WWW on 9/11/01 was 5 TB!

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



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



Reconstructed Events

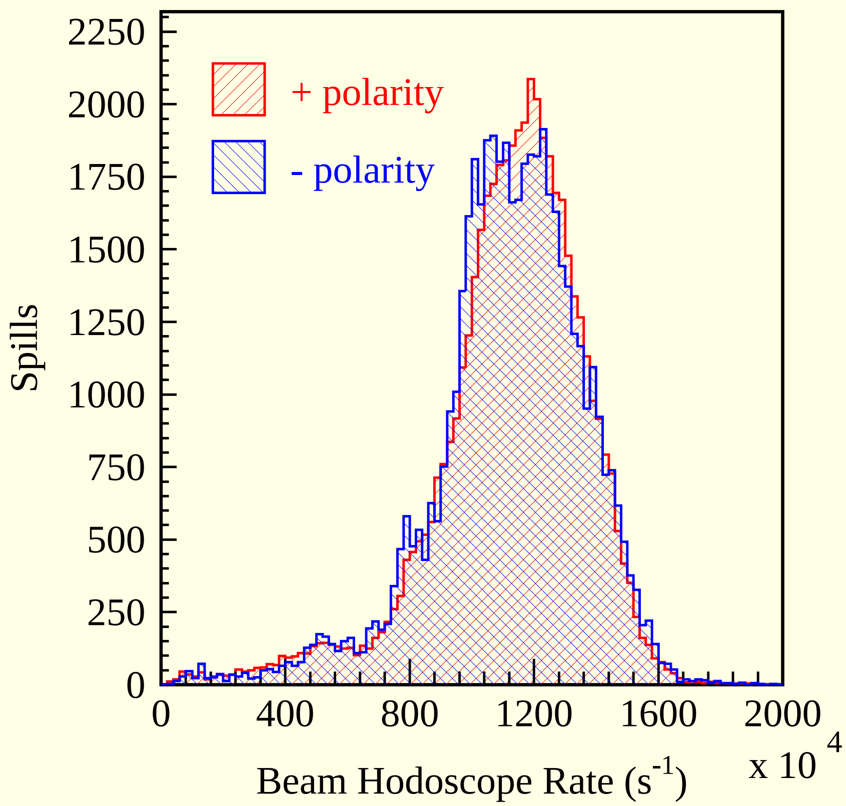
	Channeled beam polarity		
Type	+	−	Total
$\Xi \to \Lambda\pi$	458×10^6	$2\,032 \times 10^6$	$2\,490 \times 10^6$
$K \to \pi\pi\pi$	391×10^6	164×10^6	555×10^6
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6

Care Taken to Minimize Differences in + and − Running

- Targets changed to equalize secondary-beam rates.

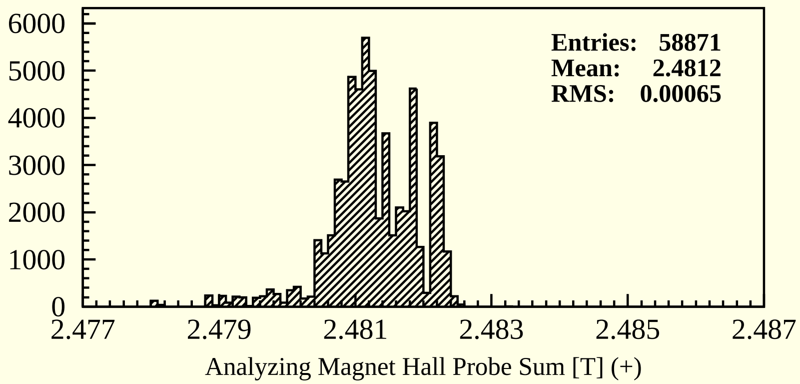
  + polarity: 2.0 cm Cu

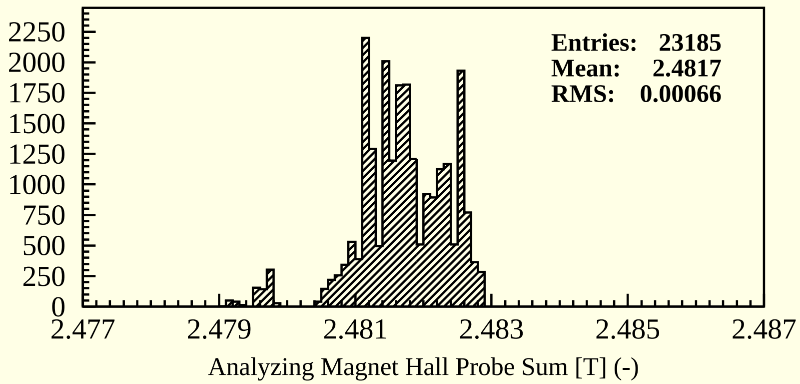
  − polarity: 6.0 cm Cu



- About a 1% difference in rates.

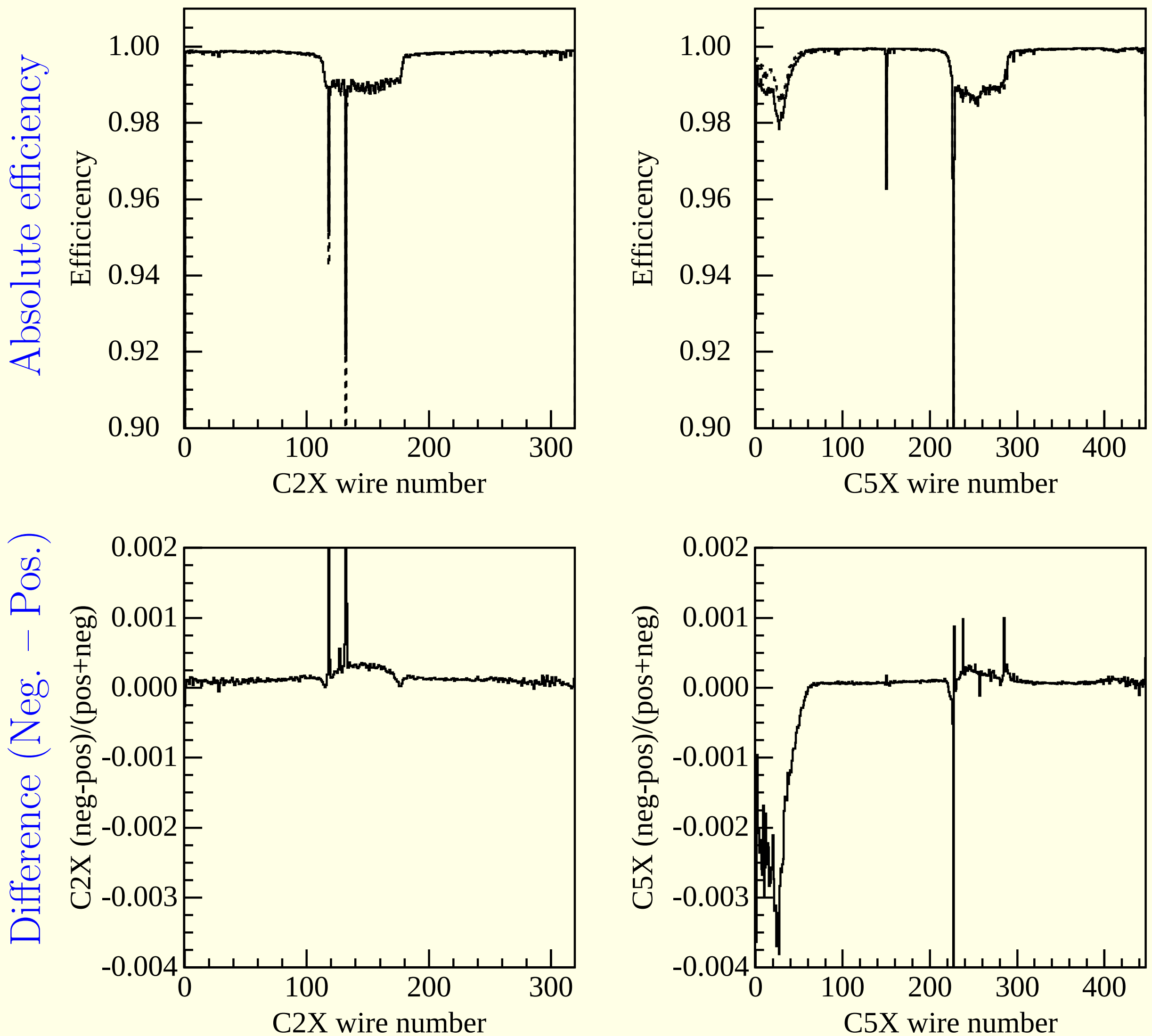
- When flipping polarity, field magnitude kept within $\sim 2\times10^{-4}$.
- This corresponds to a $\sim$0.3 mm deflection difference at 10 m for the lowest momentum ($\sim$10 GeV/c pions).





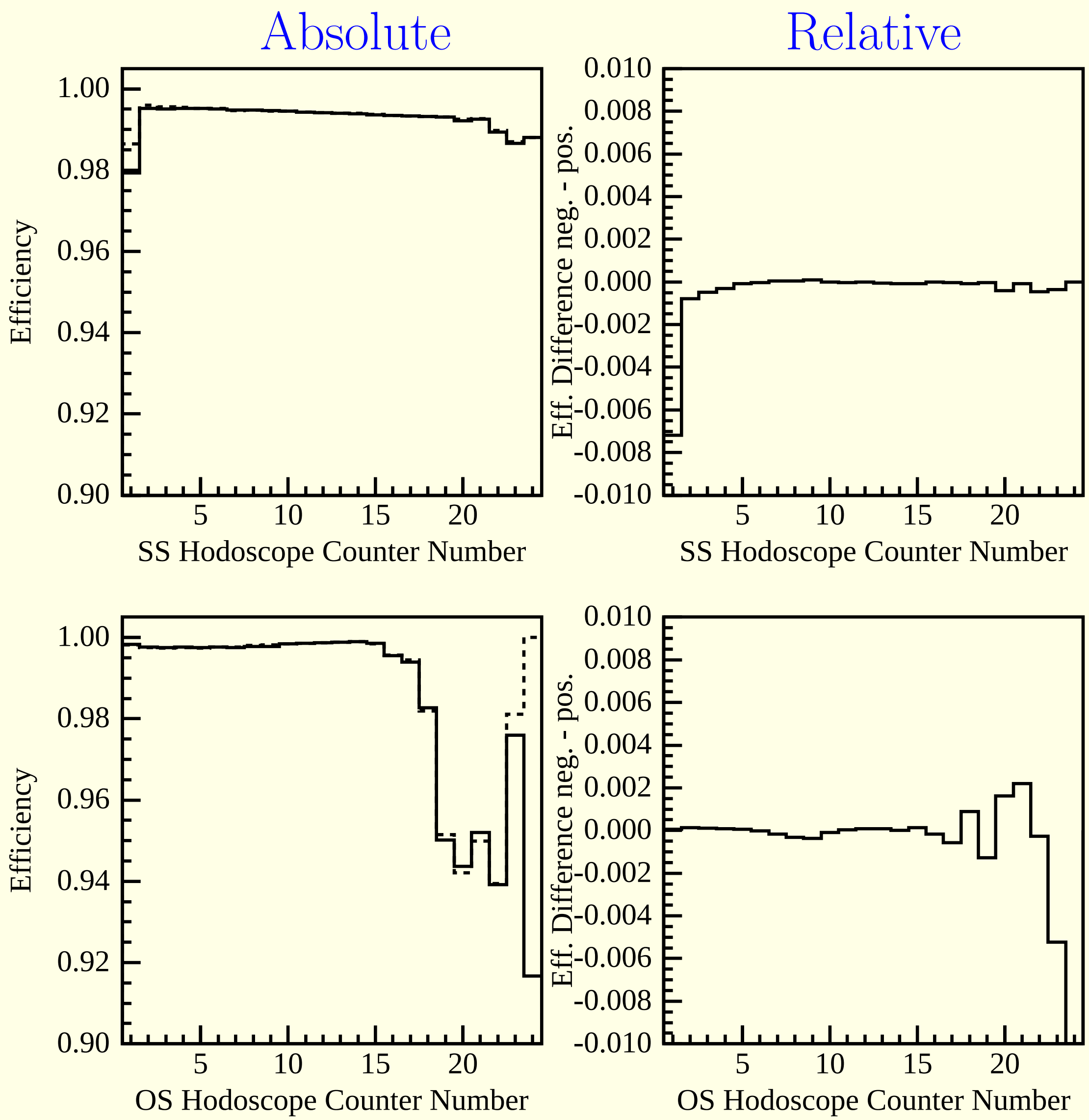
Little Difference in PWC Efficiencies from + and − Running

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



Little Difference in Hodo Efficiencies from + and − Running

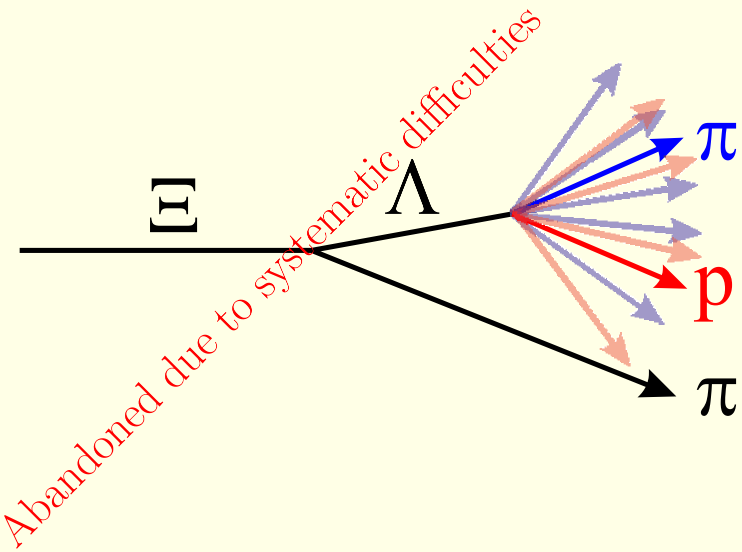
- − data: solid line.
- + data: dashed line.
  - Differences where it matters <0.1%.
  - Redundant counters make real inefficiencies vanishingly small.
  - Two rows on OS side.
  - Two particles on SS side.



Two Different *CP* Analyses Attempted

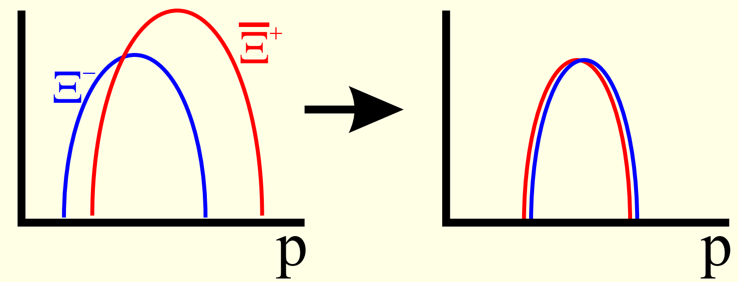
Hybrid Monte Carlo Method:

- 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: ~20 billion events needed.



Weighting Method:

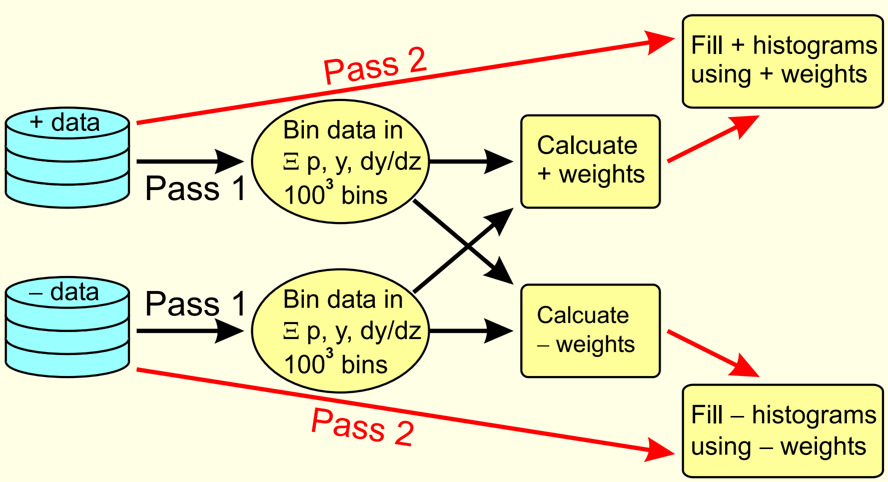
- Compare uncorrected $\cos\theta$ distributions.
- Force the Ξ^- and $\overline{\Xi}^+$ events to have similar momentum and spatial distributions by appropriate weighting.
- Advantage: No Monte Carlo needed to measure apparatus acceptance, smaller statistical error.
- Disadvantage: inflexible, event-size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

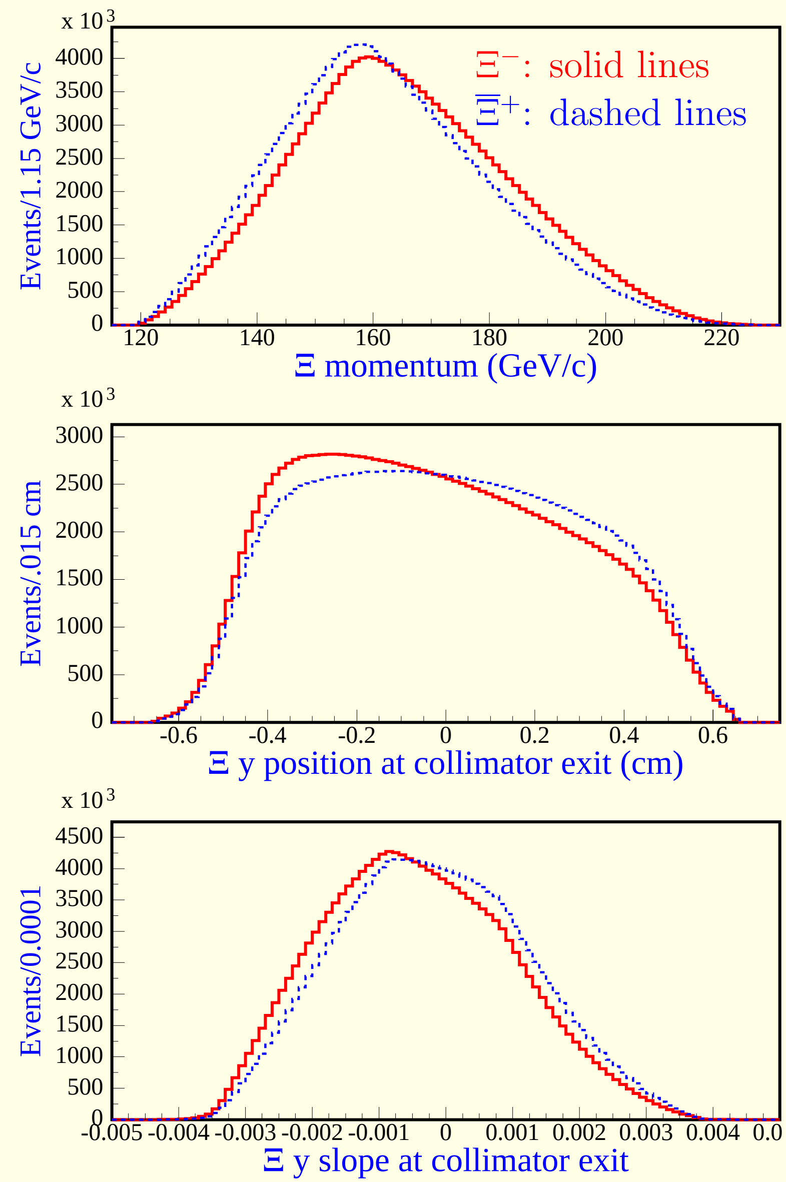


Large data set, ~1 billion events, in both cases makes the analysis difficult.

Weighting Technique

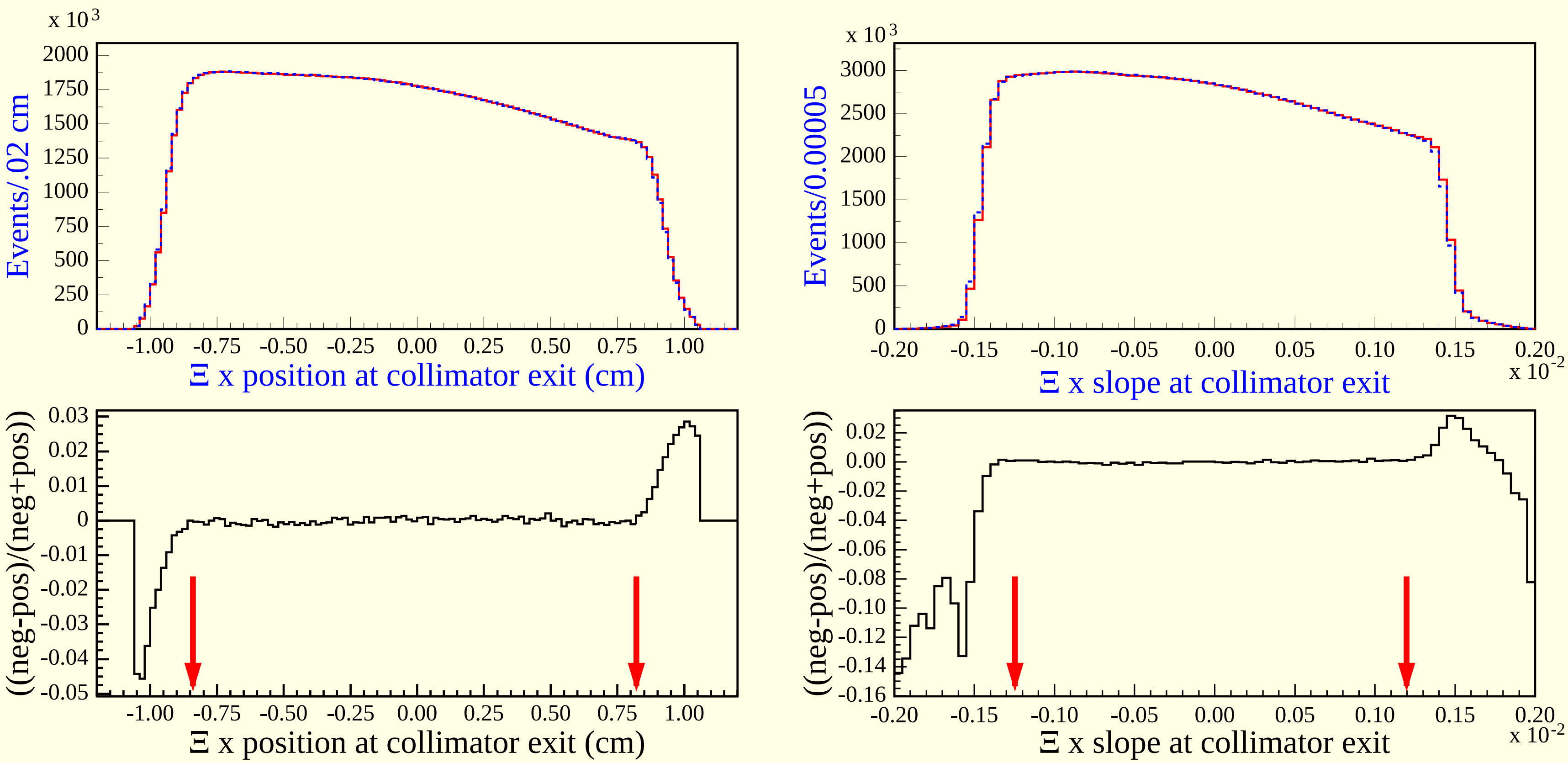
- Problem: Geometical acceptance identical for Ξ^- and $\overline{\Xi}^+$ decay products only if parent Ξ^- and $\overline{\Xi}^+$ have same momentum and inhabit the same phase space exiting the collimator.
- They are not the same due to different production dynamics.
- Solution: Weight the Ξ^- and $\overline{\Xi}^+$ 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.





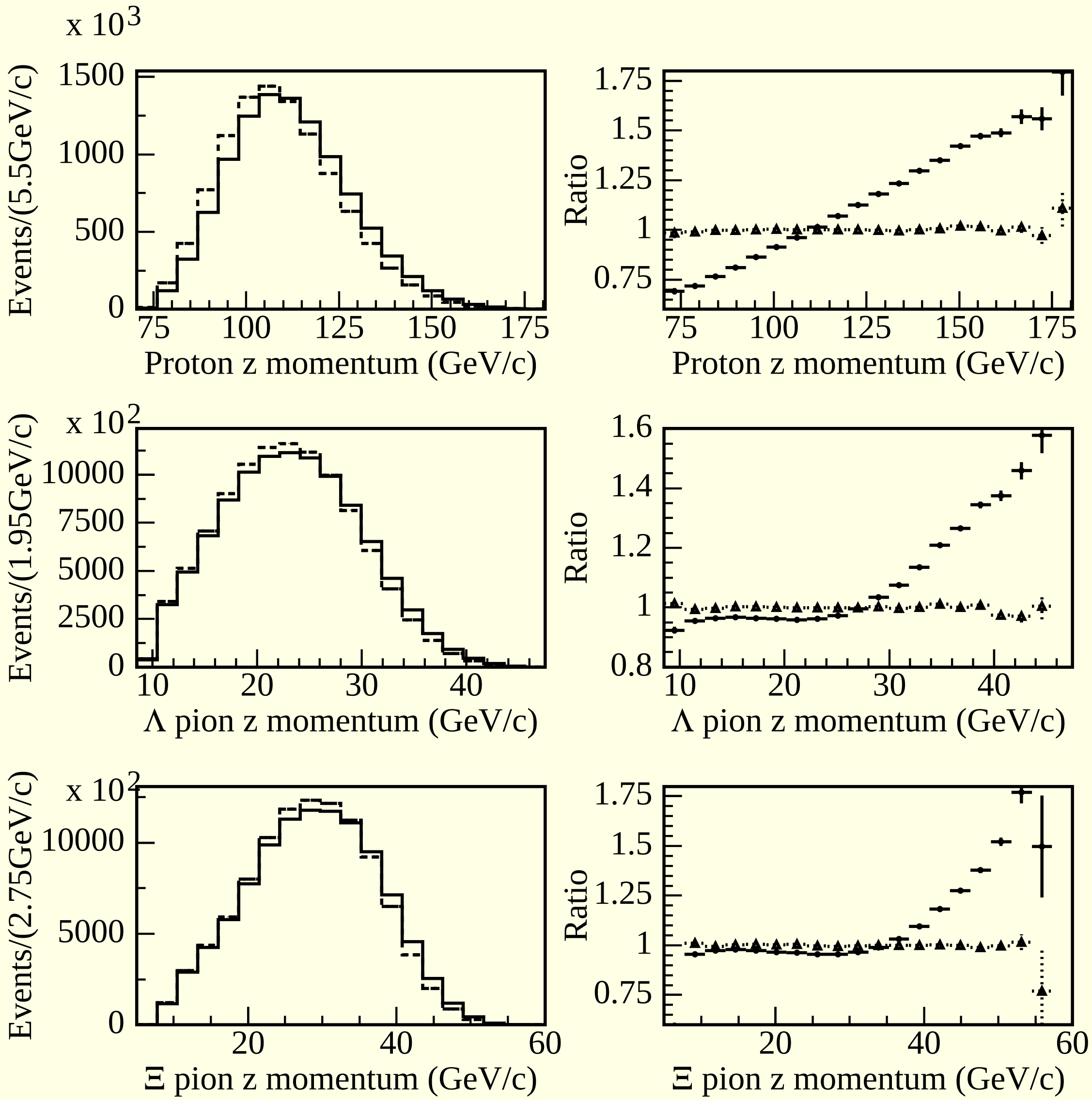
Ξ^- and $\overline{\Xi}^+$ x Slopes and Positions not Weighted

- Not momentum dependent ⇒ 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

− Solid lines
+ dashed lines



Ratio

o: before weighting
△ after weighting

Extracting the CP Asymmetry

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

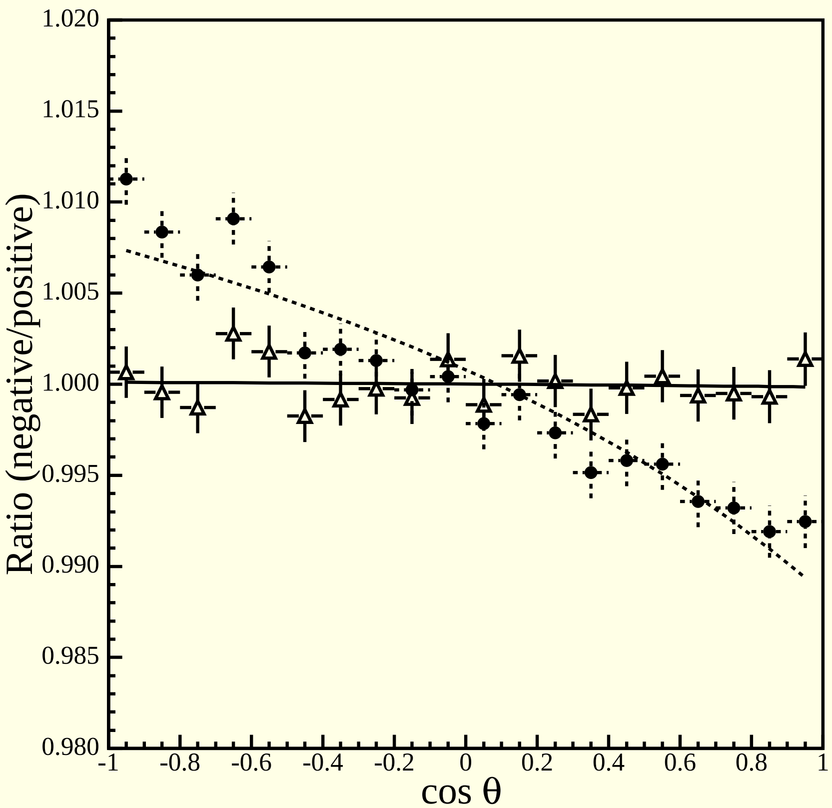
$$\frac{dN_-}{d\cos\theta_-} = A_-\frac{N_-}{2}(1+\alpha_\Xi\alpha_\Lambda\cos\theta_-) \qquad \frac{dN_+}{d\cos\theta_+} = A_+\frac{N_+}{2}(1+\overline{\alpha}_\Xi\overline{\alpha}_\Lambda\cos\theta_+)$$

- 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:

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

to extract asymmetry δ:

$$\begin{aligned} \delta &= \alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda \\ A_{\Xi\Lambda} &= \frac{\delta}{\alpha_\Xi\alpha_\Lambda + \overline{\alpha}_\Xi\overline{\alpha}_\Lambda} = \frac{\delta}{2\alpha_\Xi\alpha_\Lambda} \\ &= 1.71\,\delta \end{aligned}$$



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

Monte Carlo Tests

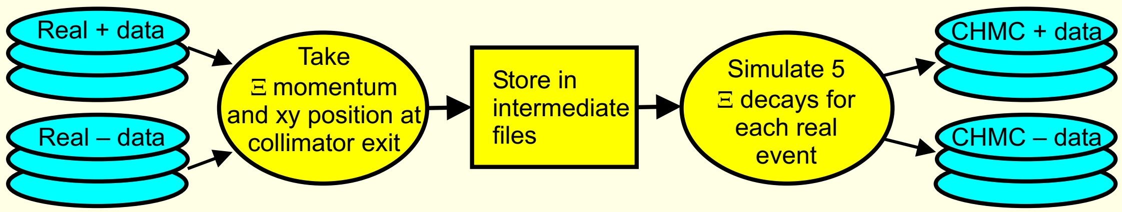
Final result has no Monte Carlo dependence!

Important! Monte Carlo only used to:

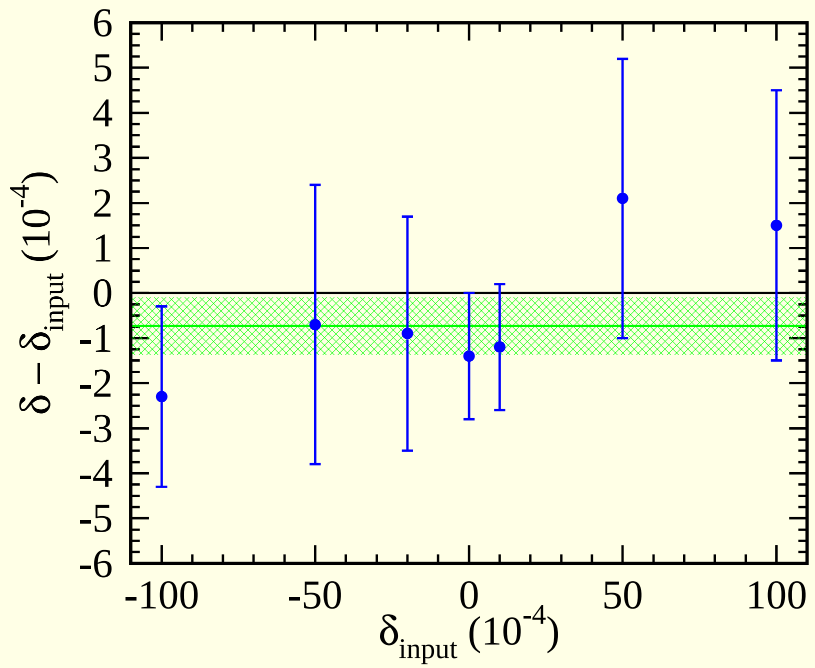
- Verify code and algorithm.
- Study a few systematics.

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

Solution:



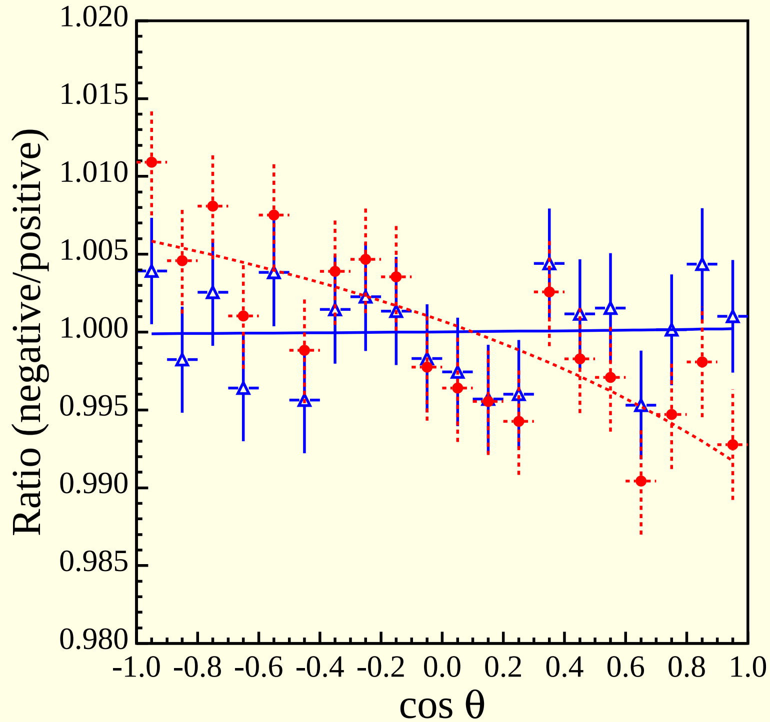
We get the input asymmetry back ⟹



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

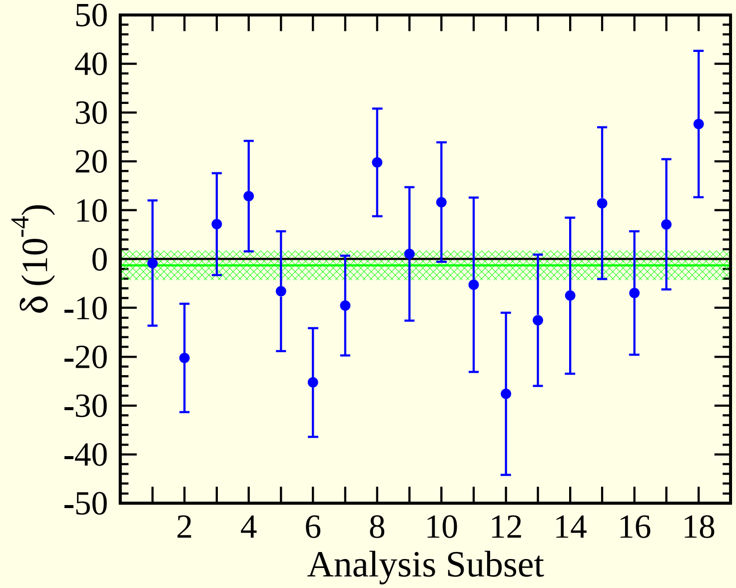
The CP Asymmetry $A_{\Xi\Lambda}$ from Weighting Method

- Data broken up into 18 sets, 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

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

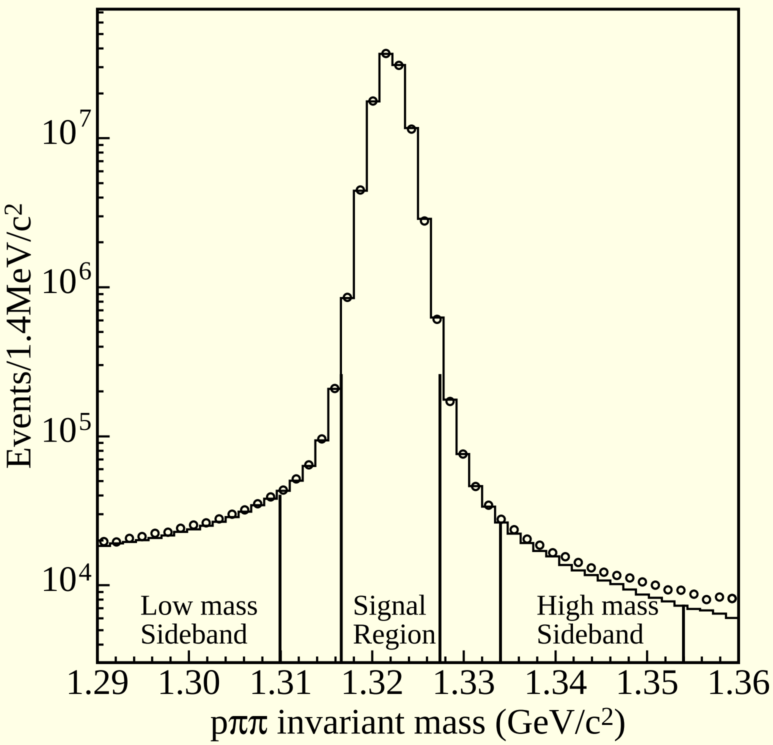


Weighted average of all 18 data sets:

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

Background Subtraction Has Little Effect

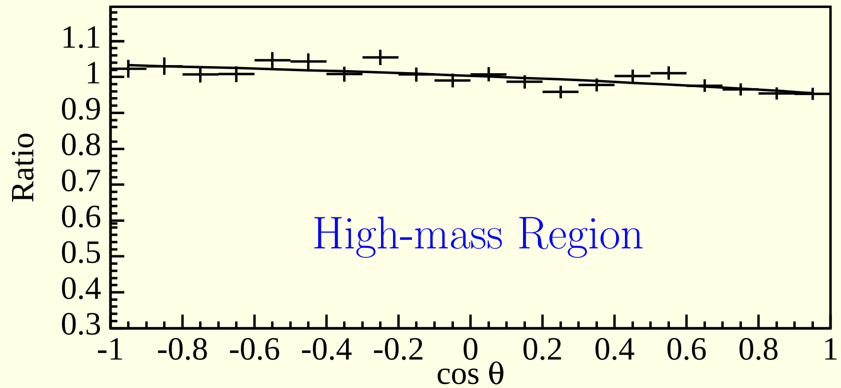
- Triple Gaussian fit with fourth-order polynomial for background.
- Background fraction:
  Ξ^-: 0.43% (lines)
  $\overline{\Xi}^+$: 0.41% (circles)

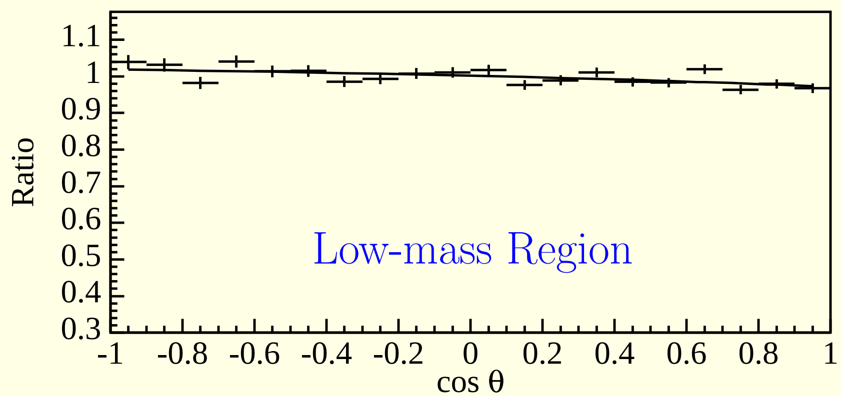


Low mass: $\delta = (-2.2 \pm 0.5) \times 10^{-2}$
High mass: $\delta = (-3.8 \pm 0.7) \times 10^{-2}$

- Weighted background asymmetry:

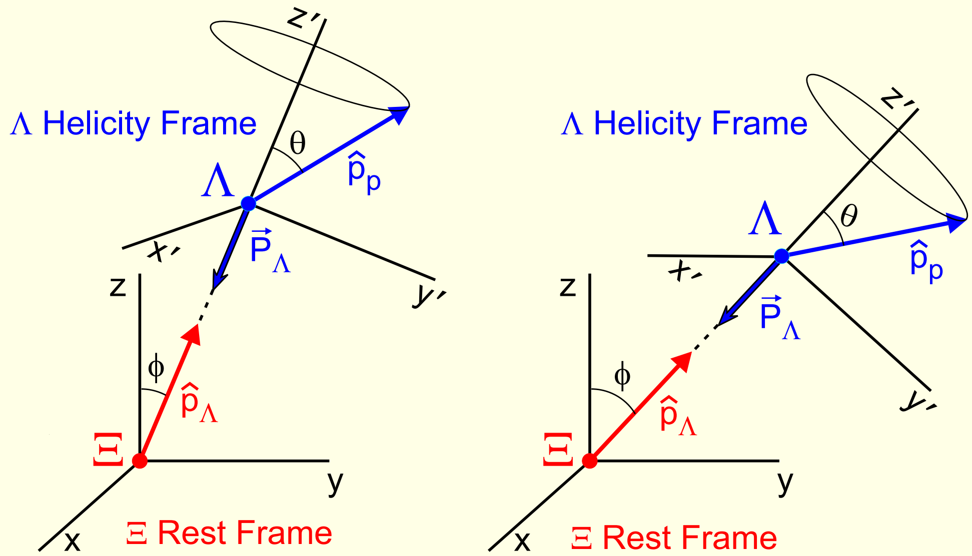
$$A_{\Xi\Lambda}(bs) = (0.0 \pm 5.1) \times 10^{-4}$$



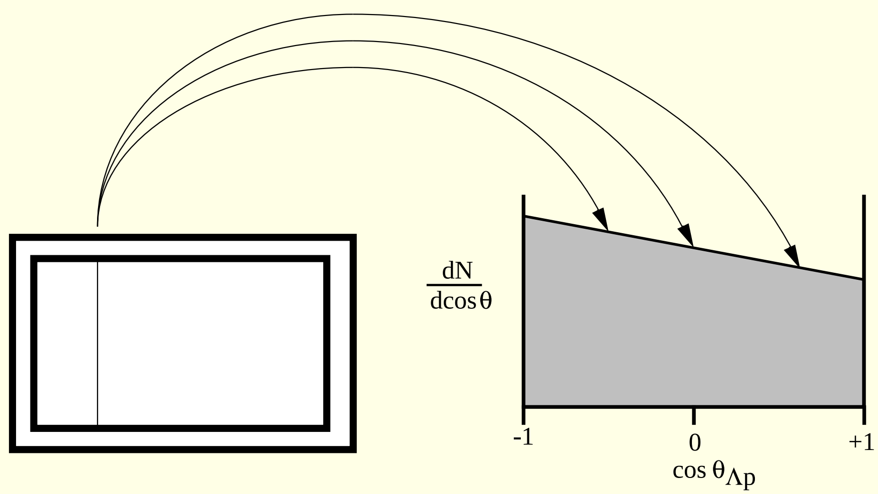


Helicity Frame Analysis Naturally Minimizes Biases

- 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	2.4
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

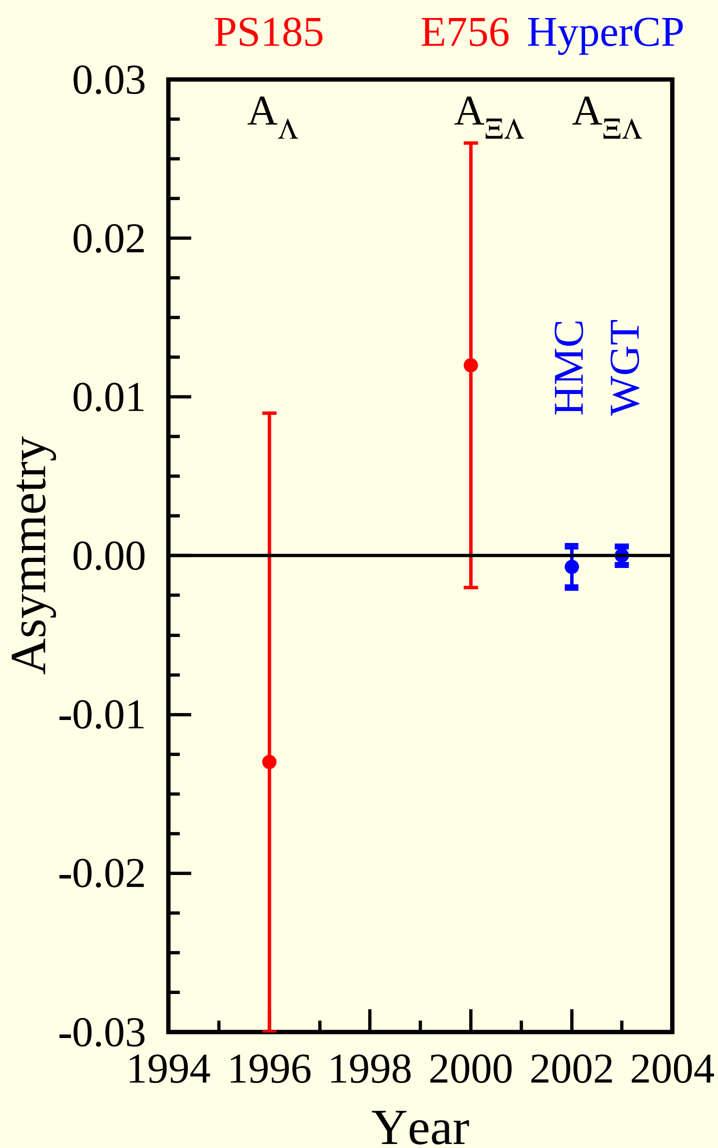
$$A_{\Xi\Lambda} = [0.0 \pm 5.1(\mathrm{stat}) \pm 4.4(\mathrm{syst})] \times 10^{-4}$$

Check with HMC Technique:

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

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

$\Rightarrow 20\times$ 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.

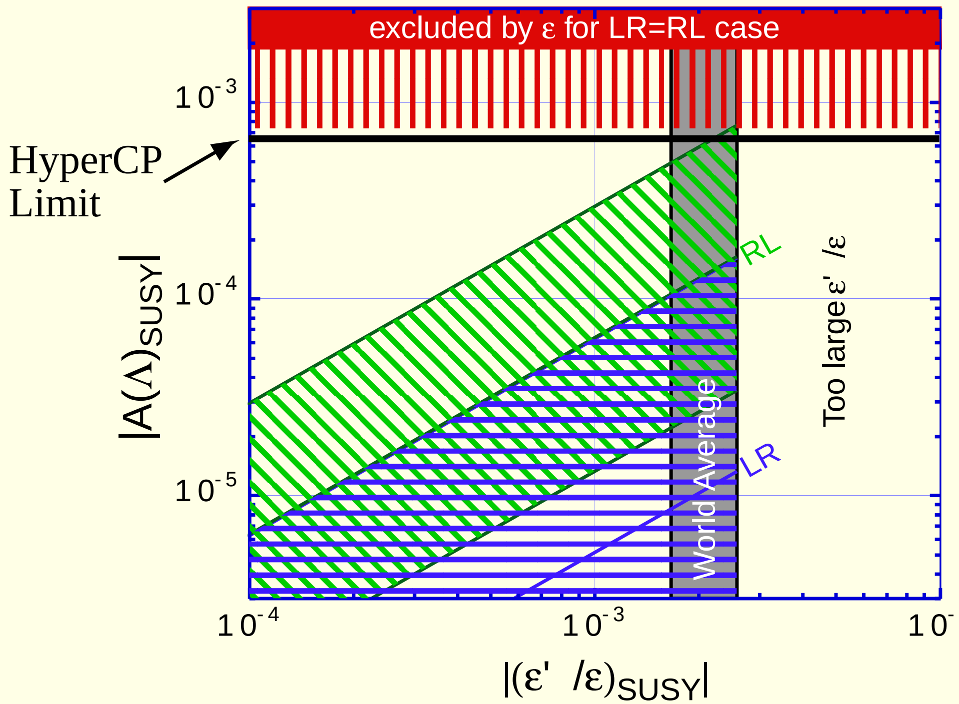
- *HyperCP* finds no evidence of CP violation in $\Xi^{\pm}$ and Λ decays:

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

- 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.

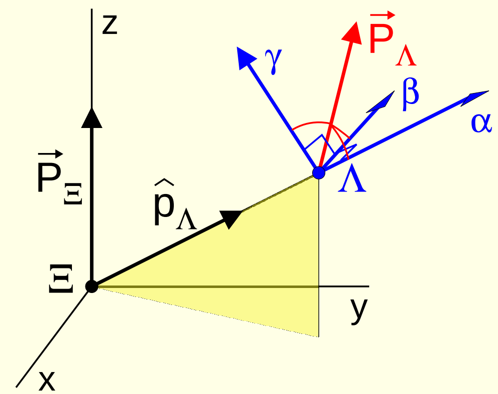


Backup Slides

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:

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

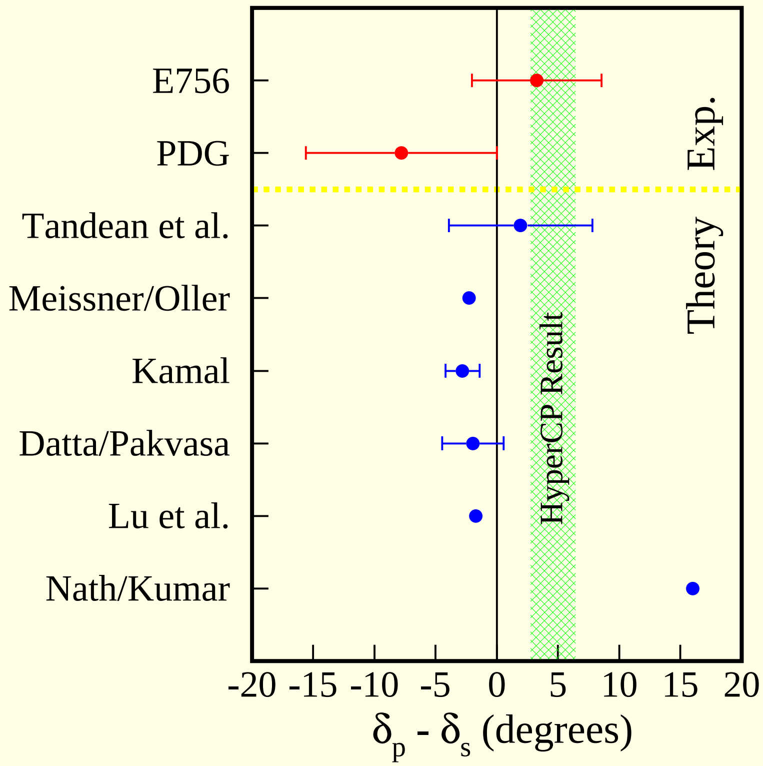


$$\beta_\Xi = -0.037 \pm 0.011(\text{stat}) \pm 0.010(\text{syst})$$
$$\gamma_\Xi = 0.888 \pm 0.0004(\text{stat}) \pm 0.006(\text{syst})$$

- Using the known value of α_Ξ:

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

- 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:

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

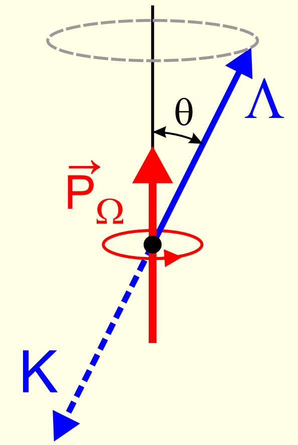
- Here:

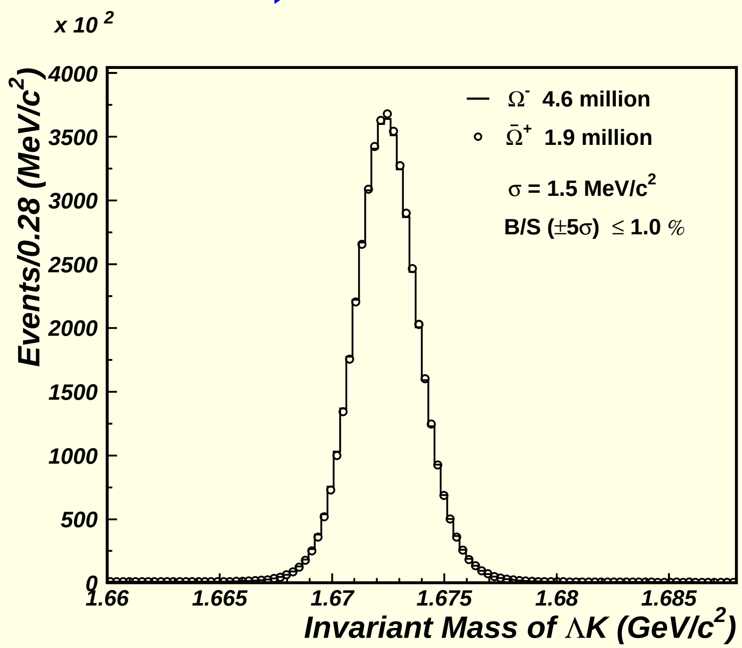
$$\alpha_\Omega = \frac{2\mathrm{Re}(P^* D)}{|P|^2 + |D|^2}$$

- 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:

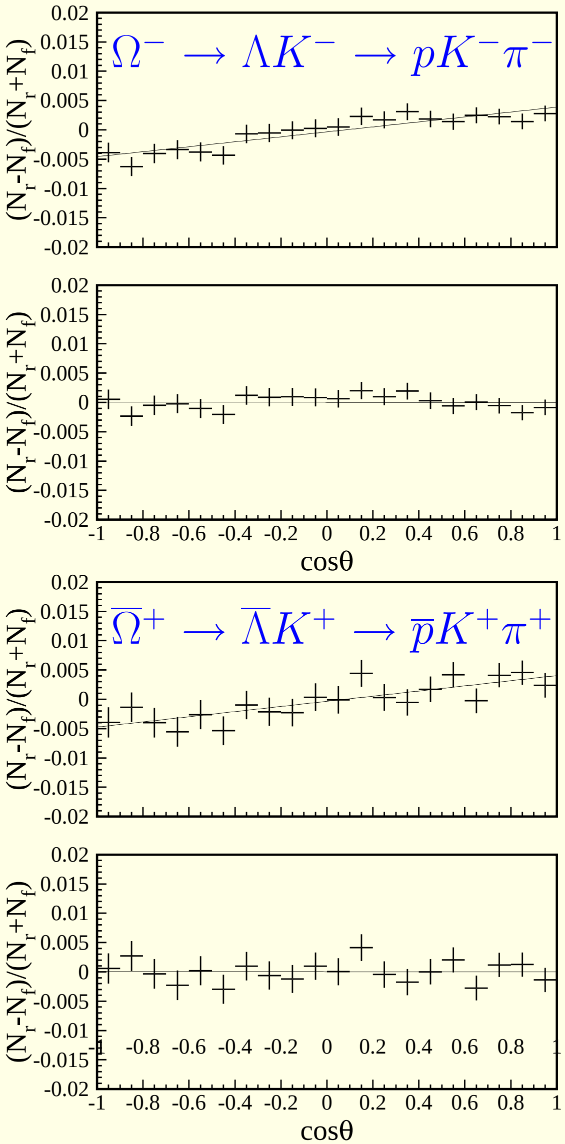
$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega \alpha_\Lambda \cos\theta)$$

- Large data sample, little background.



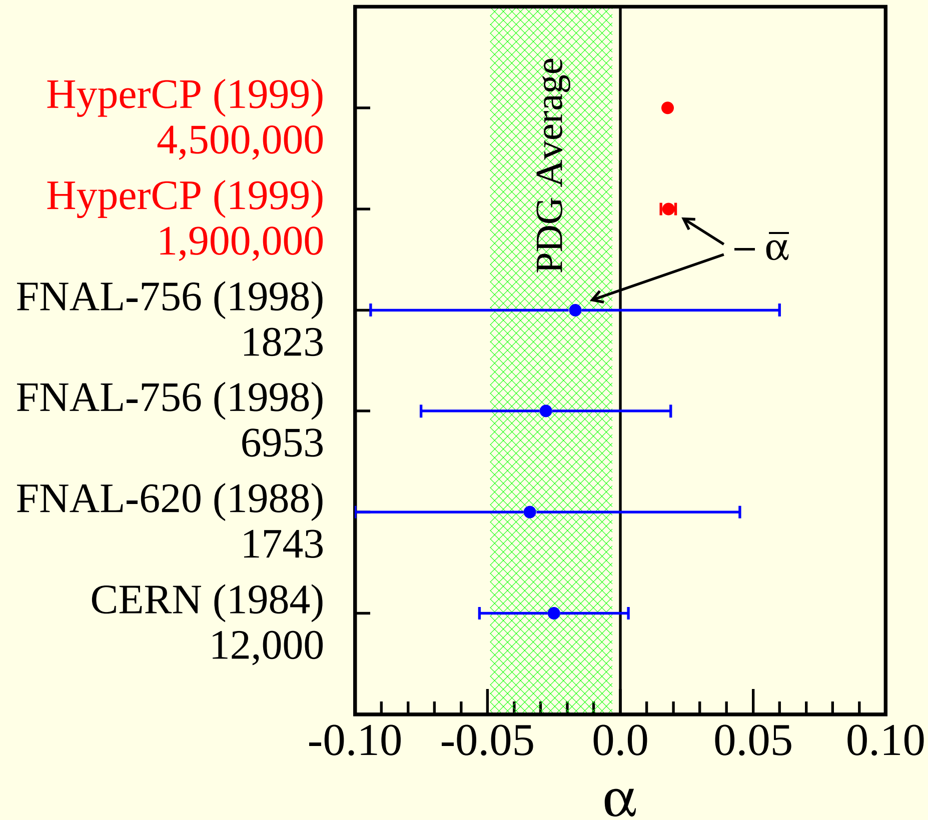


Preliminary Measurement of α_Ω and $\overline{\alpha}_\Omega$ in $\Omega^- \to \Lambda K^-$ Decays



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.