Precision Measurements with the *HyperCP* Spectrometer at Fermilab

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HyperCP Physics Goals

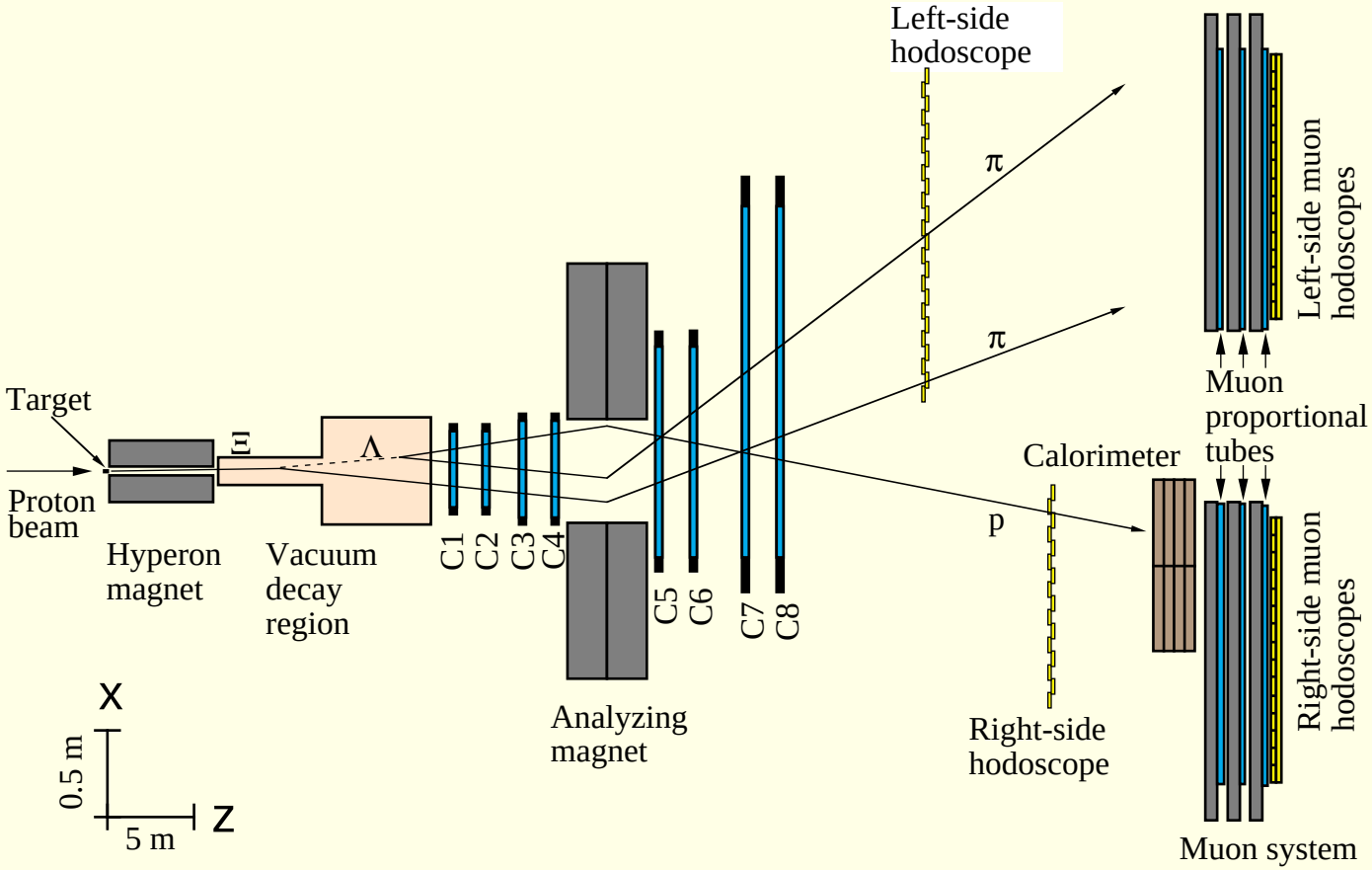
Primary Goal:

- A search for exotic sources of CP violation in $\Xi^-/\overline{\Xi}^+$ and $\Lambda/\overline{\Lambda}$ decays.

Secondary Goals:

- Search for CP violation in $\mathrm{K}^\pm \to 3\pi$ and $\Omega^\pm \to \Lambda K^\pm$ decays.
- Search for rare and forbidden hyperon and charged kaon decays:
  - Lepton number nonconservation in $\Xi^- \to p\mu^-\mu^-$.
  - Flavor changing neutral currents in hyperon and charged kaon decays: $\Omega^- \to \Xi^-\mu^+\mu^-$, $\Sigma^+ \to p\mu^+\mu^-$, $\Omega^- \to \Xi^-\mu^+\mu^-$, $K^\pm \to \pi^\pm\mu^+\mu^-$.
  - $\Delta S > 1$ decays: $\Xi^- \to p\pi^-\pi^-$, $\Omega^- \to \Lambda\pi^-$, $\Omega^- \to pK^-\pi^-$, $\Omega^- \to p\pi^-\pi^-$.
  - $\Omega^- \to \Xi^-\pi^+\pi^-$.
- Measure various hyperon production and decay properties:
  - $\Xi^-(\overline{\Xi}^+)$ and $\Omega^-(\overline{\Omega}^+)$ polarization.
  - β decay parameter in Ξ^- decays, and hence the $\Lambda\pi$ strong phase shift.
  - α decay parameter in $\Omega^\pm \to \Lambda K^\pm$ decays.
  - Hyperon production cross sections.

The *HyperCP* Spectrometer



- 800 GeV/c incident proton beam.
- 10–15 MHz, 167 GeV/c charged beam.
- 8 high-rate, narrow-pitch wire chambers.
- Muon system for rare and forbidden hyperon and kaon decays.

- Simple, low-bias trigger using hodoscopes and calorimeter.

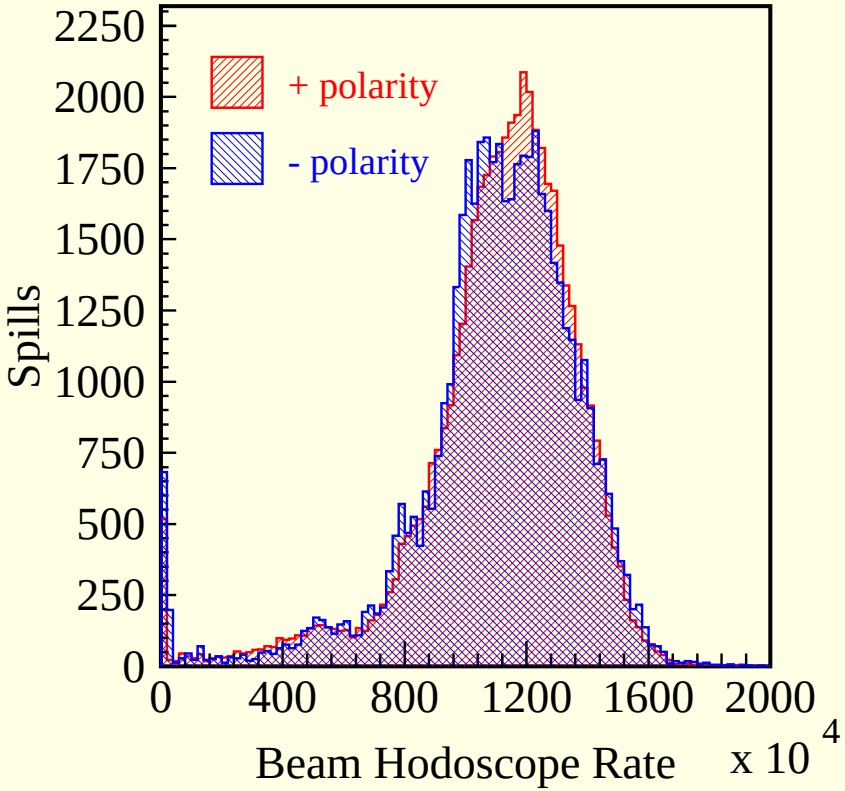
  SS($\geq$1 hit)·OS($\geq$1 hit)·Cal($\geq$40 G eV)

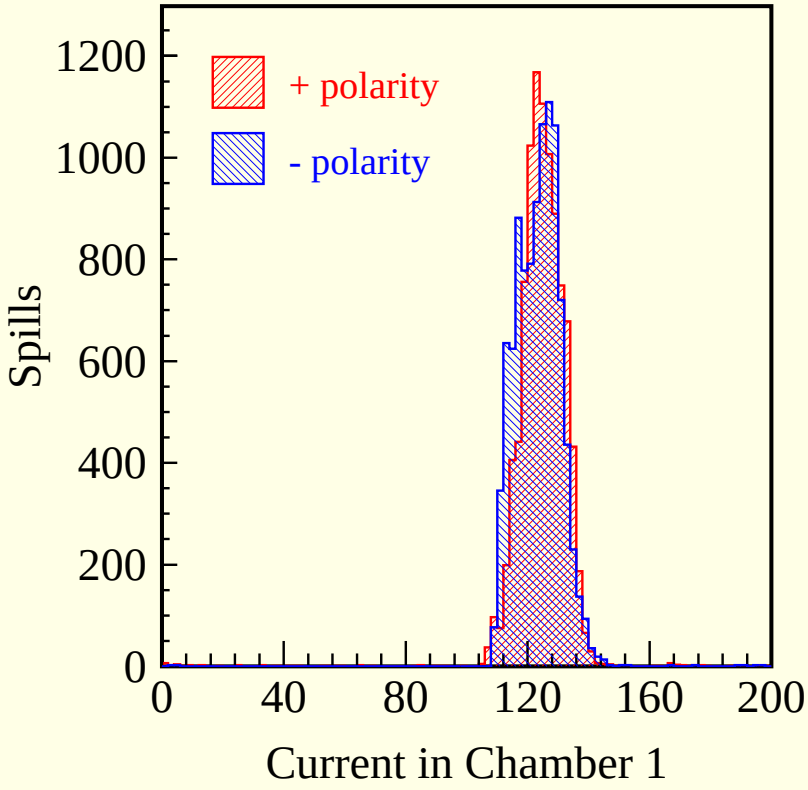
Secondary Beam Rates Equalized by Target Interchange

- Target length changed to equalize channeled beam rates.

  + polarity: 2.0 cm Cu

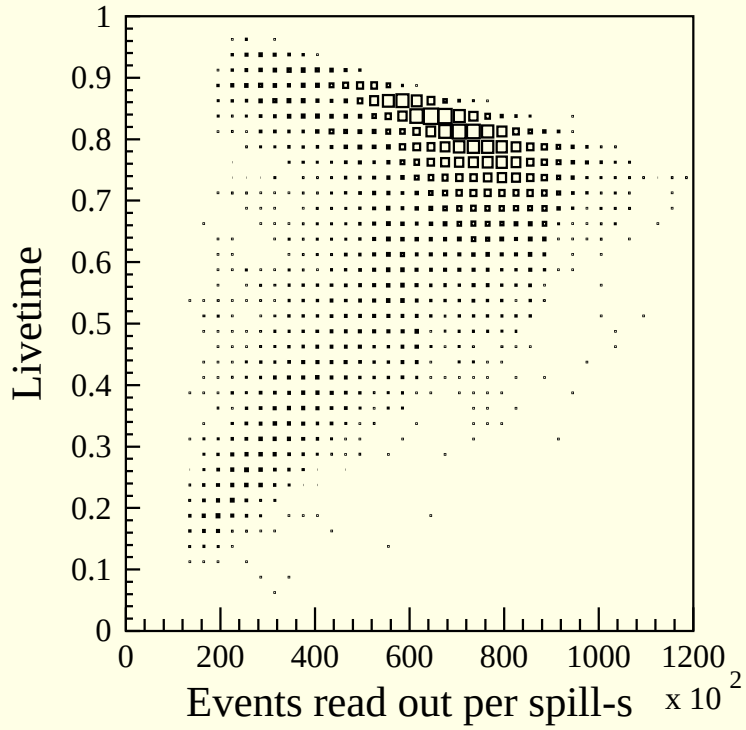
  − polarity: 6.0 cm Cu

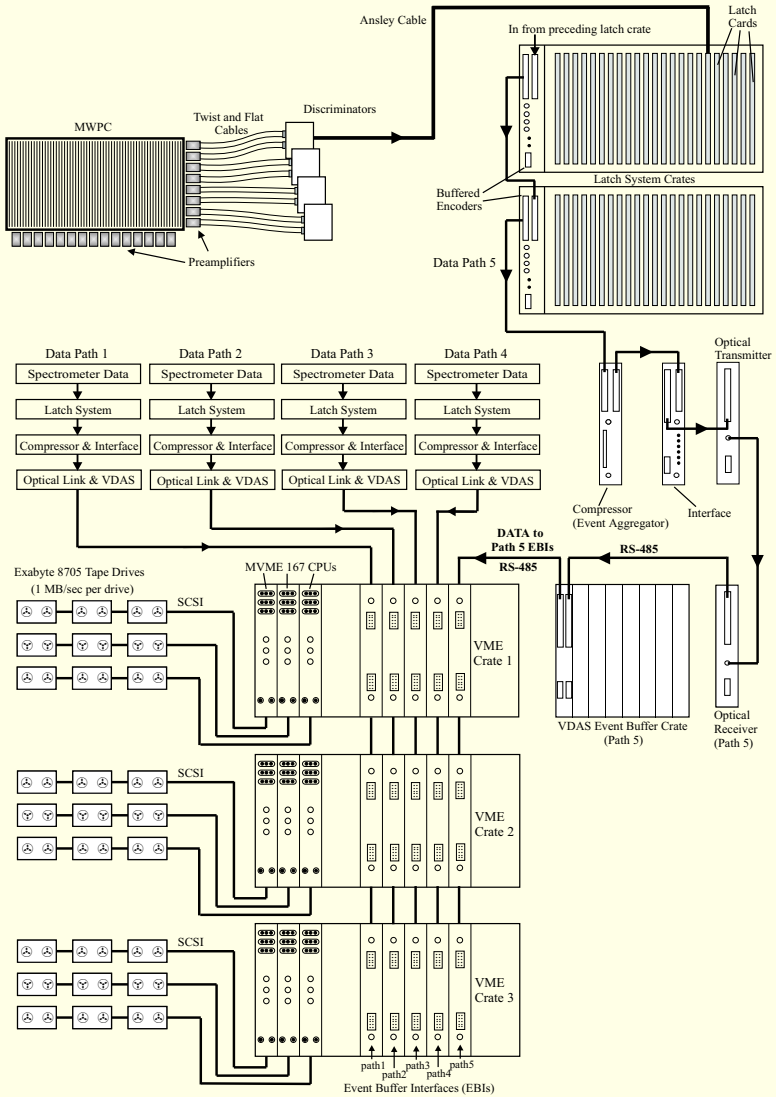




HyperCP Data Acquisition System

- All custom front ends: no CAMAC, Fastbus, or VME.
- Sustained data logging rate of 27 MB/s onto 27 Exabyte 8705 tapes.
- Maximum trigger rate of about 100,000 events per second:





HyperCP Yields

- In 12 months of data taking we recorded one the largest data sample 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

HyperCP Data Set Enormous!

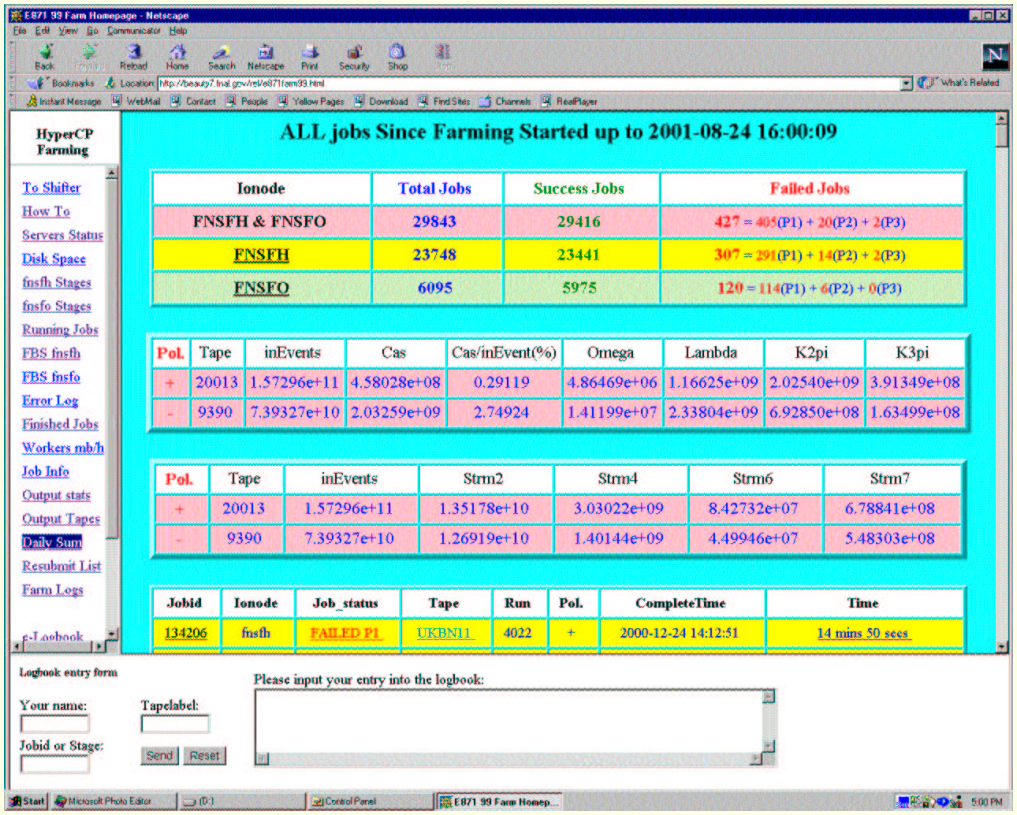
- Data volume compared to other, much larger experiments (E. Augé, EPS HEP 2001).

Parameters	Aleph	Babar	*HyperCP*	CDF	CMS
Event Size (KB)	250	50	0.5	250	1000
Events/yr (10^9)	0.004	2	240	2	2
Data/yr (TB)	1	100	120	450	2000
Manpower	300	500	42	600	2000

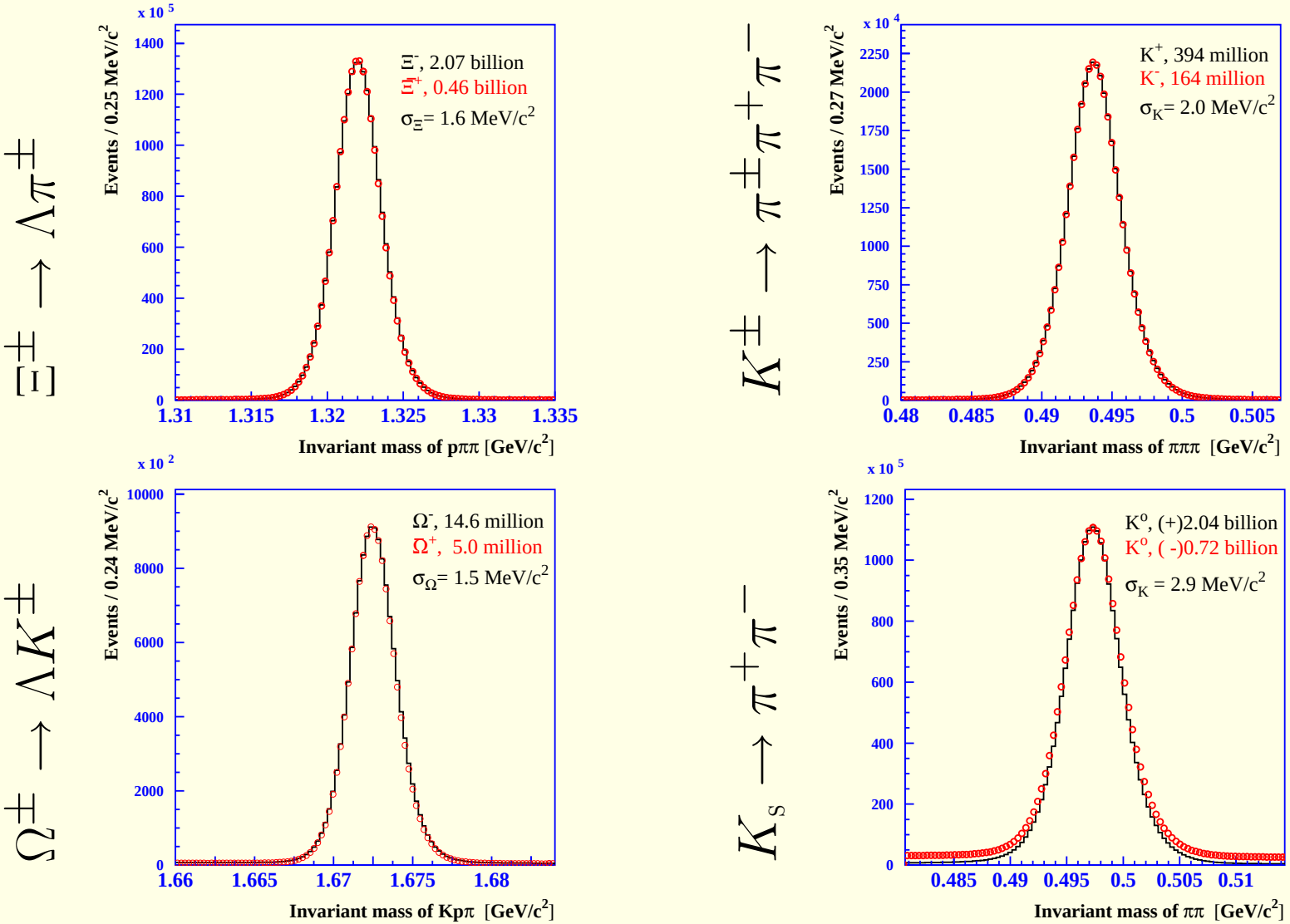
- Note:
  - One copy of the Encyclopaedia Britannica: 1 GB.
  - The World Wide Web as of September 11, 2001: 5 TB.
  - A video store (5,000 videos): 8 TB.
  - The Library of Congress (not counting pictures): 20 TB.
  - The Internet Archive (from 1996 to October 2001): 100 TB.
  - It would take 576 years to download all this data at 56 kbaud.

Data Reconstructed on Fermilab Computer Farm

- Done by three people(!) using a web-based interface.
- Took 11 months at about a 364 GB/day rate.
- Called "Tour de Force — by a small experiment," in summary talk at the *International Conference on Computing in High Energy and Nuclear Physics*
- PostgreSQL database used to keep track of data.
- A total of 35,847,274 histograms with information on reconstruction and detector performances were generated automatically in the farm processing.



Masses from the Farm Analysis



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 several $\times 10^{-3}$.
- 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

Short Primer on Nonleptonic Hyperon Decays

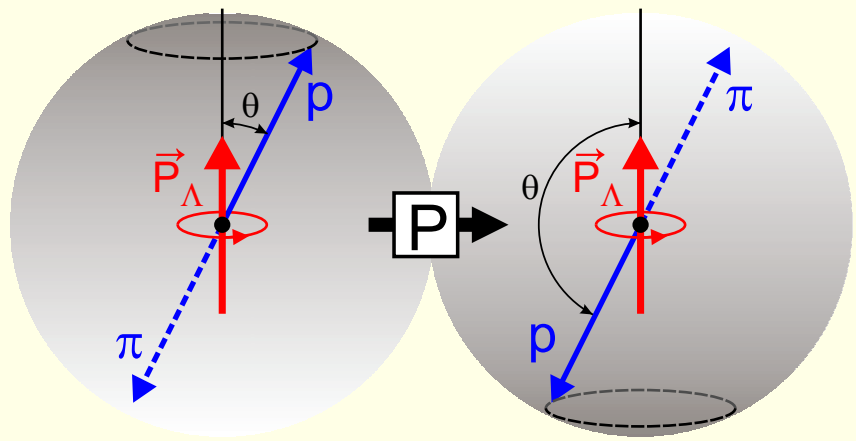
$$\Xi^- \to \Lambda\pi^- \qquad \Lambda \to p\pi^-$$

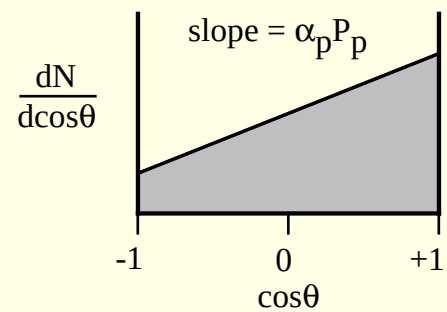
- **Decay violates parity.** Hence angular distribution of daughter not isotropic (if parent is polarized)

$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_p P_p \cos\theta)$$

- **The magnitude of the parity violation is given by α_p.**
- The slope of the daughter baryon $\cos\theta$ distribution given by:

$$\alpha_p P_p$$

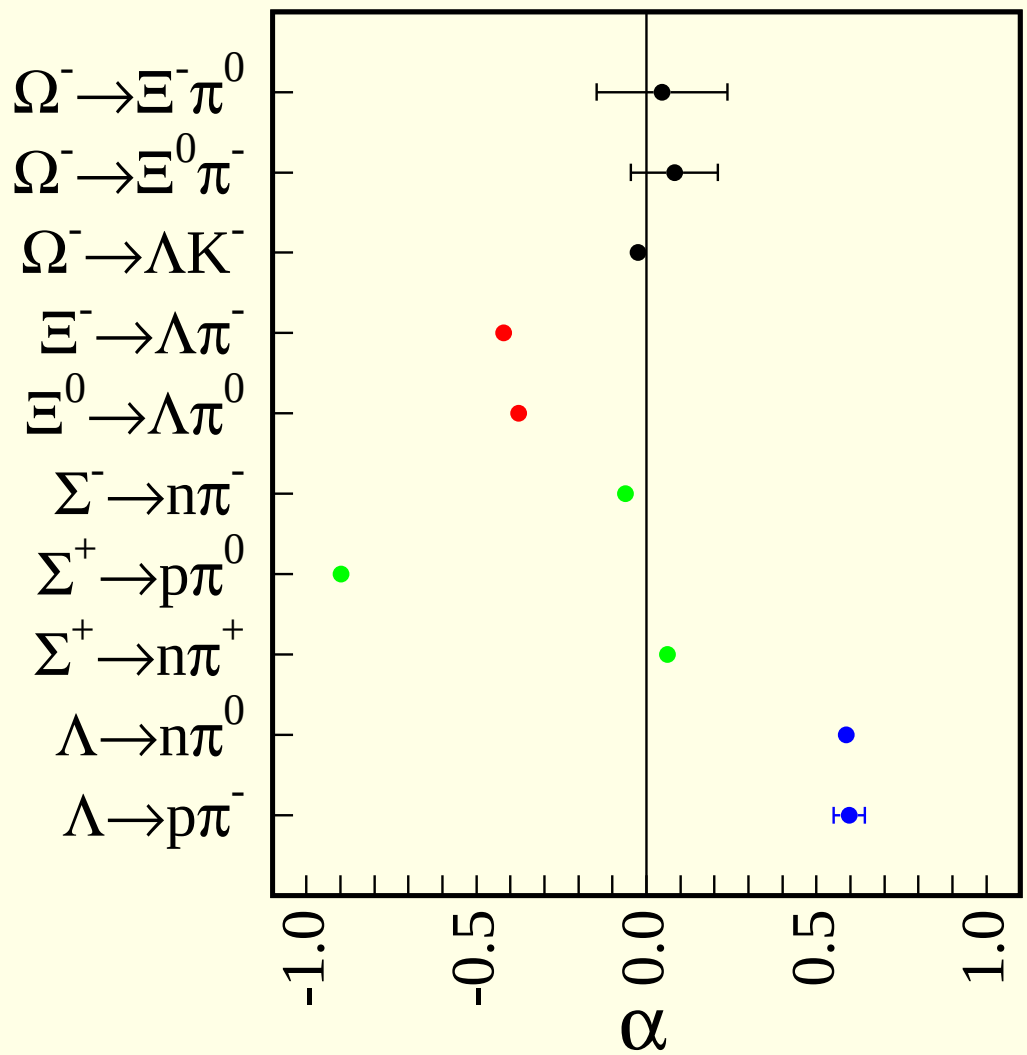




- **The daughter is polarized:**

$$\vec{P}_d = \frac{(\alpha_p + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta_p(\vec{P}_p \times \hat{p}_d) + \gamma_p(\hat{p}_d \times (\vec{P}_p \times \hat{p}_d))}{(1 + \alpha_p \vec{P}_p \cdot \hat{p}_d)} \implies \vec{P}_d = \alpha_p \hat{p}_d \text{ if } \vec{P}_p = 0$$

Hyperon α Parameters



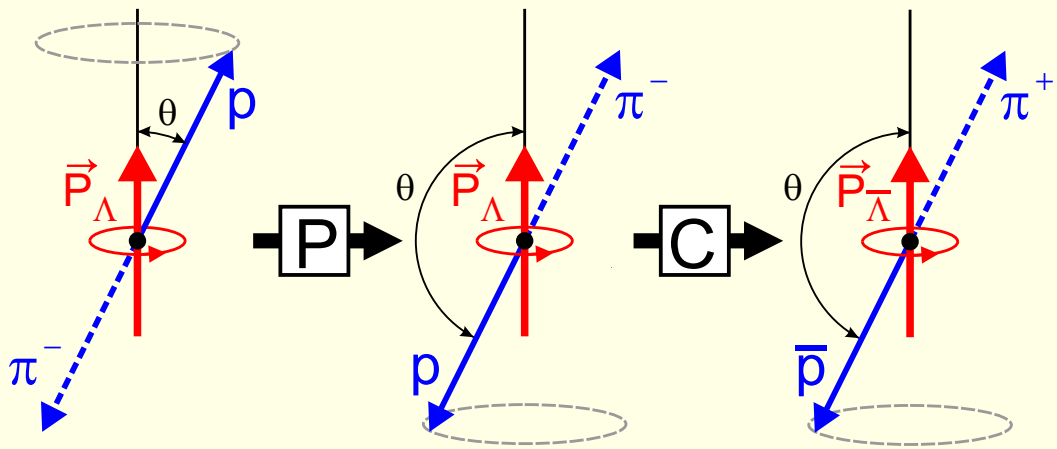
- All are non-zero except for the three in Ω^- decays.

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:

$$\Lambda \longrightarrow p\pi^- \qquad \frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta)$$

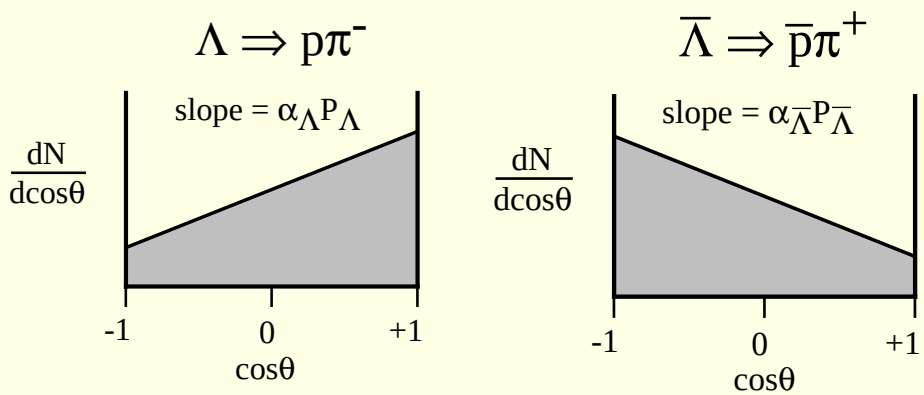
Under *CP* the antiproton likes to go in the direction opposite to the $\overline{\Lambda}$ spin:



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

If *CP* is violated the slope of the proton $\cos\theta$ distribution is *not* the *exact* opposite of the slope of the antiproton $\cos\theta$ distribution.

$$\overline{\alpha}_\Lambda \neq -\alpha_\Lambda$$



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:

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

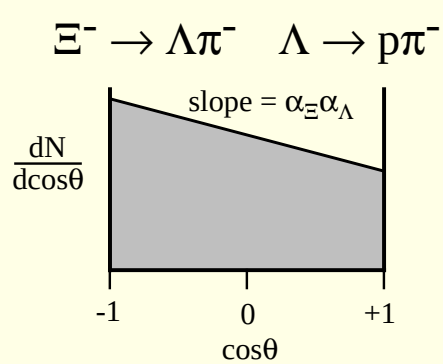
If the Ξ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the Λ is found in a helicity state:

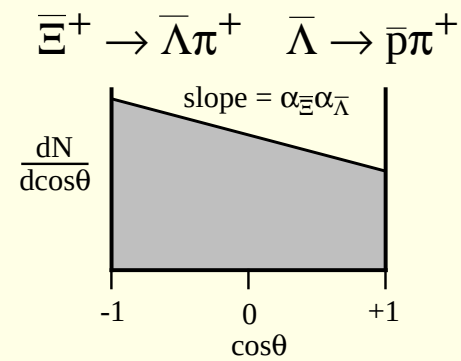
$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad\qquad \vec{P}_{\overline{\Lambda}} = \overline{\alpha}_\Xi \hat{p}_{\overline{\Lambda}}$$

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

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

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



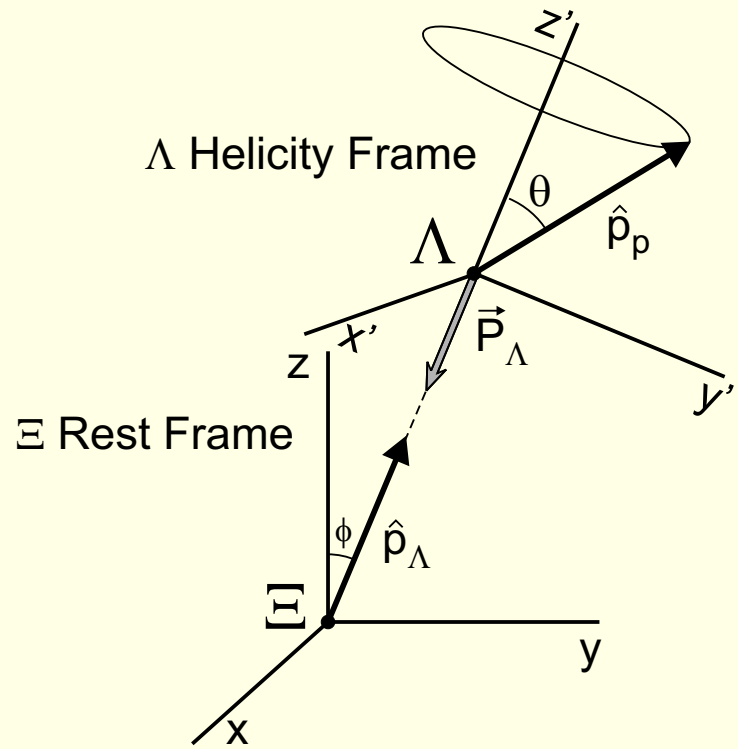


We are sensitive to both Ξ and Λ *CP* violation

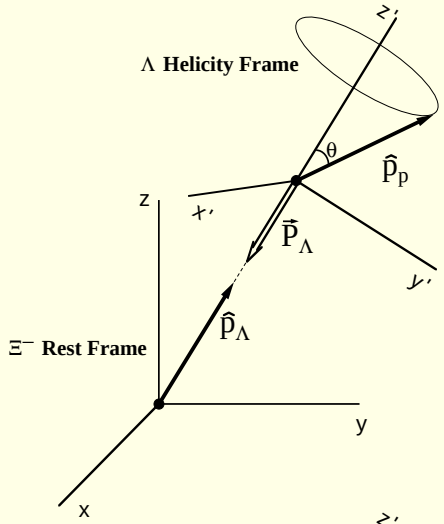
$$A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \overline{\alpha}_\Xi \overline{\alpha}_\Lambda}{\alpha_\Xi \alpha_\Lambda + \overline{\alpha}_\Xi \overline{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda$$

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.

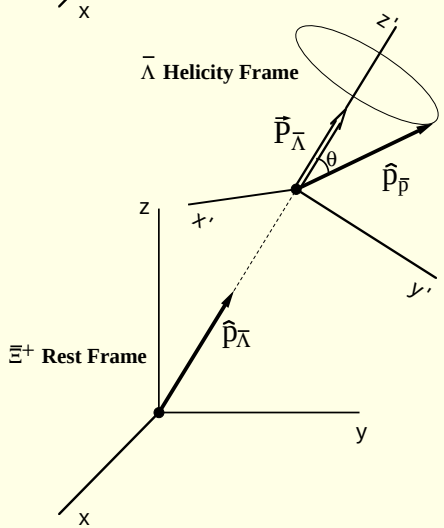


If CP is not violated Ξ^- and $\overline{\Xi}^+$ decays appear identical



$$\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^-$$

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



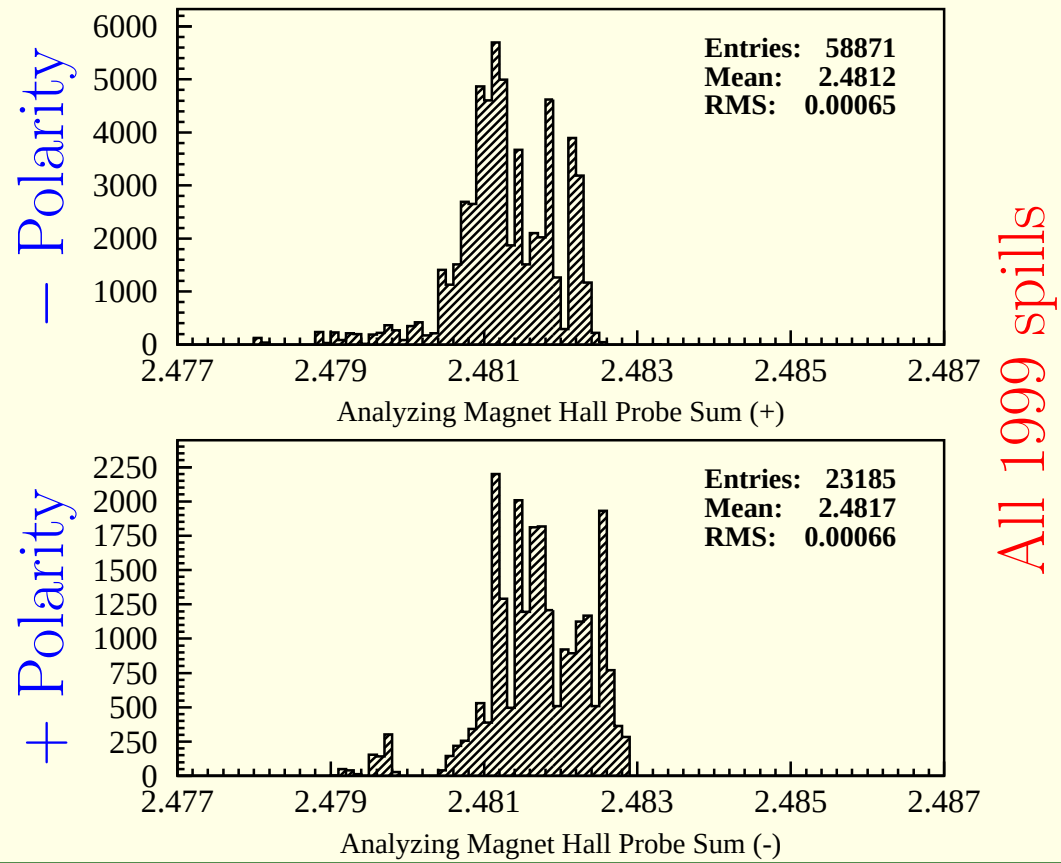
$$\overline{\Xi}^+ \rightarrow \overline{\Lambda}\pi^+ \rightarrow \overline{p}\pi^+\pi^+$$

$$\begin{aligned}\frac{\mathrm{dP}}{\mathrm{d}\cos\theta} &= \frac{1}{2}(1 + \alpha_{\overline{\Xi}} \alpha_{\overline{\Lambda}} \cos\theta) \\ &= \frac{1}{2}(1 + (-\alpha_\Xi)(-\alpha_\Lambda) \cos\theta) \\ &= \frac{1}{2}(1 + \alpha_\Xi \alpha_\Lambda \cos\theta)\end{aligned}$$

If we exactly flip the spectrometer magnetic fields and we keep the chamber, hodoscope, and calorimeter efficiencies the same we have a CP invariant apparatus.

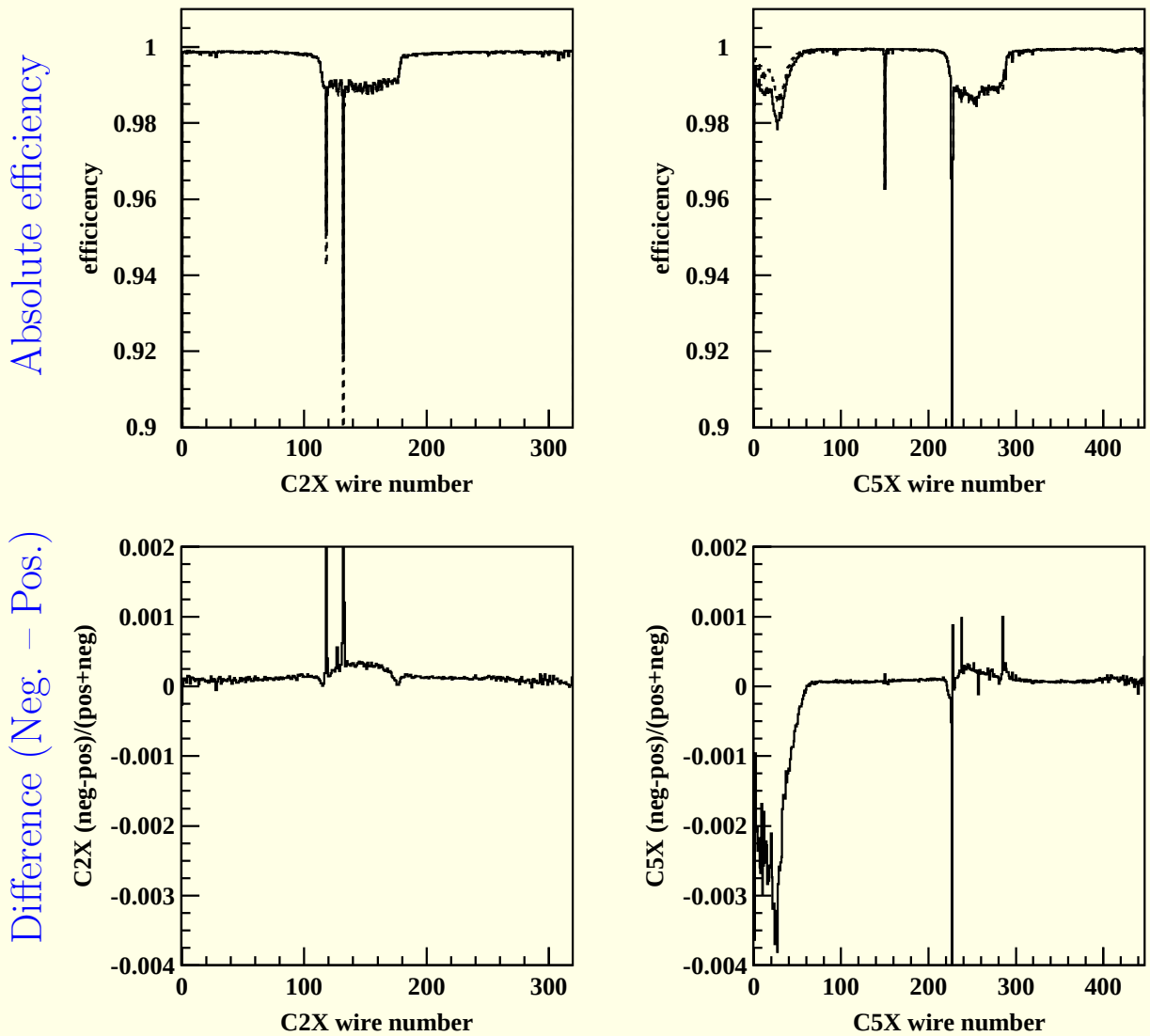
Spectrometer Magnetic Field Difference Small

- Hall probes measured field to 1×10^{-4} T precision.
- When flipping polarity, field magnitude kept within $\sim2\times10^{-4}$.
- This corresponds to a $\sim$0.3 mm deflection difference at 10 m for the lowest momentum ($\sim$10 GeV/c pions).



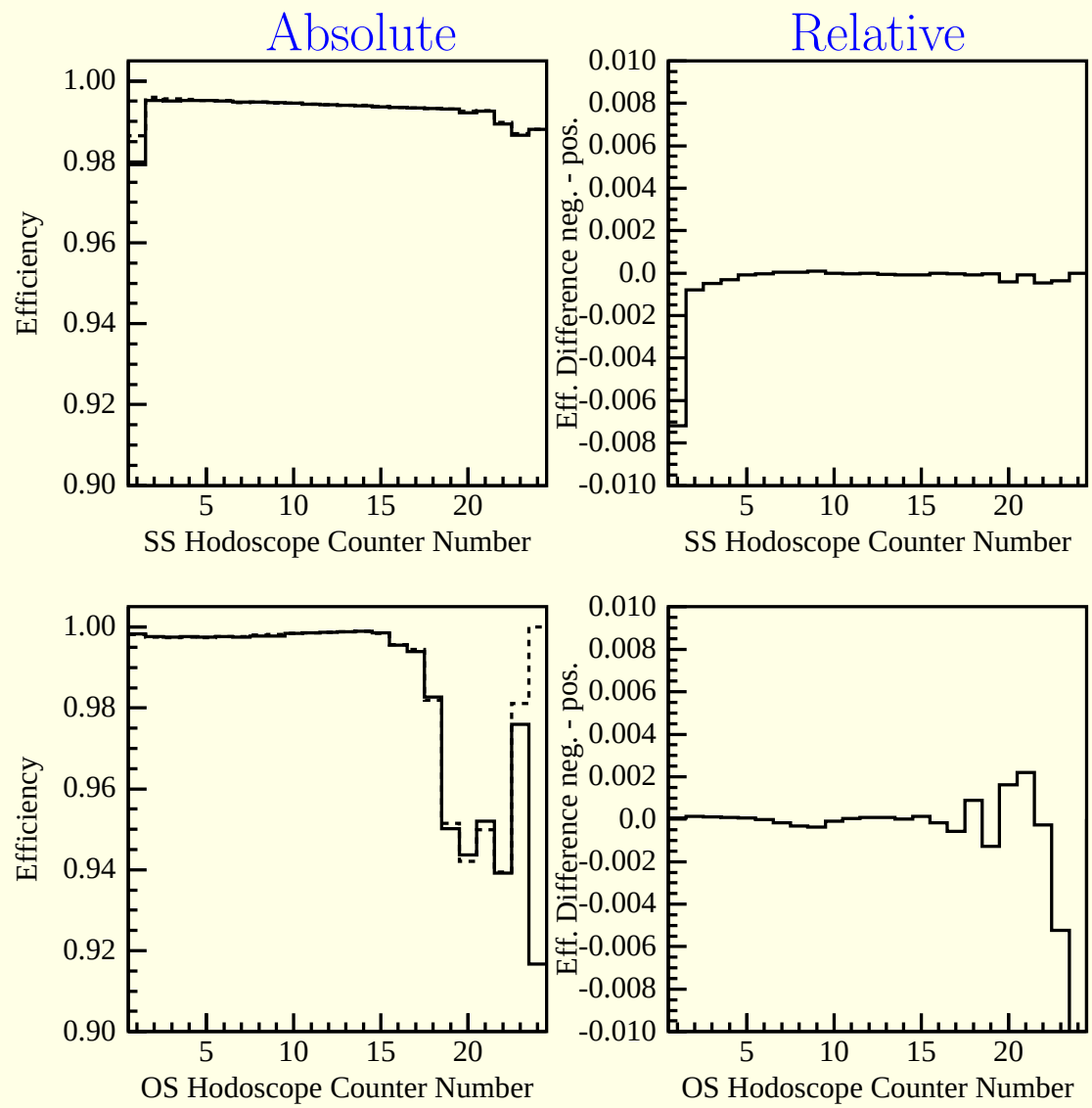
Chamber Efficiencies from Positive and Negative Running

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

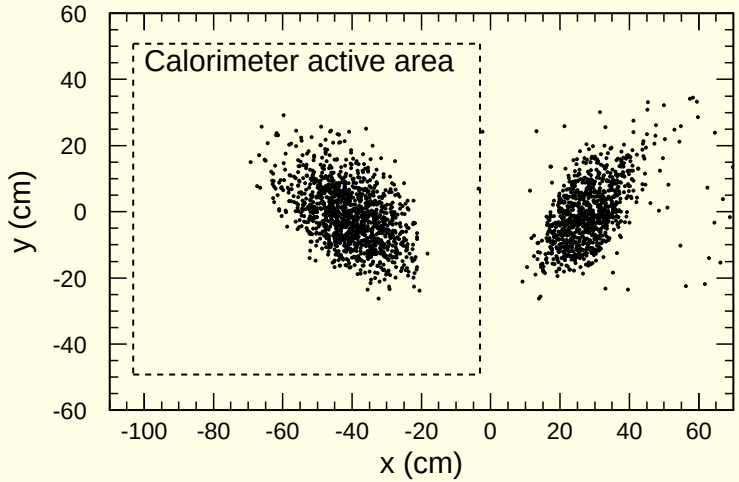


Hodoscope Efficiencies from Positive and Negative Running

- − 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.



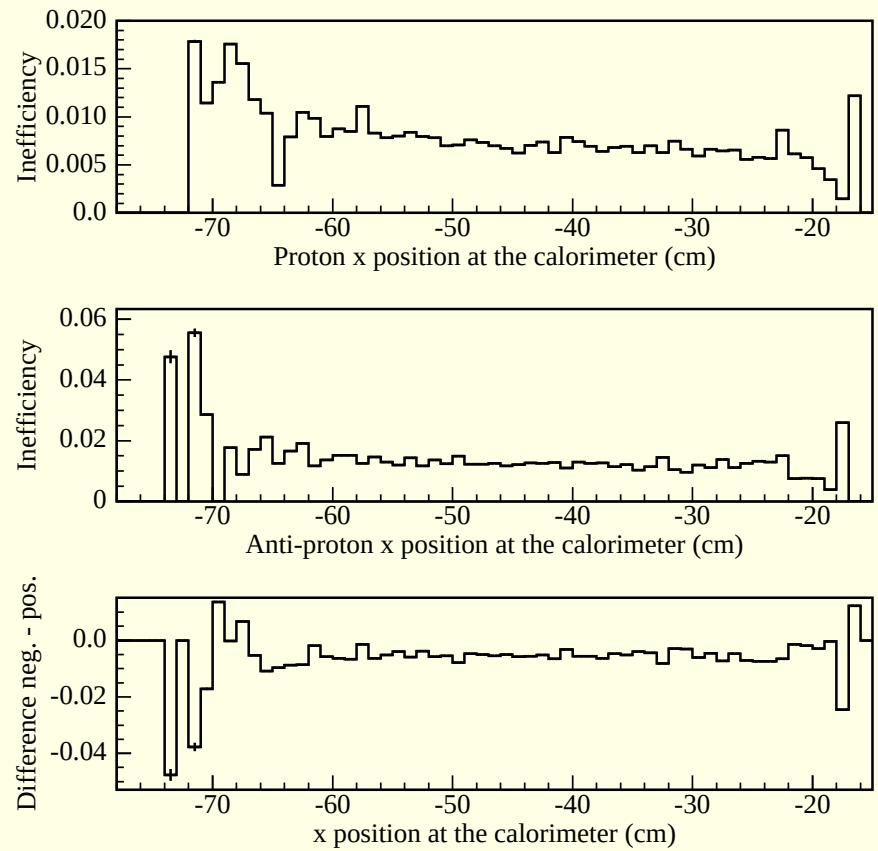
Calorimeter Efficiencies from Positive and Negative Running



- Proton momentum has x and y dependence $\Rightarrow$ Calorimeter efficiency has x and y dependence.
- No slope dependence in difference in calorimeter efficiency.
- Difference in positive and negative efficiencies due to different rates in calorimeter.

Trigger:

CAS = SS($\geq$1 hit)·OS($\geq$1 hit)·Cal($\geq$40 GeV)



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. Their 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.

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

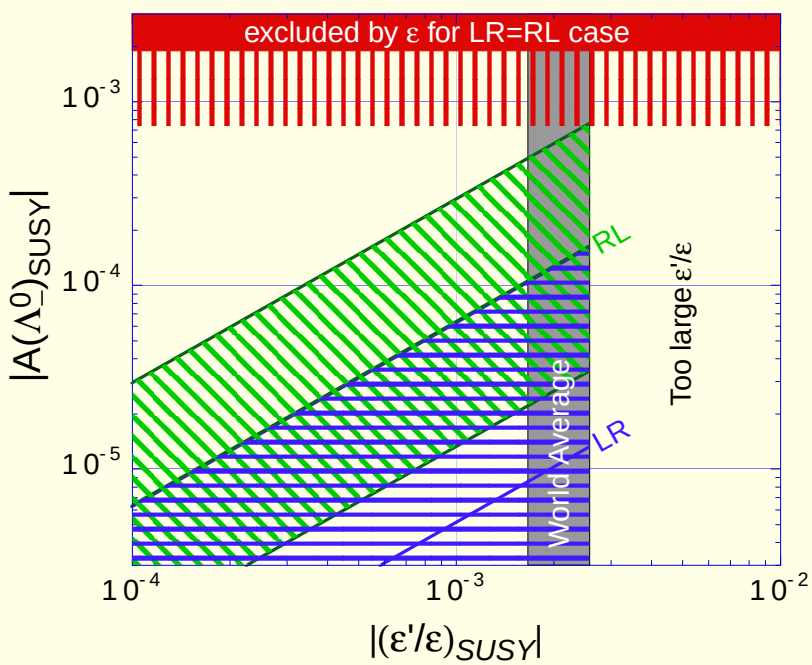
What do we Expect: Theoretical Predictions

- Beware of theorist's predictions. Calculations are notoriously difficult, and results are not reliable to better than an order of magnitude.

  "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.

- Standard Model predictions range from about $10^{-4} - 10^{-5}$.
- Hyperon CP violation not the same as kaon CP violation!
- For example, some supersymmetric models that do not generate ϵ'/ϵ can lead to A_Λ of $O(10^{-3})$.

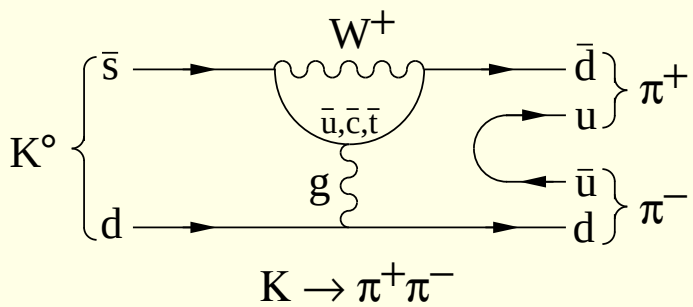


He et al., PRD 61 (2000) 071701(R).

Comparison of ϵ'/ϵ and A_Ξ, A_Λ

ϵ'/ϵ

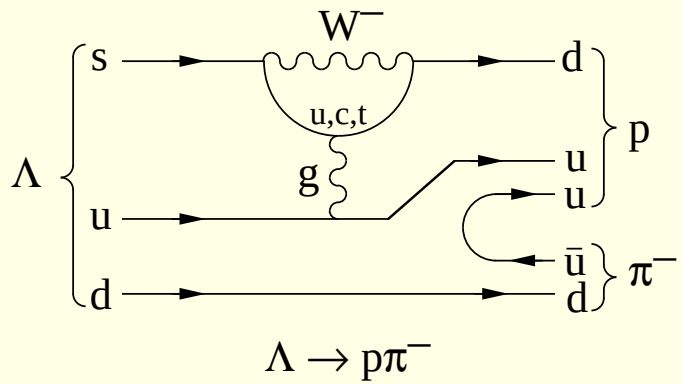
- Thought to be due to the Penguin diagram in the Standard Model.



- Expressed through a different CP-violating phase in the $I = 0$ and $I = 2$ amplitudes.
- Probes only parity violating amplitudes.

$A_{\Xi\Lambda}$

- Thought to be due to the Penguin diagram in the Standard Model.



- Expressed through a different CP-violating phase in the S- and P-wave amplitudes.
- Probes parity violating and conserving amplitudes.

"Our results suggest that this measurement is complementary to the measurement of ϵ'/ϵ, in that it probes potential sources of CP *violation at a level that has not been probed by the kaon experiments."*

He and Valencia, PRD52 (1995) 5257.

Difference between *HyperCP* and ϵ'/ϵ Experiments

- Kaon experiments measure simultaneously 4 different decays with 2 different apparatus:

$$\left.\begin{array}{rcl} \mathrm{K_L} & \rightarrow & 2\pi^\circ \\ \mathrm{K_S} & \rightarrow & 2\pi^\circ \end{array}\right\} \text{calorimeter}$$

$$\left.\begin{array}{rcl} \mathrm{K_L} & \rightarrow & \pi^+\pi^- \\ \mathrm{K_S} & \rightarrow & \pi^+\pi^- \end{array}\right\} \text{wire chambers}$$

$$\frac{(\mathrm{K_S} \rightarrow 2\pi^\circ)/(\mathrm{K_L} \rightarrow 2\pi^\circ)}{(\mathrm{K_S} \rightarrow \pi^+\pi^-)/(\mathrm{K_L} \rightarrow \pi^+\pi^-)} = 1+6\left(\frac{\epsilon'}{\epsilon}\right)$$

- $\mathrm{K_L} \rightarrow 2\pi^\circ$, $\pi^-\pi^+$ have small branching ratios.

- HyperCP measures alternately 2 identical decays with identical apparatus:

$$\begin{array}{rcl} \Xi^- & \rightarrow & \Lambda\pi^- \\ & & \mapsto p\pi^- \\ \overline{\Xi}^+ & \rightarrow & \overline{\Lambda}\pi^+ \\ & & \mapsto \overline{p}\pi^+ \end{array}$$

- $\Xi \rightarrow \Lambda\pi$ and $\Lambda \rightarrow p\pi$ have large branching ratios.

What is the experimental situation?

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

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

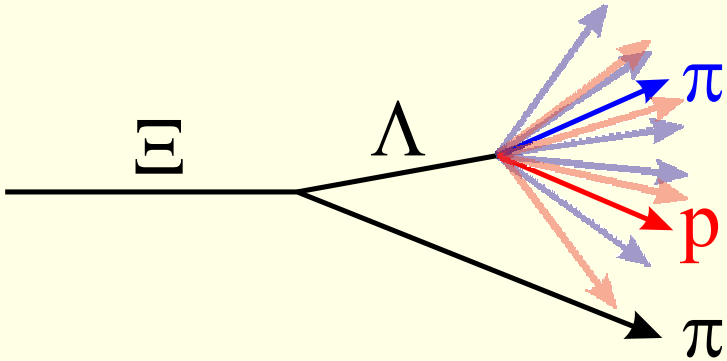
- There is a new measurement of $A_{\Xi\Lambda}$, based on the *HyperCP* technique.

Mode	Method	Limit	Exp	Date
$A_{\Xi\Lambda}$	pN $\to \Xi\pi \to \Lambda\pi \to p\pi\pi$	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.**

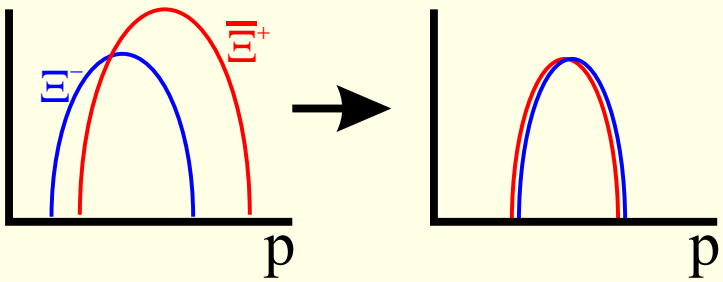
Two Different Analyses Being Done in Parallel

West Coast (LBL): 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.

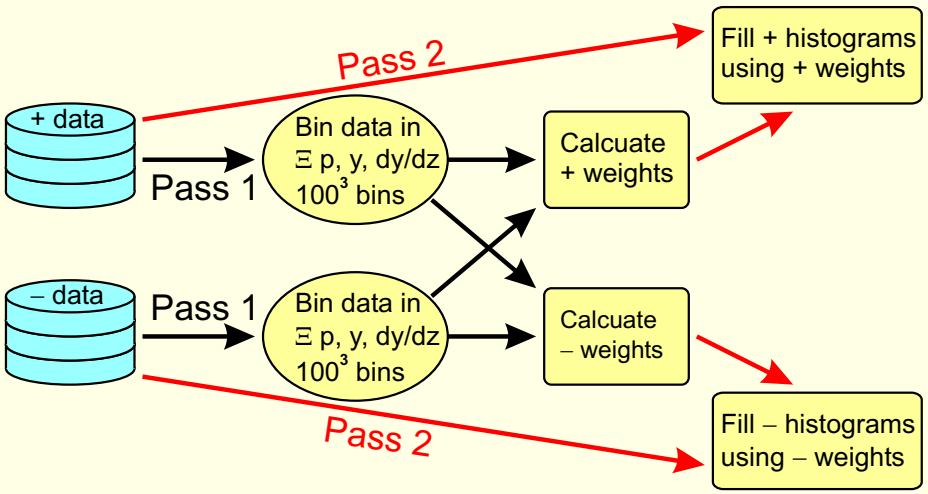
East Coast (UVa): Weighting Method

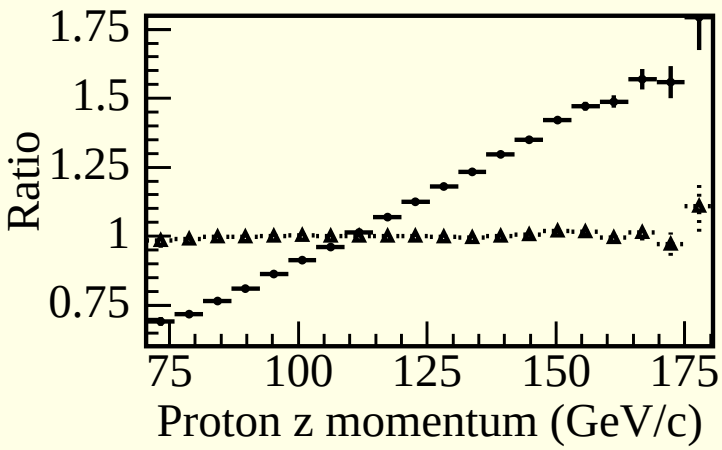


- Compare uncorrected $\cos(\theta)$ distributions.
- Force the Ξ and $\overline{\Xi}$ events to have similar momentum and spatial distributions by appropriate weighting.
- Advantage: No Monte Carlo needed to measure apparatus acceptance, smaller statistical error.
- Disadvantage: inflexible, event-size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





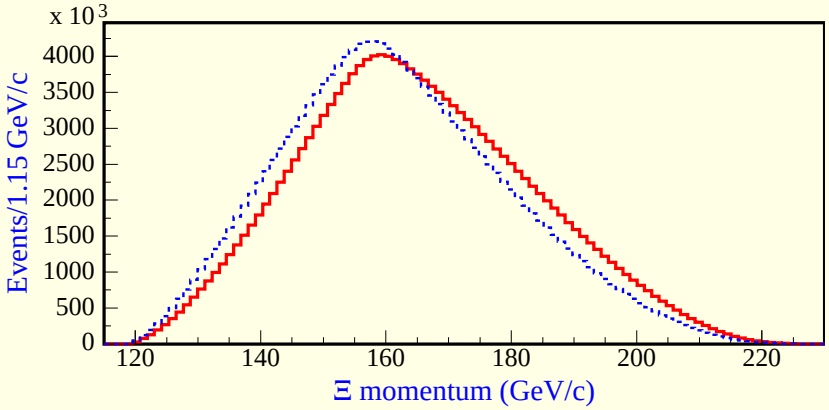
Ratio of proton to antiprotron momenta before and after weighting.

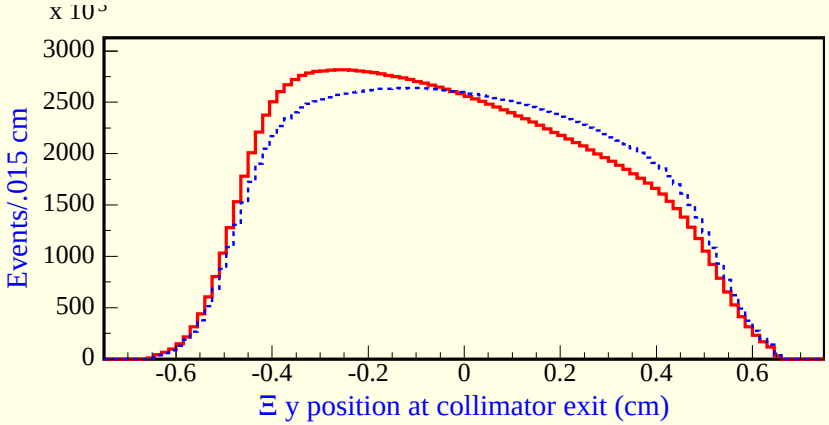
Momentum, y slope, y Position at Collimator Exit Weighted

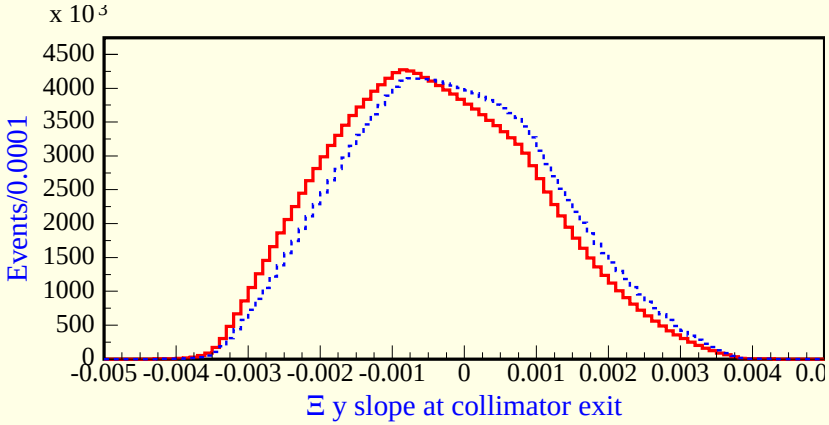
- Momentum magnitude, y slope and y position different.

Variable	# cells	Cell size
Ξ momentum	100	2.25 GeV/c
y position at collimator	100	0.013 cm
y slope at collimator	100	0.08 mrad

- Ξ^-: Solid lines
- $\overline{\Xi}^+$: Dashed lines

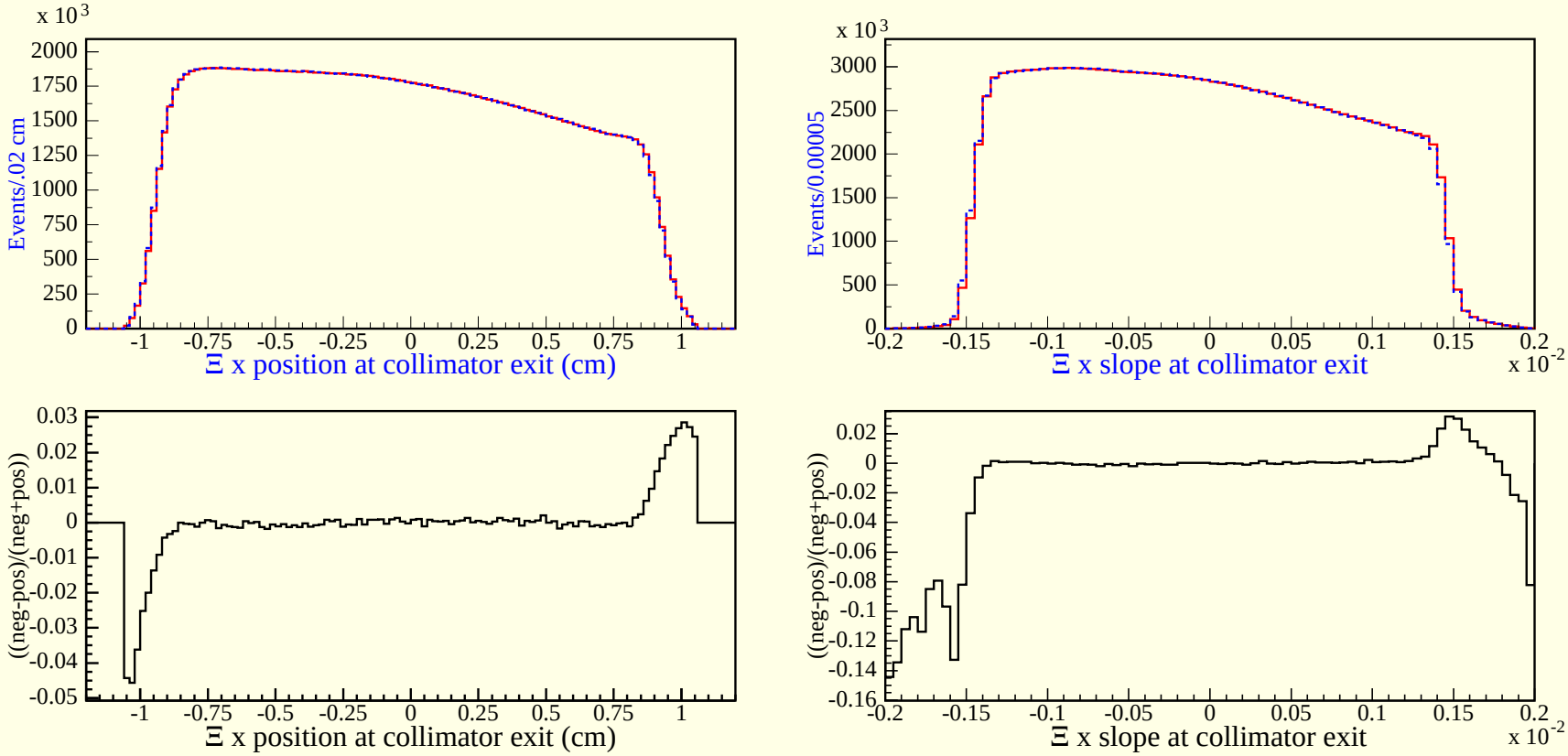






Ξ^- and $\overline{\Xi}^+$ x Slopes and Positions not Weighted

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



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:

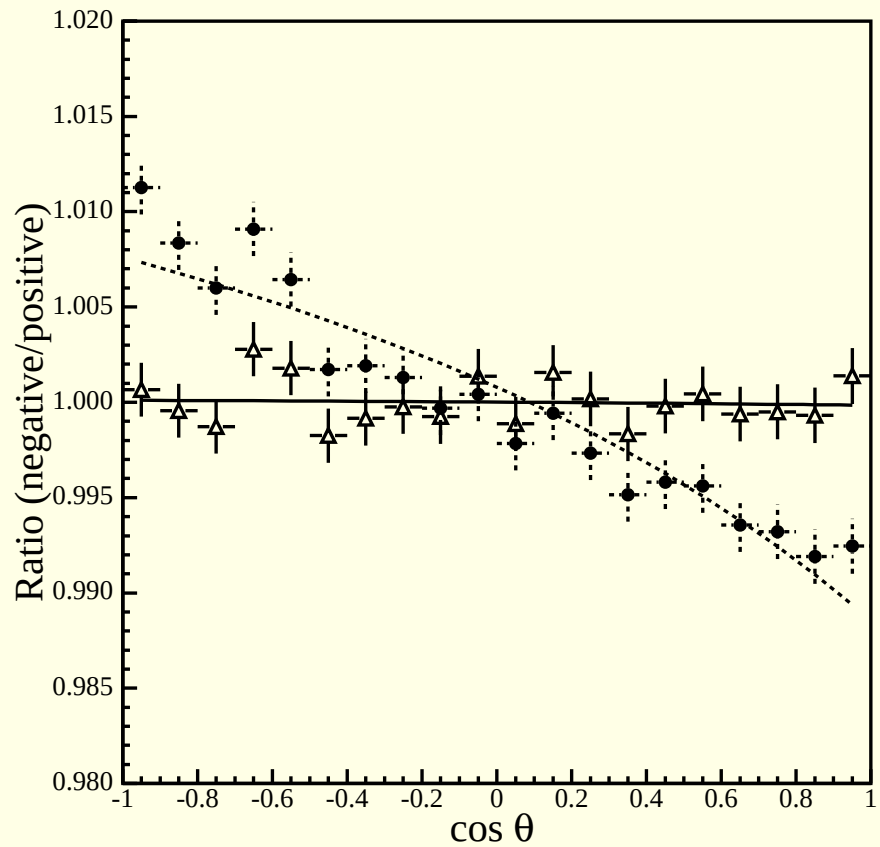
$$R(\theta,\delta) = C\frac{1+\alpha_\Xi\alpha_\Lambda\cos\theta}{1+(\alpha_\Xi\alpha_\Lambda-\delta)\cos\theta}$$

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!



Monte Carlo Tests

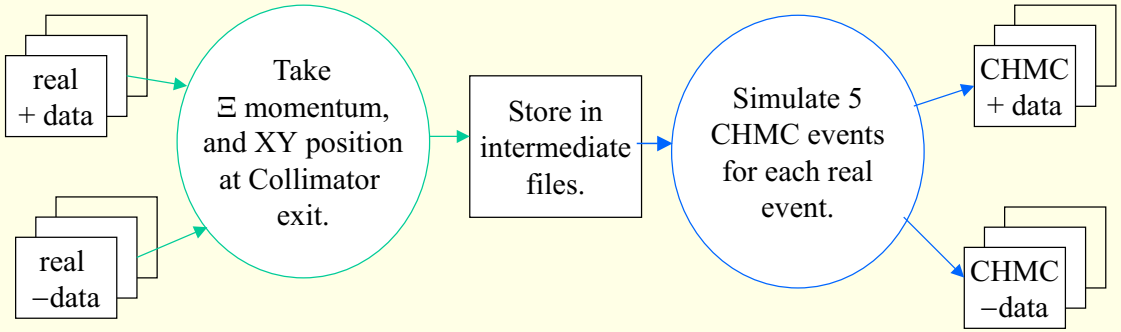
Important! Monte Carlo only used to:

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

Final result has no Monte Carlo dependence!

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

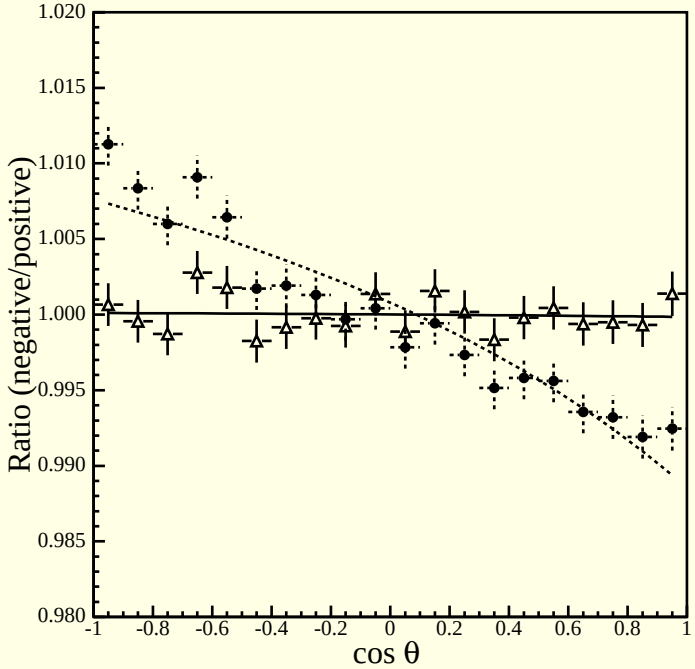
- Take Ξ, $\vec{p}$, x and y from real data at exit of collimator ⇒ CHMC (Cascade Hybrid Monte Carlo).
- Run on Fermilab farms.



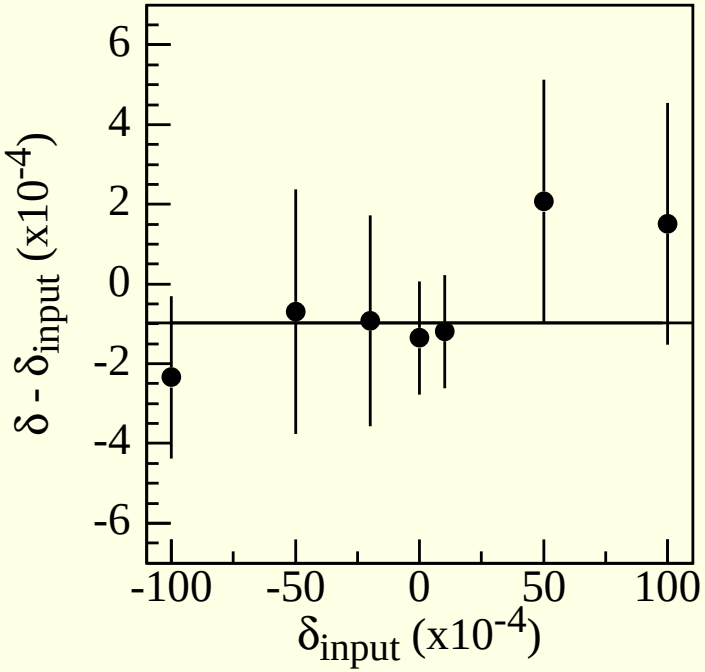
Monte Carlo Results

With an input $\delta = 0$:

$$\delta = (-1.35 \pm 1.41) \times 10^{-4}$$
$$A_{\Xi\Lambda} = (2.31 \pm 2.41) \times 10^{-4}$$
$$\chi^2/\mathrm{ndf} = 0.79$$

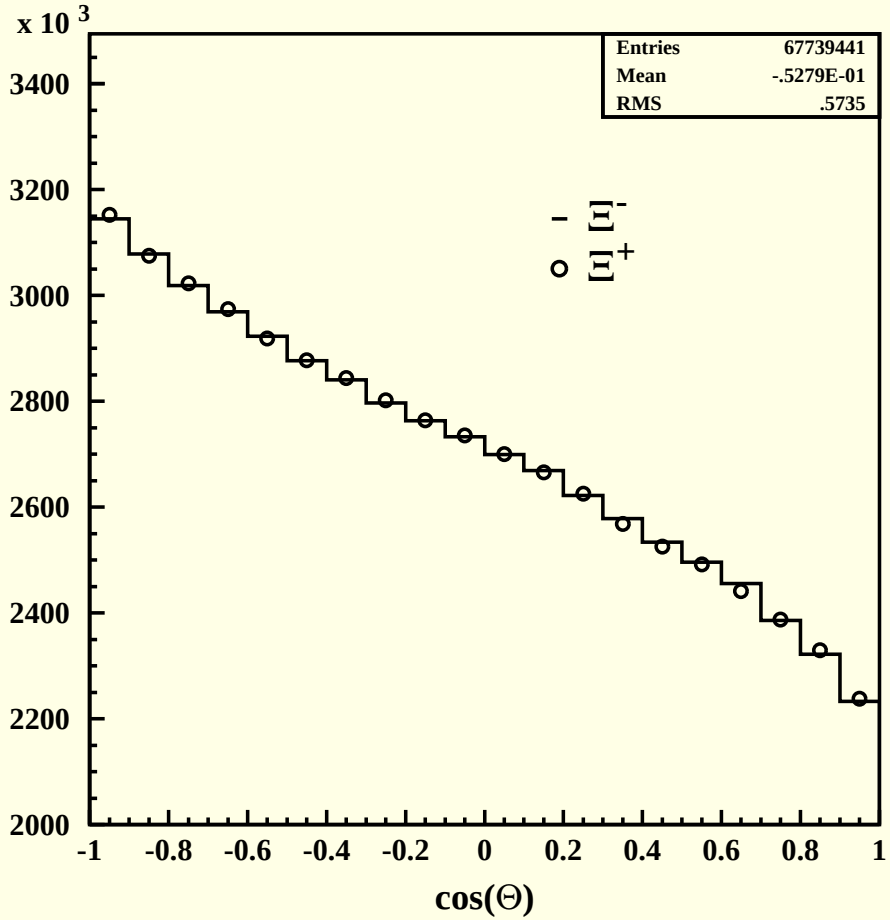


Proton $\cos\theta$ distributions, weighted and unweighted.



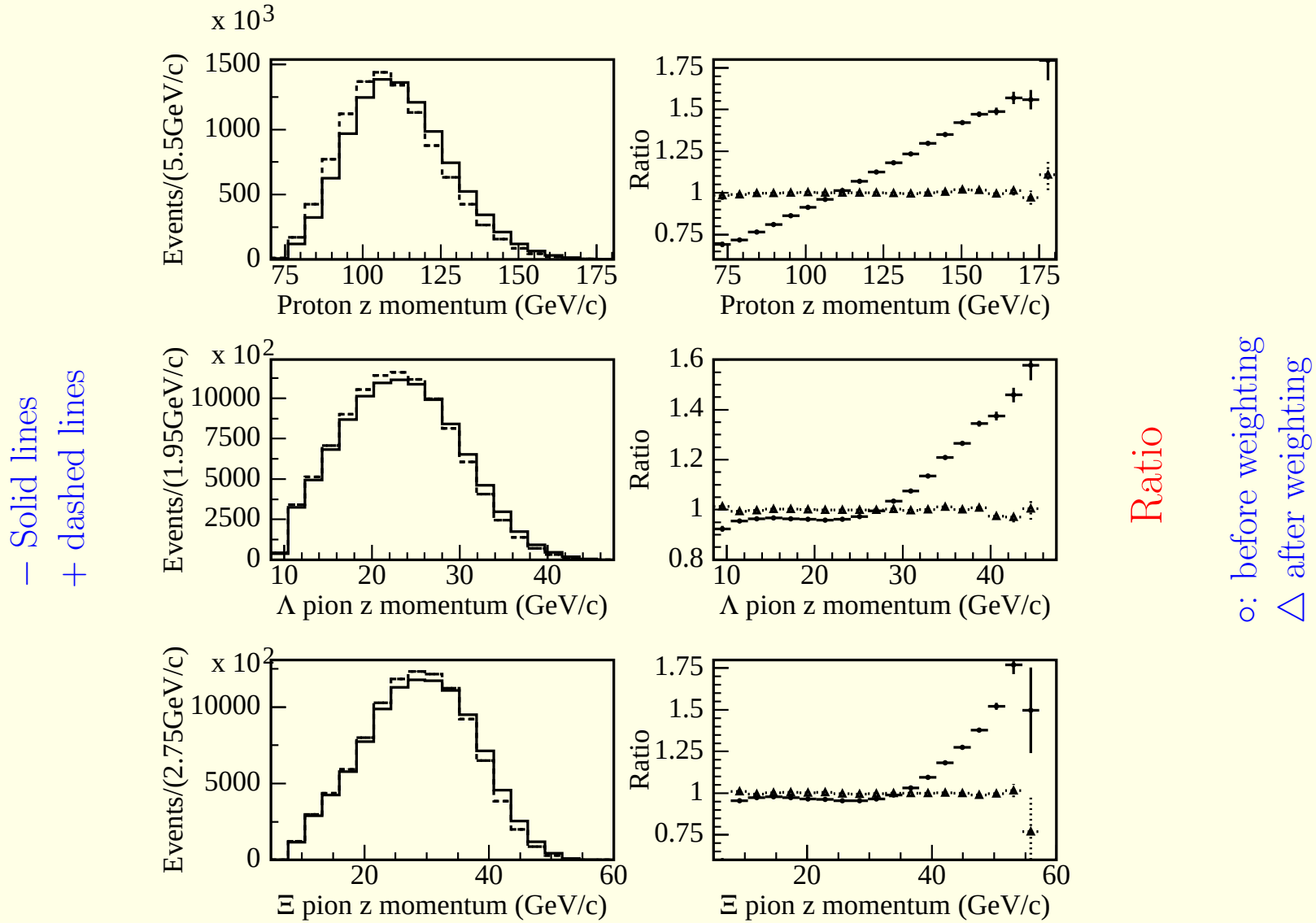
Difference between input and measured asymmetry δ as a function of input δ.

The raw proton and anti-proton cos(θ) distributions

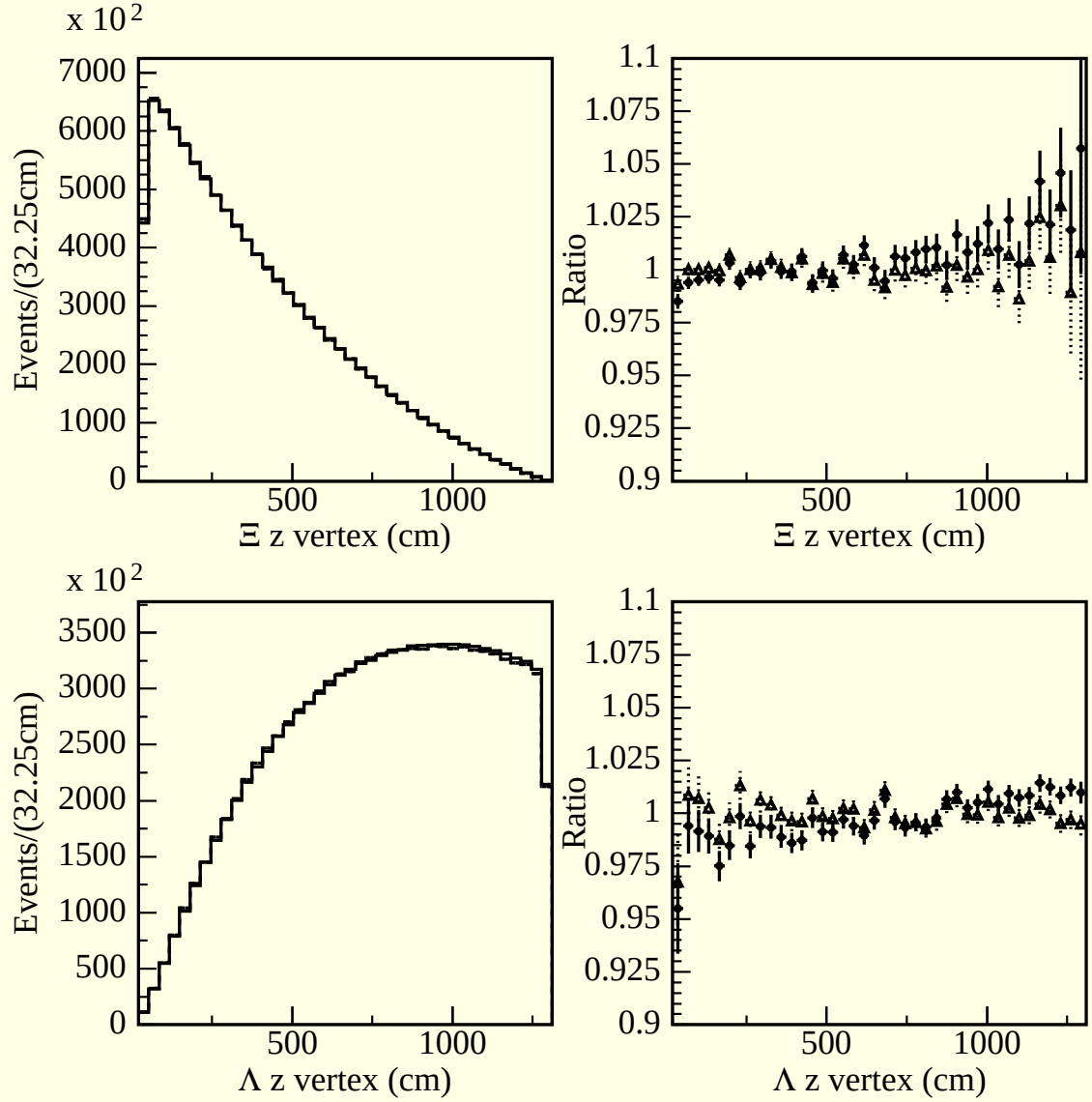


- From the farm analysis.
- No acceptance corrections have been made.
- The two momenta distributions have not been normalized to each other.

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



Λ and Ξ Decay Vertices Before/After Weighting



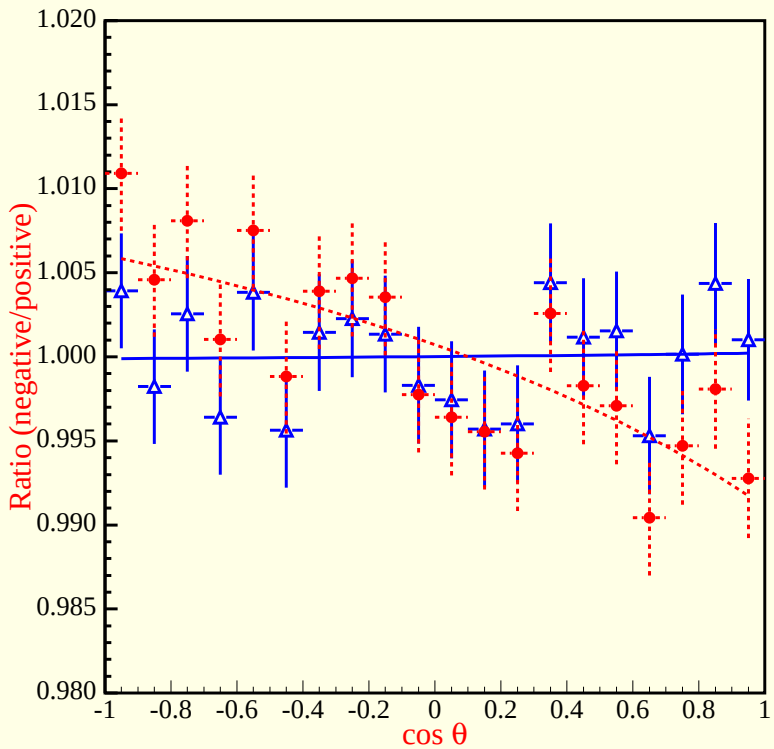
− Solid lines
+ dashed lines

Ratio

o: before weighting
△ after weighting

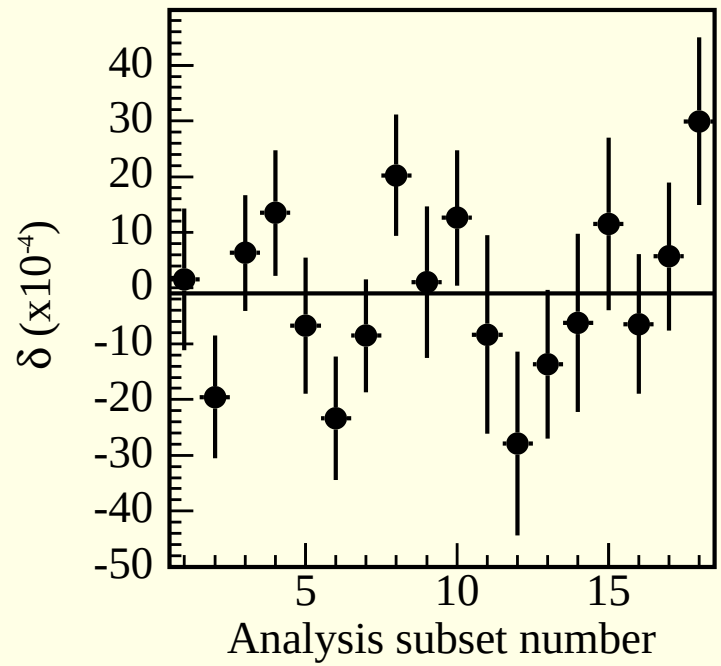
The CP Asymmetry $A_{\Xi\Lambda}$ from Weighting Method

- Data broken up into 18 sets.
- No acceptance corrections.
- No efficiency corrections.



Proton $\cos\theta$ ratio from Analysis Set 1

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



Weighted average of all 18 data sets:

$$\delta = (-0.9 \pm 3.0) \times 10^{-4}$$
$$A_{\Xi\Lambda} = (\ 1.5 \pm 5.1) \times 10^{-4}$$

$\chi^2/\mathrm{ndf} = 1.4$

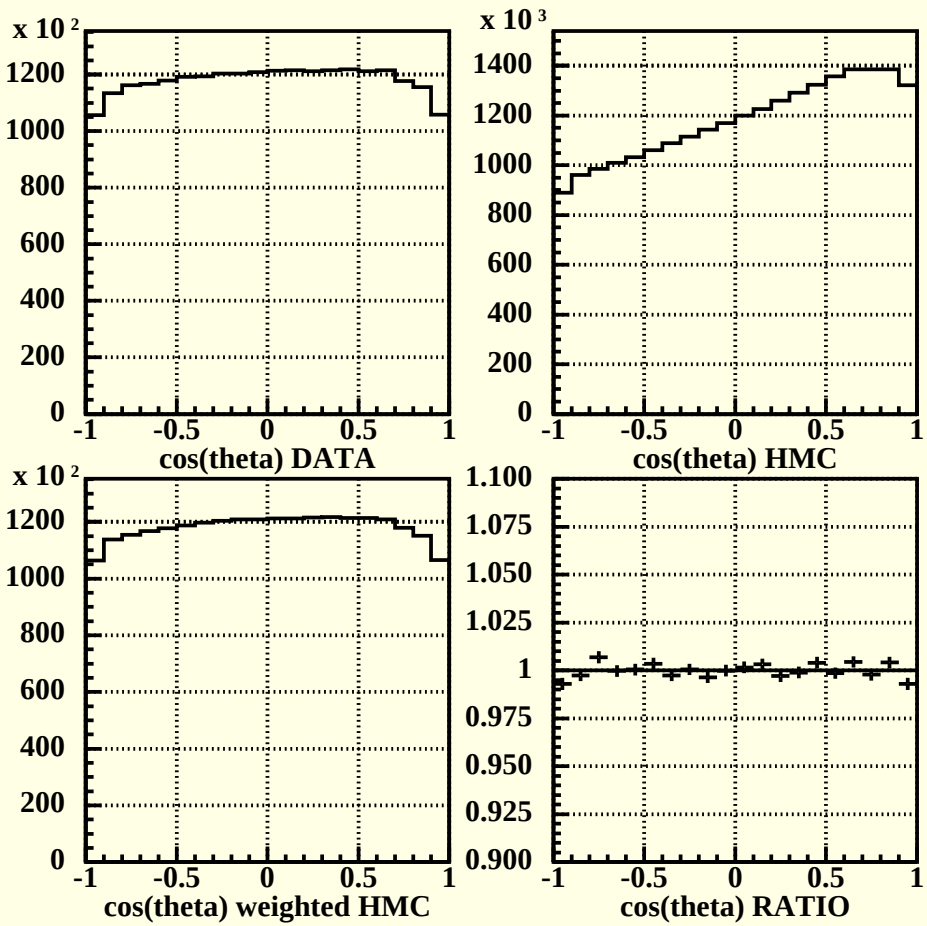
The CP Asymmetry $A_{\Xi\Lambda}$ from HMC Method

- Use real Λ decay vertex for Monte Carlo (HMC) events.
- Generate isotropic Λ decay HMC events and then weight by

$$W(\alpha_\Lambda\alpha_\Xi) = \frac{1+\alpha_\Lambda\alpha_\Xi\cos\theta_{\rm HMC}}{1+\alpha_\Lambda\alpha_\Xi\cos\theta_{\rm real}}$$

- Vary $\alpha_\Lambda\alpha_\Xi$ until best fit between data and MC is obtained.

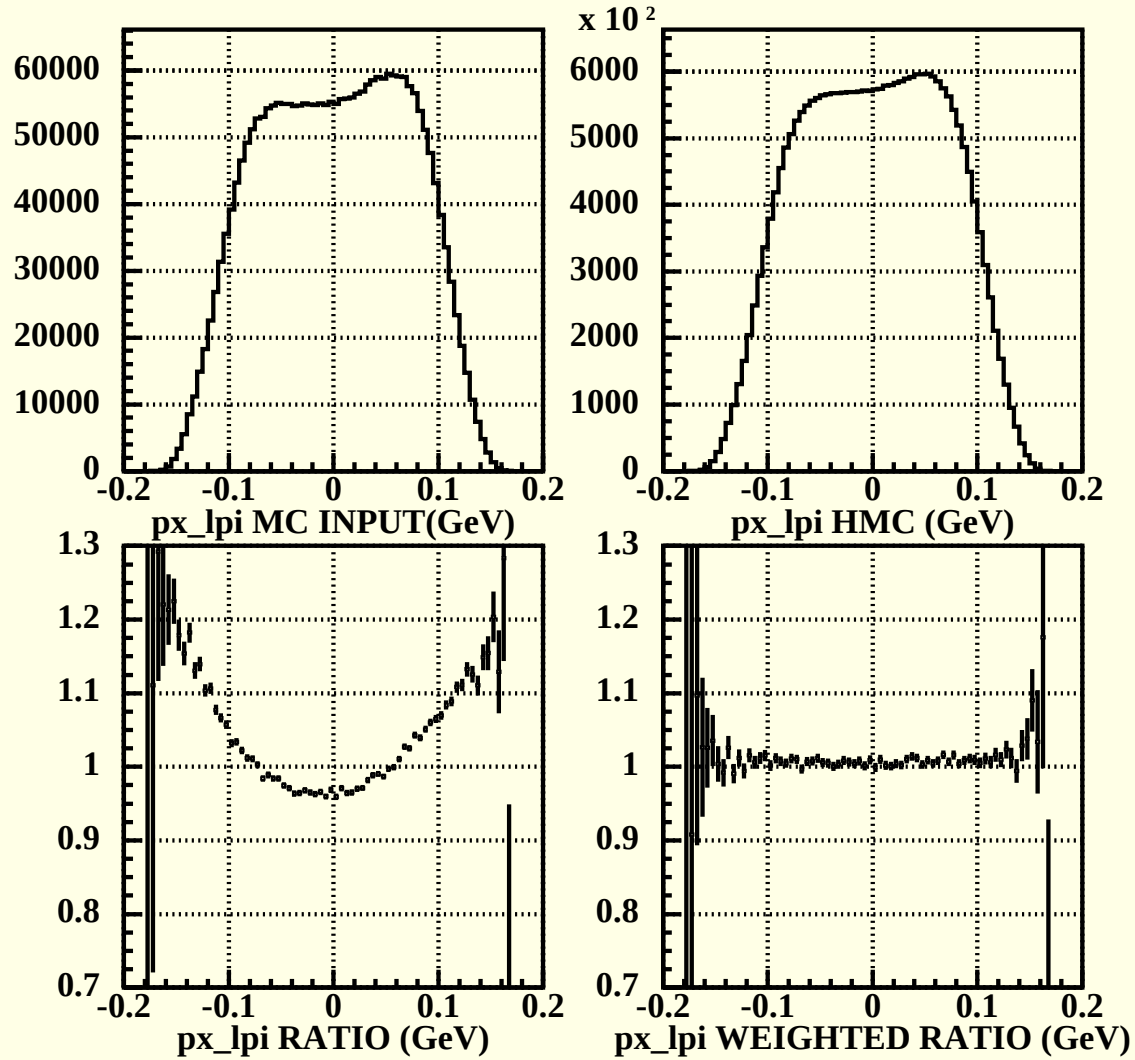
Monte Carlo verification of HMC



Input: $\alpha_\Lambda\alpha_\Xi = -0.2927$

Output: $\alpha_\Lambda\alpha_\Xi = -0.2953$, $\chi^2 = 15/19$ dof.

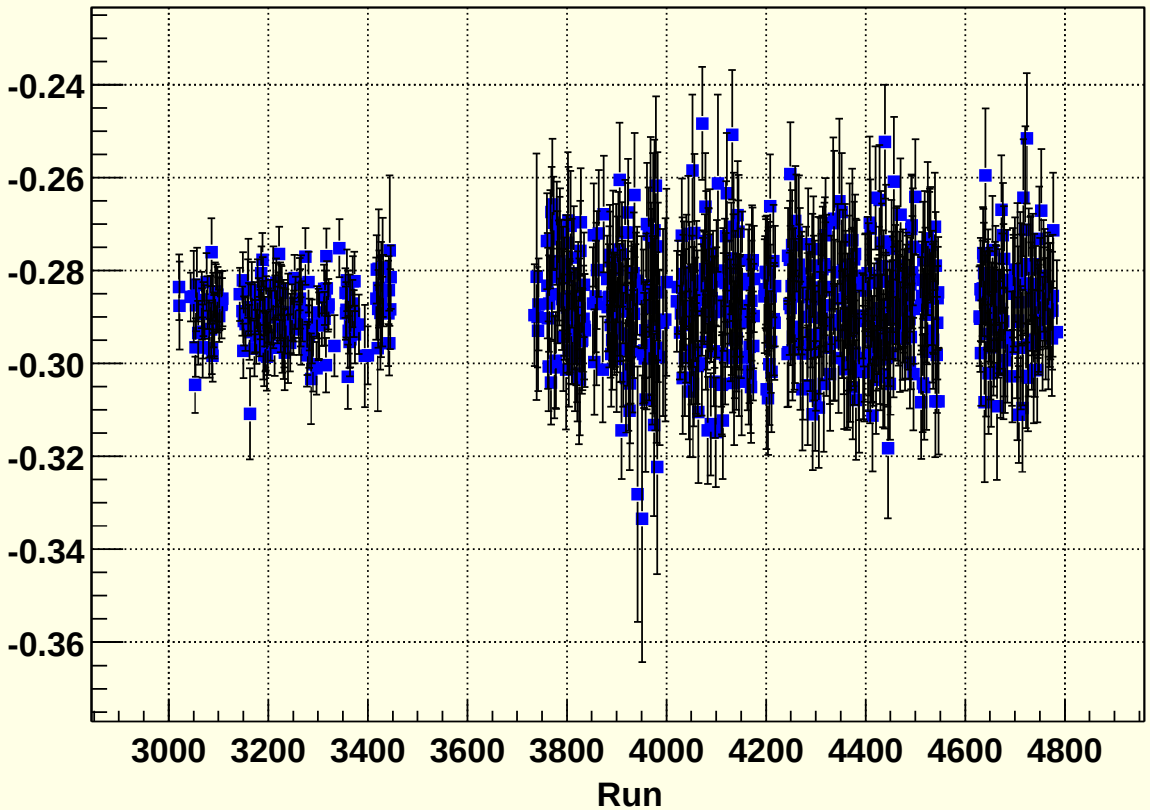
MC Weighted and Unweighted Λ-pion p_x



- Momentum $p - x$ of π_Λ weighted with previously established value of $\alpha_\Lambda \alpha_\Xi$.

HMC Measurement of $\alpha_\Lambda \alpha_\Xi$ vs Run

- Prescaled selection of entire 1997 and 199 data set:
  - 15×10^6 Ξ^-
  - 30×10^6 $\bar{\Xi}^+$



Average $\alpha_\Lambda \alpha_\Xi = -0.2880 \pm 0.0004$ (stat.) $\chi^2 = 26/19$ dof

Systematics

Any effect which adds or subtracts events unequally from the Ξ^- and $\overline{\Xi}^+$ proton and antiproton $\cos\theta$ distributions will cause a false asymmetry **if not corrected for**.

There are several classes of biases.

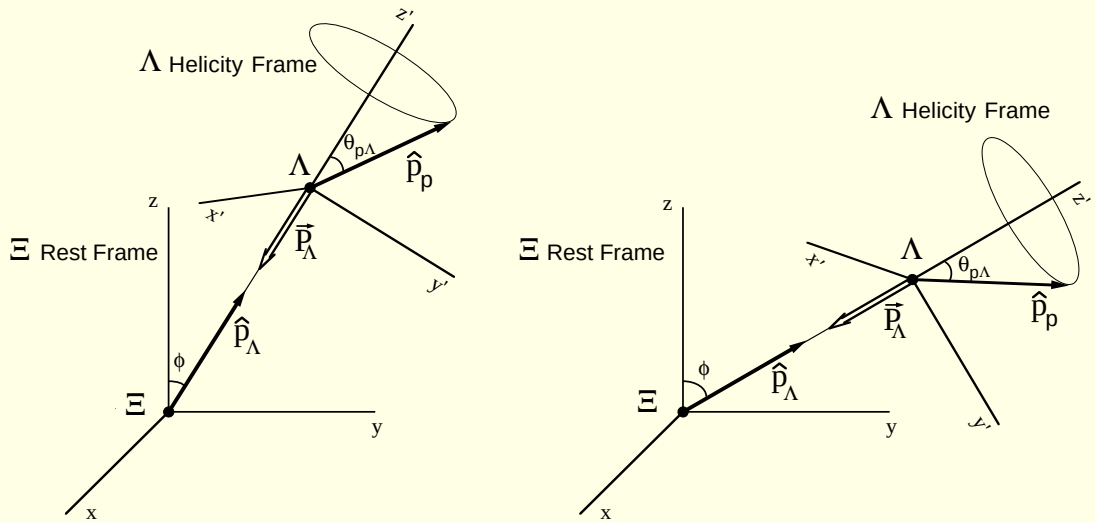
1. Acceptance differences:
   - Differences in the Ξ^- and $\overline{\Xi}^+$ momentum and position at the exit of the collimator.
   - Efficiency differences: hodoscope, trigger, and calorimeter.
   - Different reconstruction efficiencies due to different interaction cross sections with the material in the spectrometer between the π^- and π^+ and between the p and $\overline{p}$.
2. Momentum differences.
   - Differences in the spectrometer magnetic fields.
   - Effect of Earth's magnetic field.
3. Different Ξ^- and $\overline{\Xi}^+$ polarization.
   - This means that the Λ is no longer found in a simple helicity state with the polarization magnitude given by α_Ξ, but rather by:

$$\vec{P}_\Lambda = \frac{(\alpha + \vec{P}_\Xi \cdot \hat{p}_\Lambda)\hat{p}_\Lambda + \beta(\vec{P}_\Xi \times \hat{p}_\Lambda) + \gamma(\hat{p}_\Lambda \times (\vec{P}_\Xi \times \hat{p}_\Lambda))}{(1 + \alpha \vec{P}_\Xi \cdot \hat{p}_\Lambda)}$$

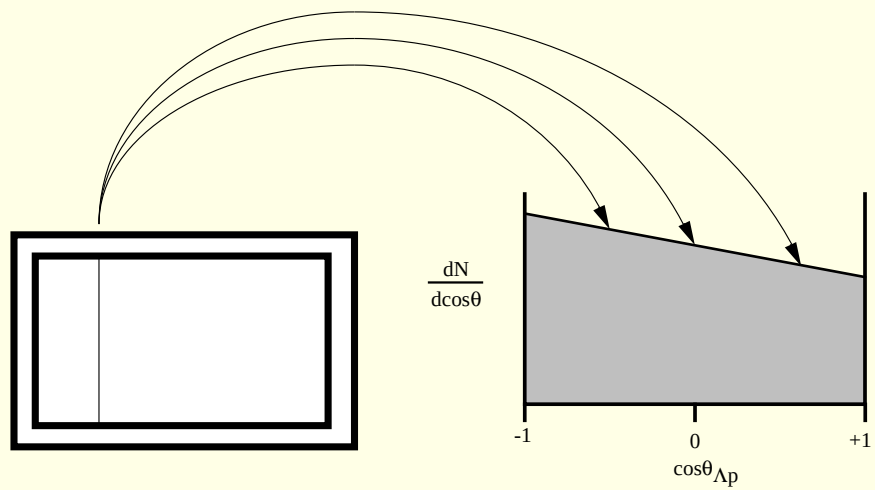
4. Different backgrounds in the two data samples.

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.



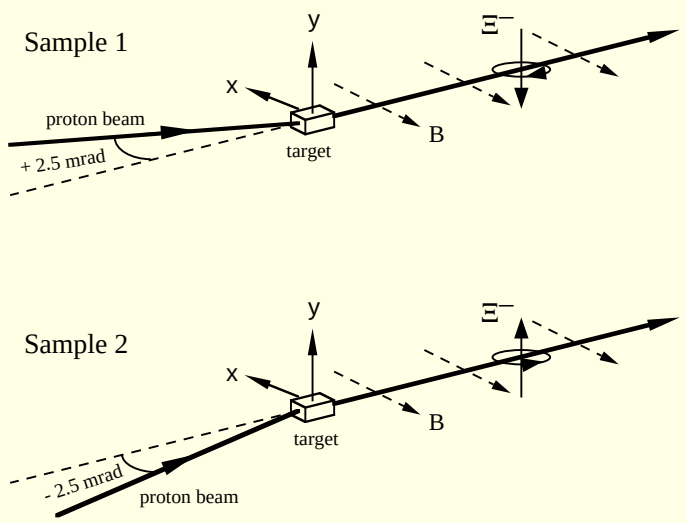
- Acceptance differences localized in a particular part of the apparatus do **not** map into a particular part of the proton (antiproton) $\cos\theta$ distribution.

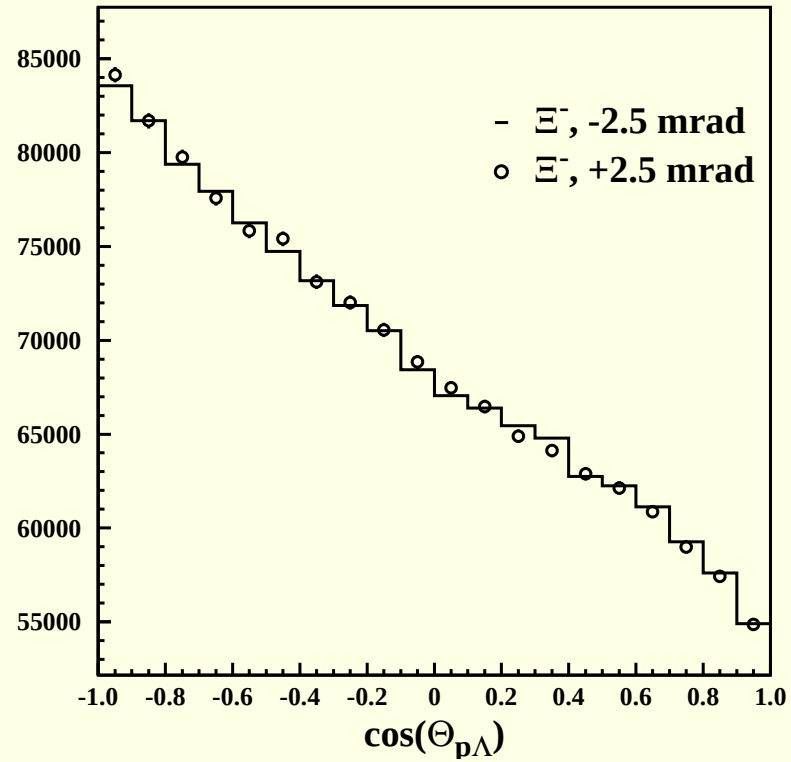


Important! Overall acceptance differences do not cause any biases.

Example: Power of Helicity Frame Analysis

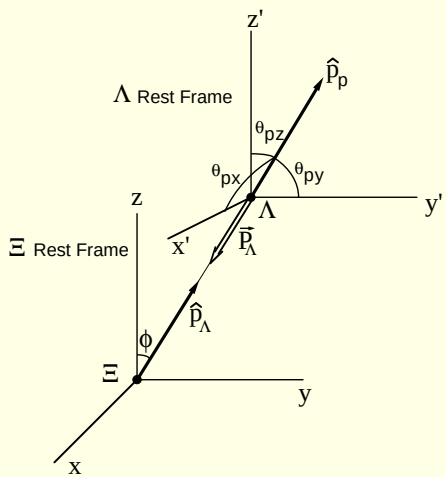
Ξ^- (-2.5 mrad) vs Ξ^- ($+2.5$ mrad)

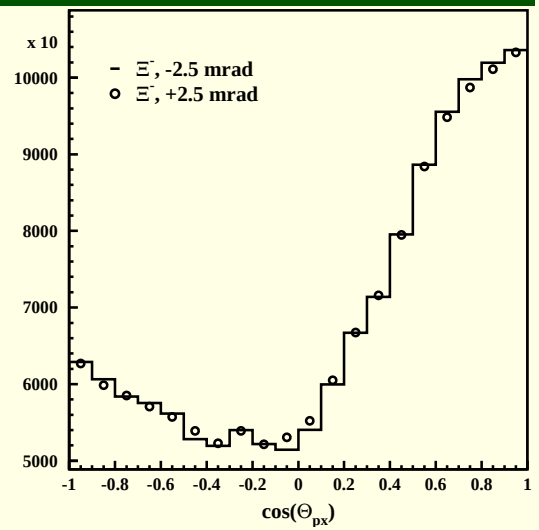




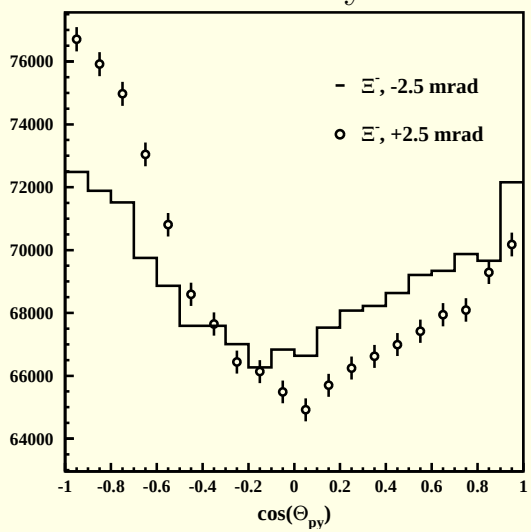
- No statistically significant effect at the several times 10^{-3} level, with no attempt of correction!

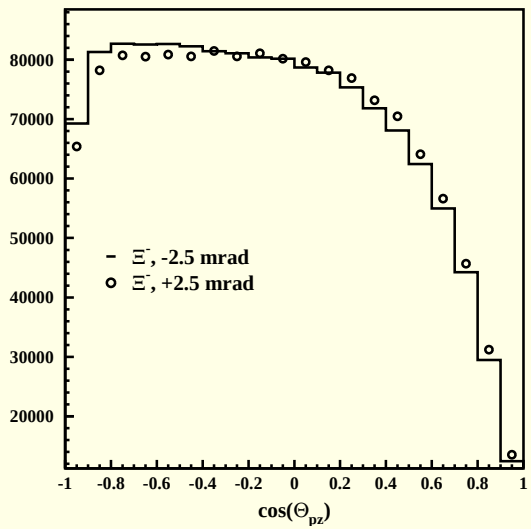
Effect of Targetting Angle on Fixed Axis Analysis





The fixed axis analysis frame.





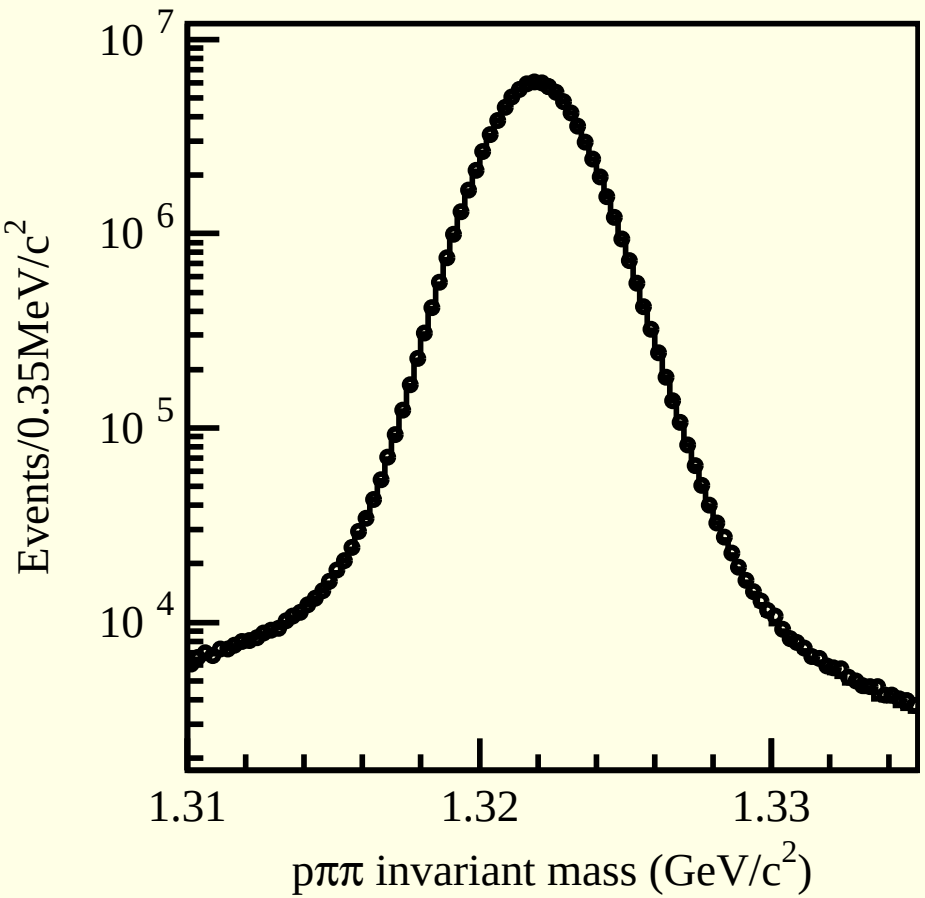
- Effect on the fixed-axis $\cos\theta_p$ distribution is huge!

Weighted Analysis Bias Error Summary

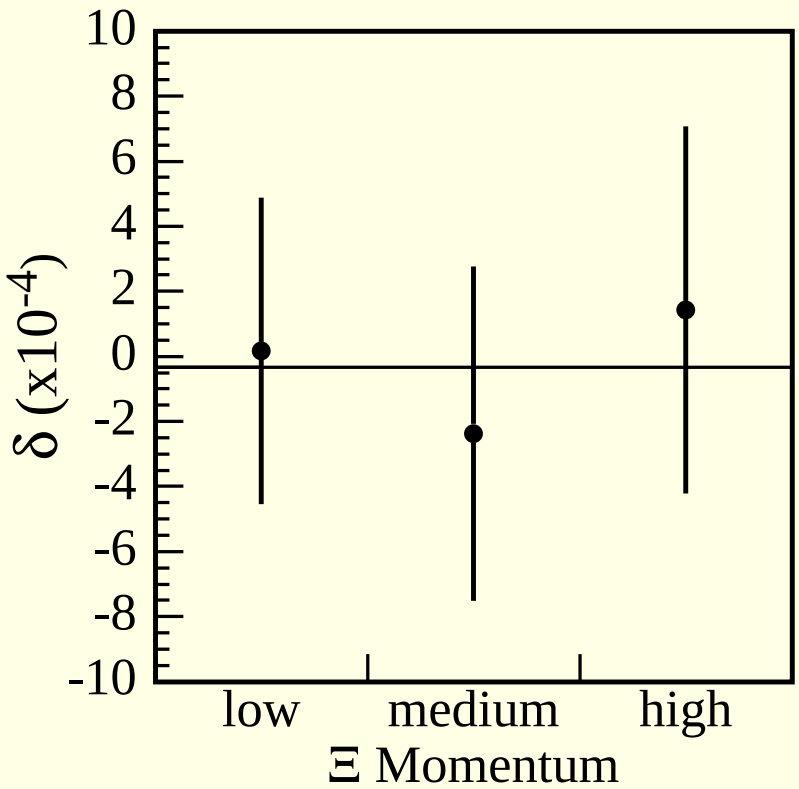
Systematic	Method	$\delta A_{\Xi\Lambda}(10^{-4})$
x position at collimator exit cut	Data	0.8
x slope at collimator exit cut	Data	1.4
Analysis magnet field	Data	1.2
PWC inefficiency	CHMC	negligible
Hodoscope inefficiency	Data	0.3
Calorimeter inefficiency	CHMC	2.5
Background	Data	2.2
Bin size	Data	0.4
CHMC error	CHMC	2.0
Particle interaction differences	MC	0.9
Error on $\alpha\alpha_{PDG}$	Data	negligible
Polarization	MC	negligible
Earth's magnetic field	CHMC	negligible
Total systematic error		4.5

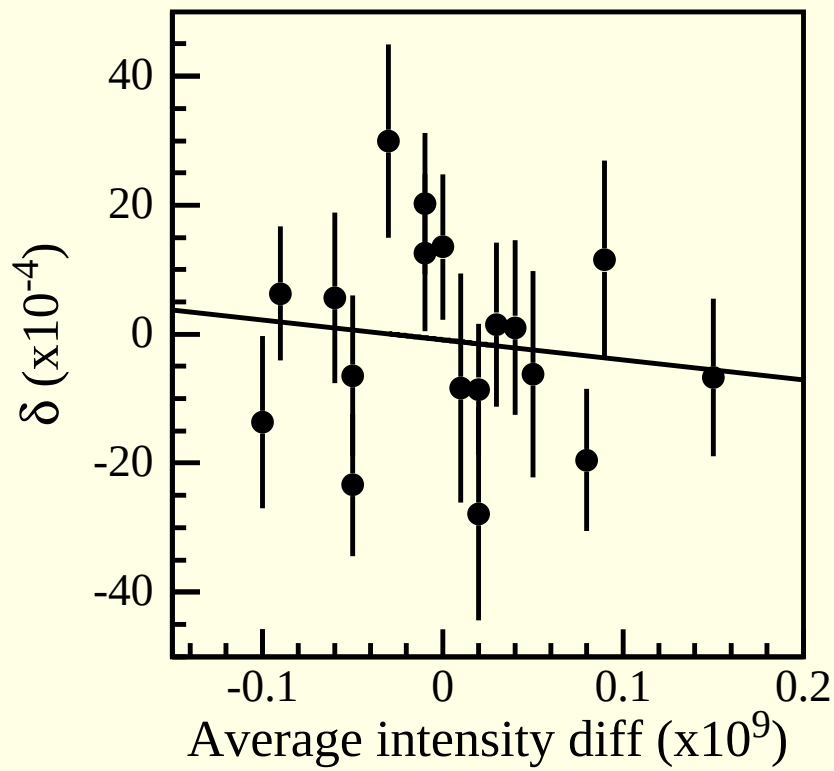
Background Bias

- Background fraction:
  Ξ^-: 0.43% (lines)
  $\bar{\Xi}^+$: 0.41% (circles)
- Regions:
  - Signal:
    1.3164 GeV/c^2– 1.3276 GeV/c^2.
  - Low mass:
    1.29 GeV/c^2– 1.31 GeV/c^2.
  - High mass:
    1.334 GeV/c^2– 1.354 GeV/c^2.
- 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:
  $A_{\Xi\Lambda}(back) = (2.2 \pm 0.5) \times 10^{-4}$



Asymmetry δ vs Momentum and Beam Intensity





Low: 120 GeV/c – 158 GeV/c
Middle: 158 GeV/c – 174 GeV/c
High: 174 GeV/c – 225 GeV/c

Preliminary Results from *CP* Violation Search

Weighting Technique:

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

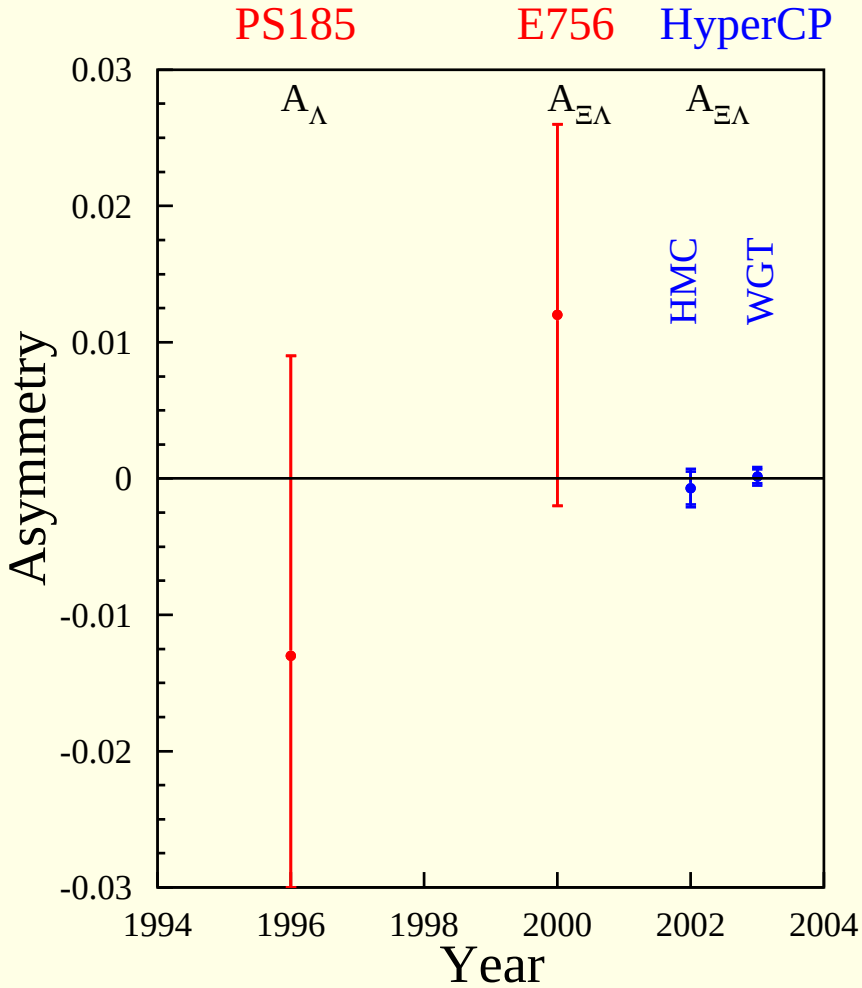
$$A_{\Xi\Lambda} = [1.5 \pm 5.1(\text{sta}) \pm 4.5(\text{sys})] \times 10^{-4}$$

HMC Technique:

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

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

- 20× improvement on previous result.



Measuring the Λ-π Strong Phase Shift

- This can be done by looking at the Λ decay distribution for **polarized** Ξ^- decays.
- For polarized Ξ^- decays the Λ is no longer found in a helicity state with magnitude α_Ξ, but has polarization:

$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad \text{unpolarized}$$

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

where:

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

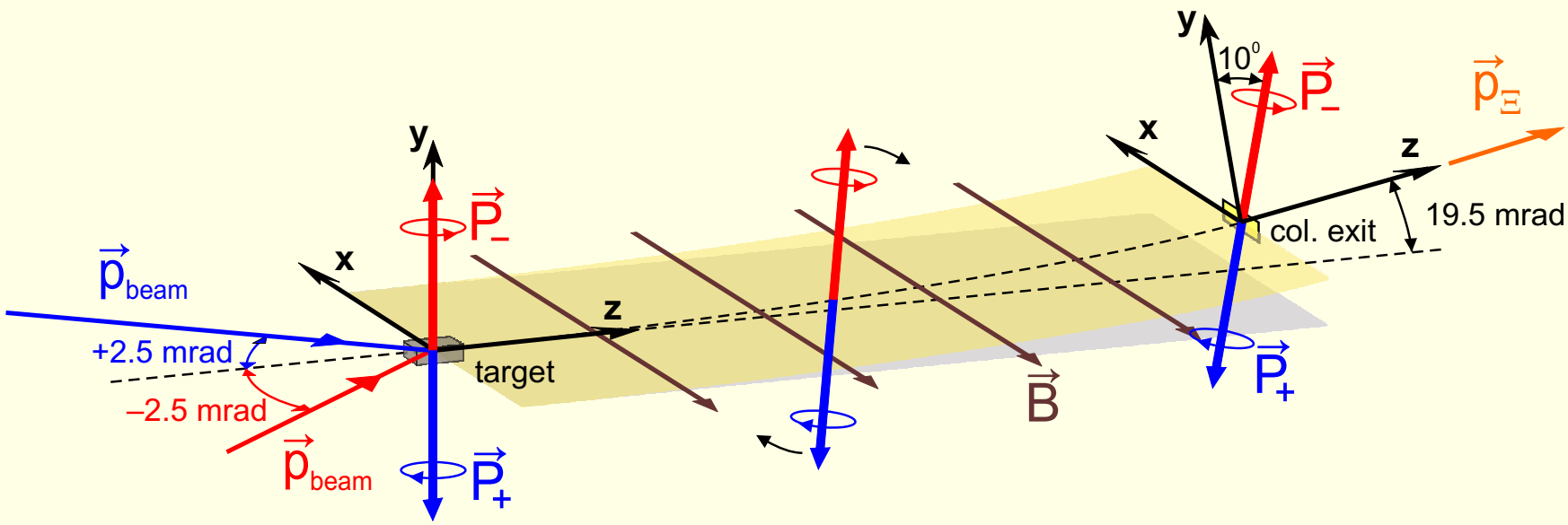
- Neglecting insignificant CP violation effects:

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

Polarized Data Taking

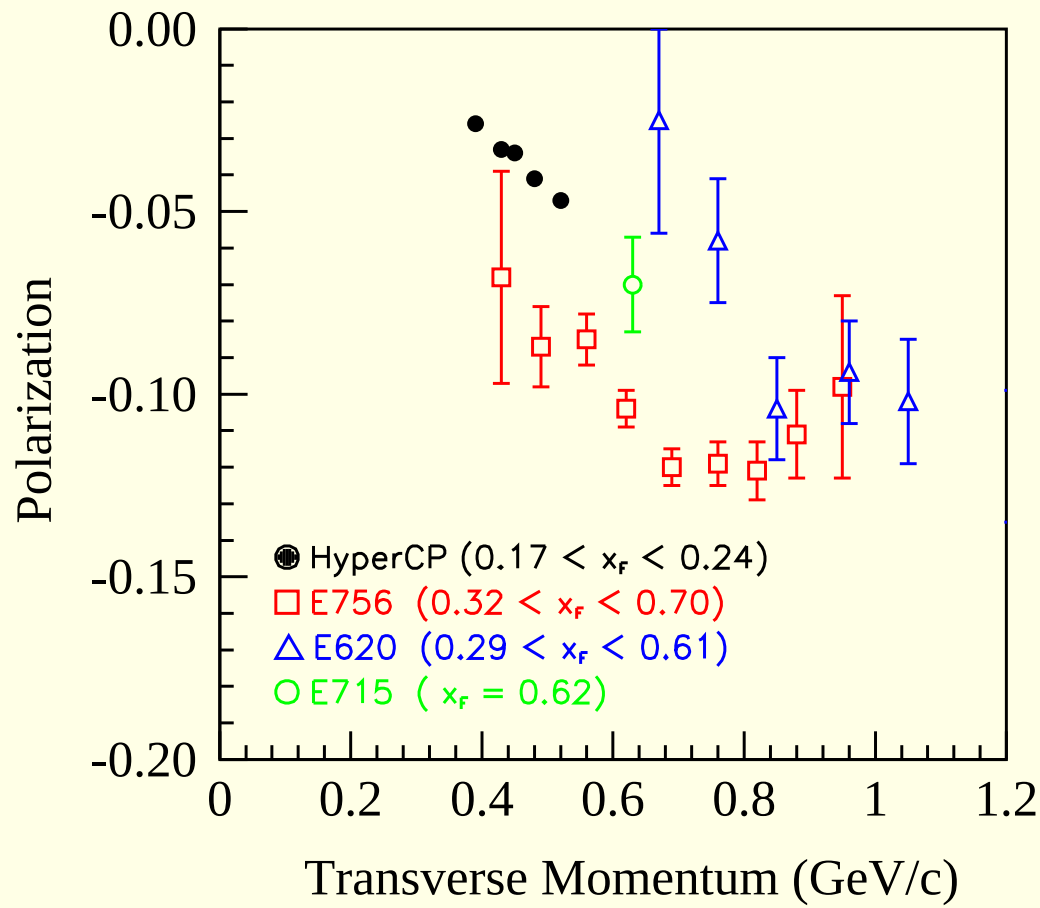
$$p + \mathrm{Cu} \rightarrow \Xi^- \Uparrow + \mathrm{X}$$

- *HyperCP*'s polarized data sample is data rich, but polarization poor.
  - 142 million polarized Ξ^- events
  - Mean polarizaton 3.6% @ $\langle p_T \rangle = 0.46$ GeV/c, $\langle x_F \rangle = 0.2$.
  - Max. targetting angle (± 2.5 mrad), and hence polarization, limited by beamline elements.



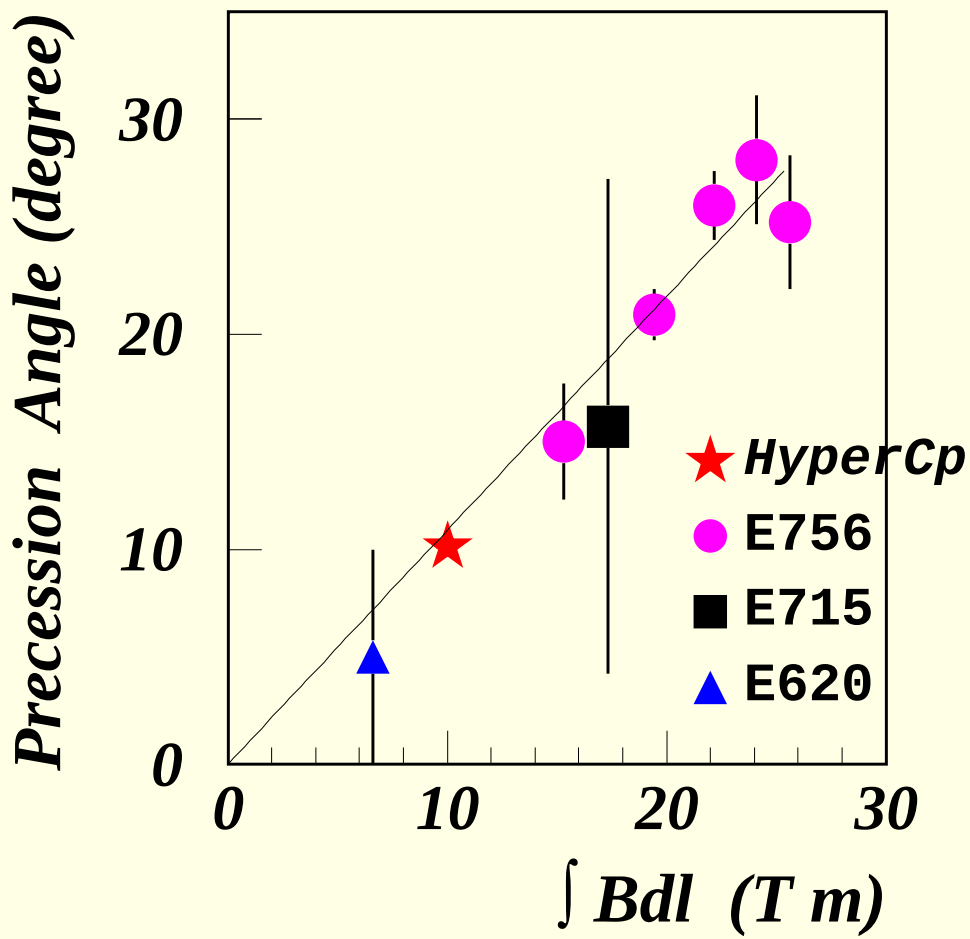
The Ξ^- Polarization

- Polarization extracted from the asymmetry in the Λ decay using a Hybrid Monte Carlo method.
- Bias cancelled by subtracting $+2.5$ mrad from -2.5 mrad asymmetry.
- Mean polarization: $\sim 3.6\%$ @ $\langle p_t \rangle = 0.46$ GeV/c $\langle x_F \rangle = 0.2$.
- Small polarization makes extracting β particularly difficult.



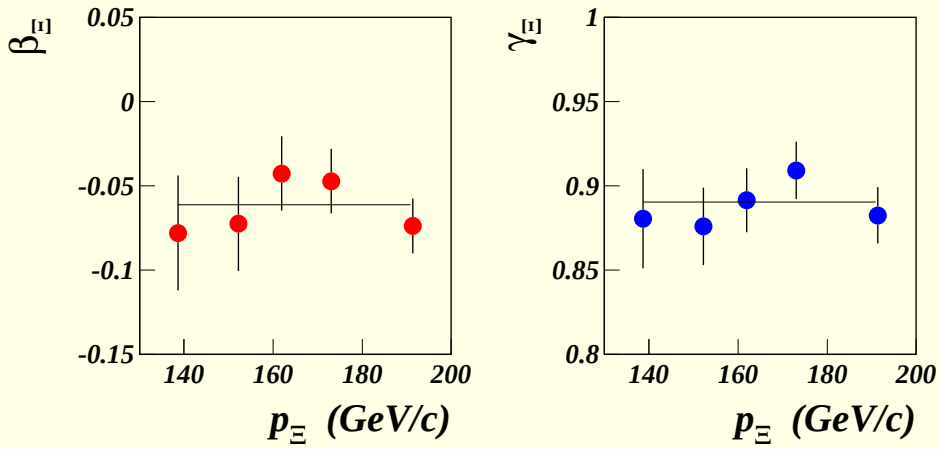
Ξ^- Precession Angle Consistent with Previous Measurements

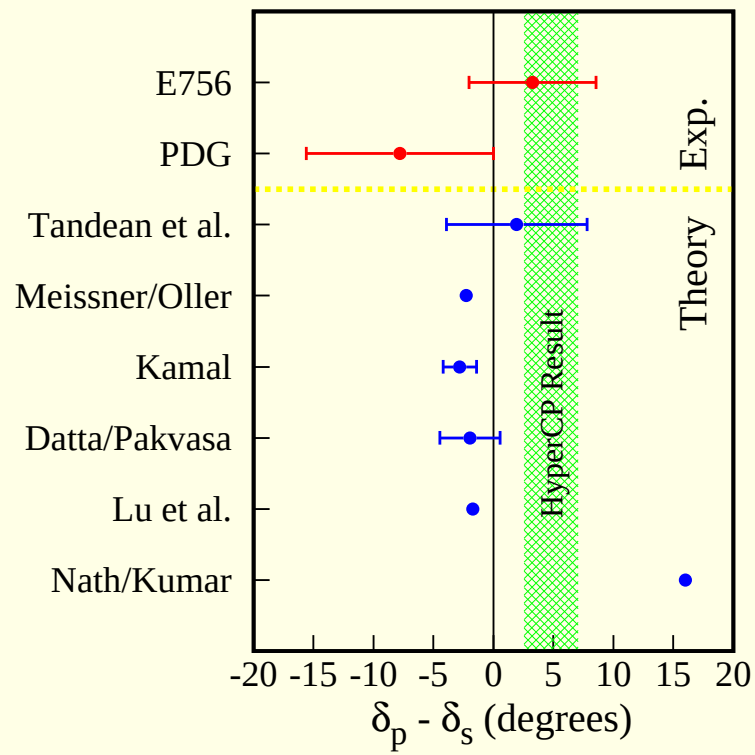
- $\mu_\Xi = (-0.65555 \pm 0.0056)\mu_N$ Consistent with PDG value.
- Small field integral precludes competetive measurement of μ_Ξ.



Preliminary Measurement of the Λ-π Phase Shift

$\beta_\Xi = -0.061 \pm 0.010^{+0.022}_{-0.019}$ $\gamma_\Xi = 0.890 \pm 0.010^{+0.011}_{-0.007}$





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

$$\delta_P - \delta_S = \tan^{-1}\left(\frac{\beta_\Xi}{\alpha_\Xi}\right) = (4.6 \pm 1.3^{+2.4}_{-2.8})^\circ$$

- 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.

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

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

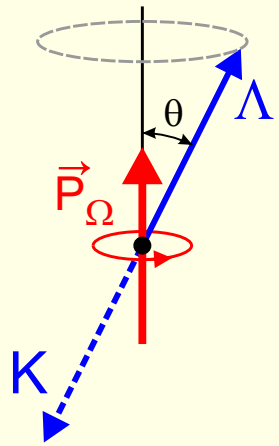
- Although spin-3/2, $\Omega^- \to \Lambda K^-$ decay goes much like the other hyperon two-body decays:

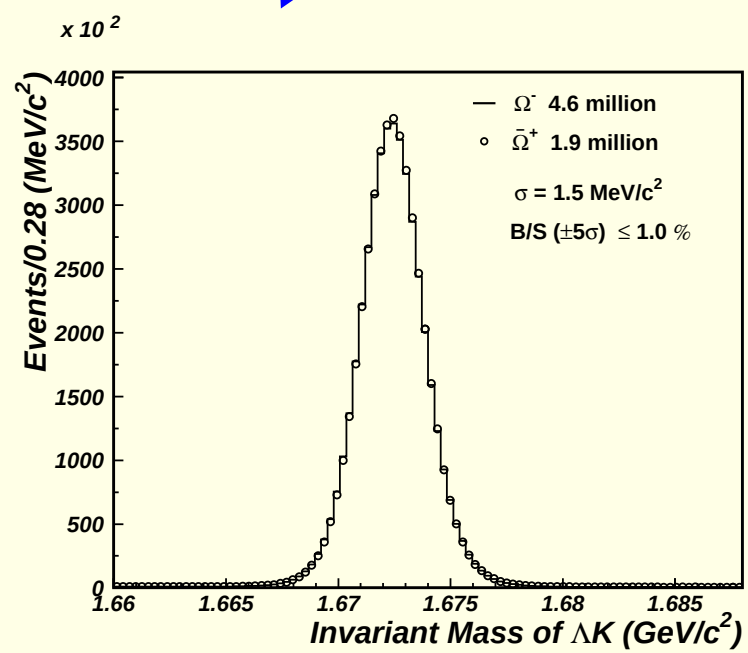
$$\frac{dP}{d\cos\theta} = \frac{1}{2}(1 + \alpha_\Omega P_\Omega \cos\theta)$$

- 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 searching for an asymmetry using a Hybrid Monte Carlo analysis in the Lambda Helicity Frame.
- Large data sample, little background.

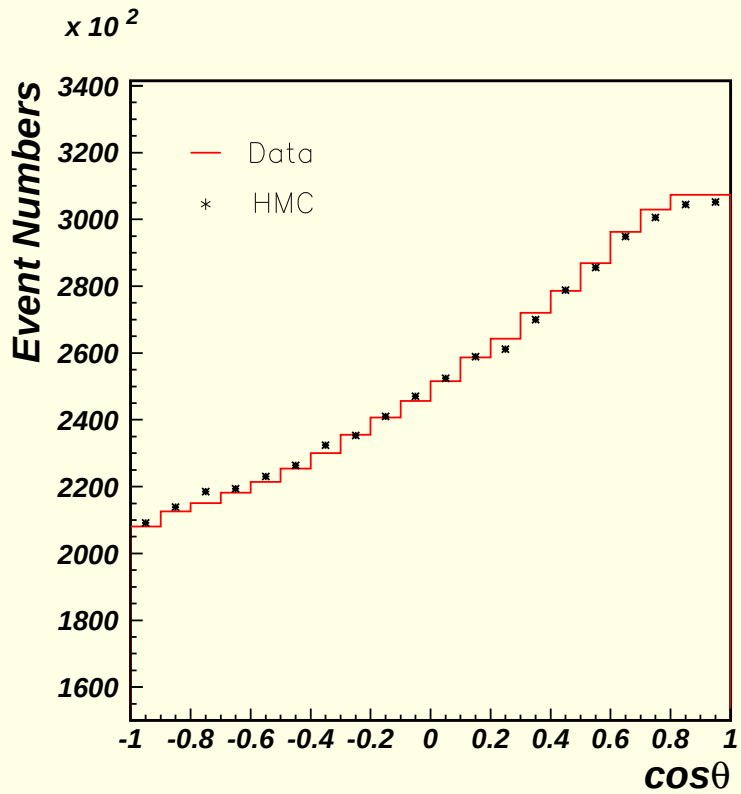




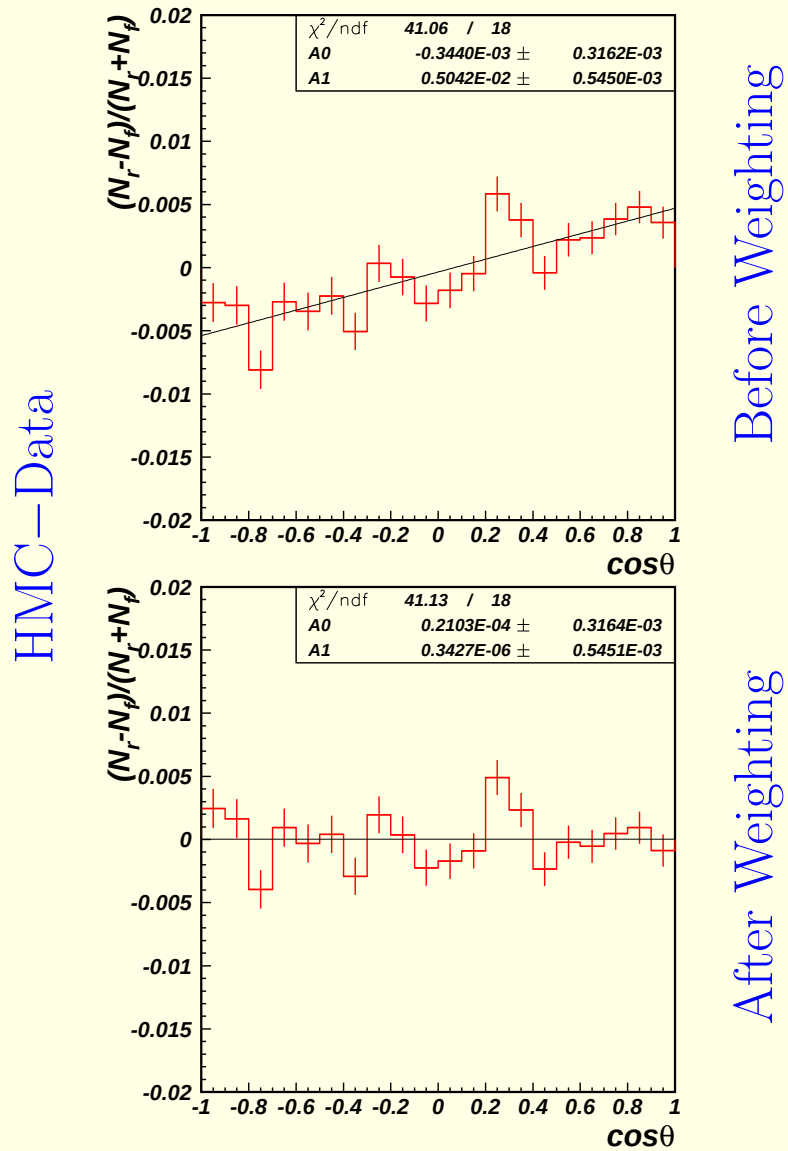
Extracting Proton $\cos\theta$ Slope

- HMC analysis using Λ helicity frame
- 1999 data
- Raw proton $\cos\theta$ fit:

$$S_m = (1.32 \pm 0.11) \times 10^{-2}$$

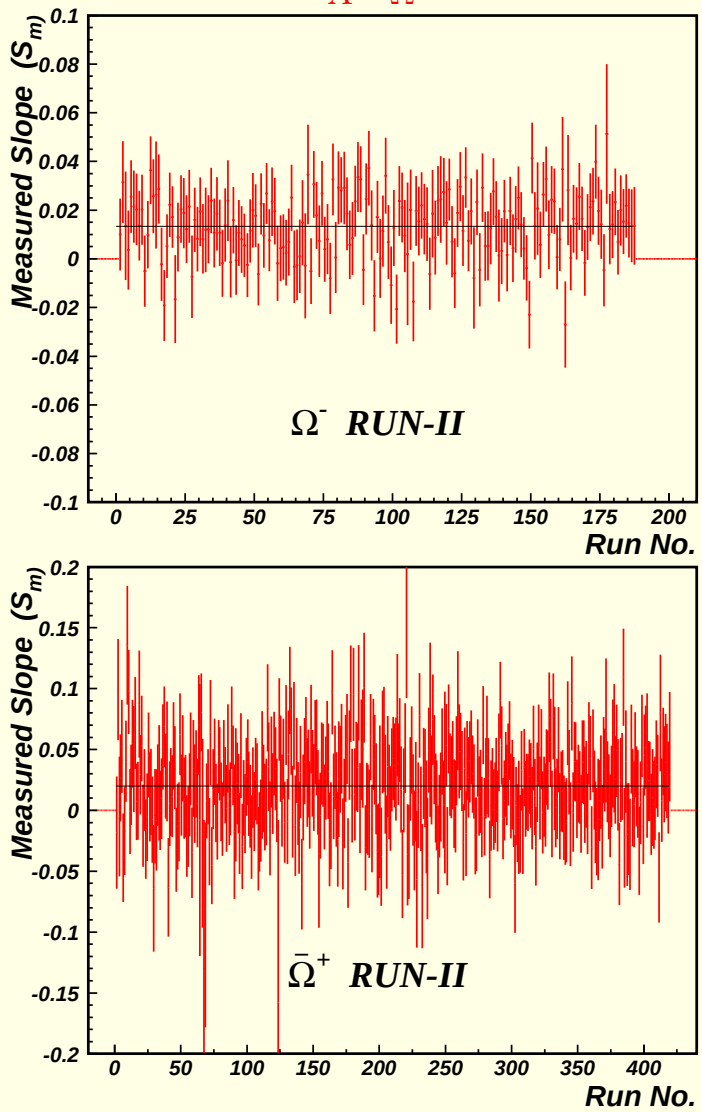


Proton $\cos\theta$ slope before weighting.



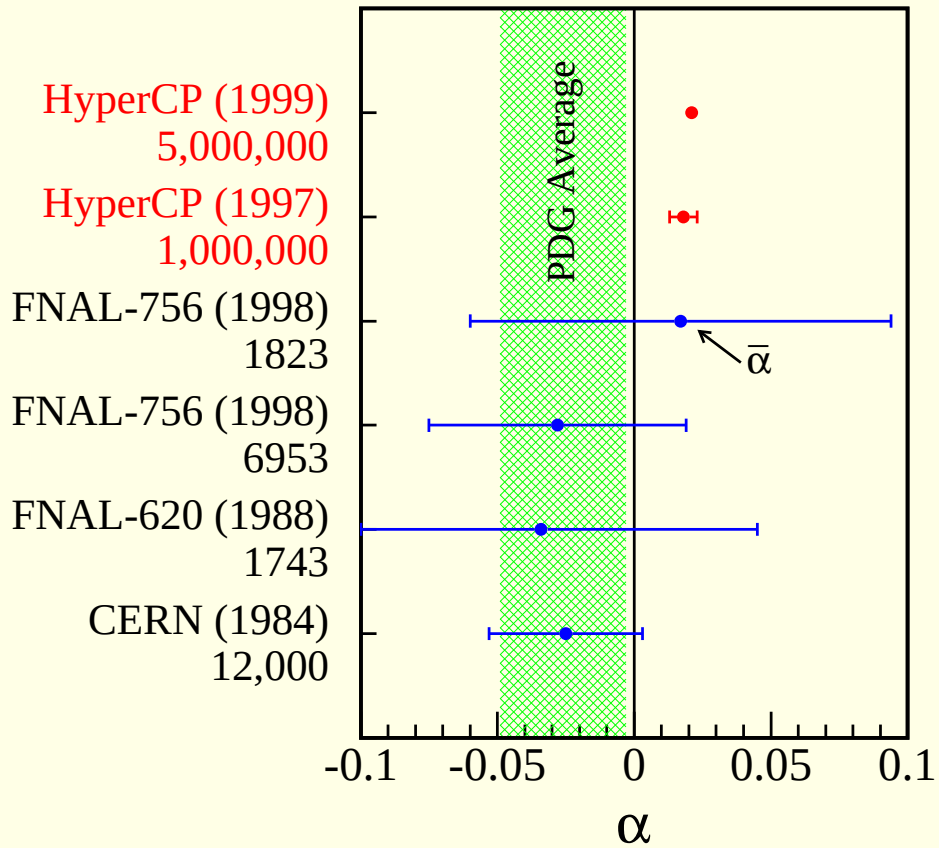
Preliminary Results

$\alpha_\Lambda \alpha_\Omega$



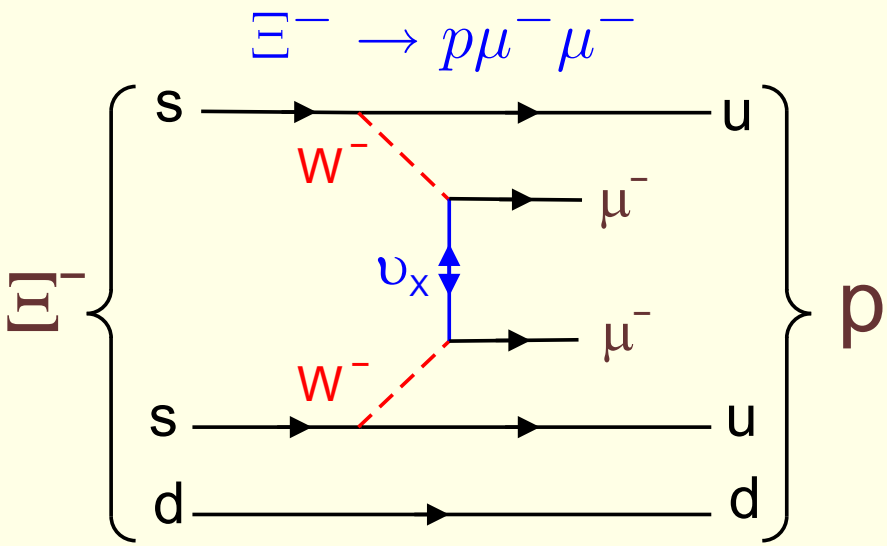
1999: $\alpha_\Omega = [2.01 \pm 0.17(\text{stat.})] \times 10^{-2}$

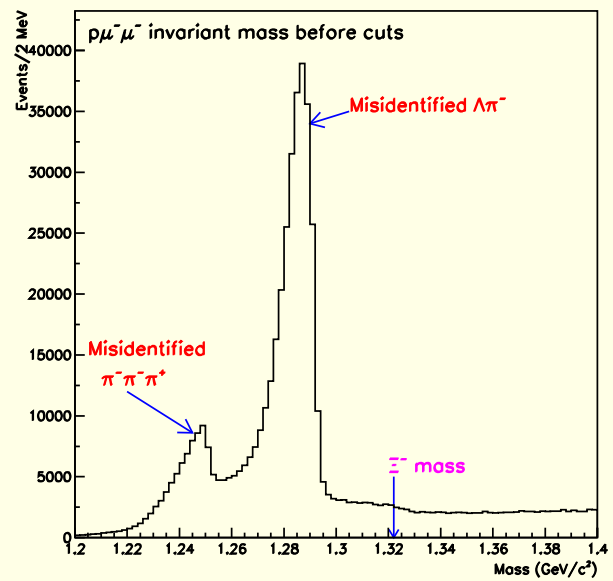
1997: $\alpha_\Omega = [1.84 \pm 0.46(\text{stat.})] \times 10^{-2}$



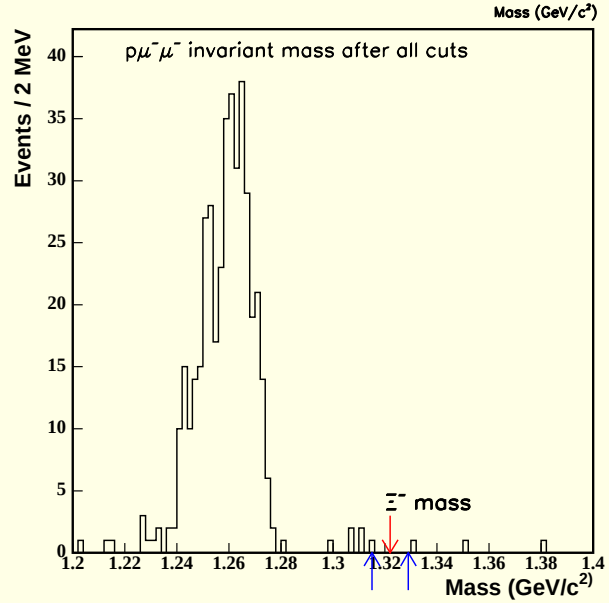
$\Leftarrow$ Can search for CP violation in $\Omega^-/\overline{\Omega}^+$ decays.

Search for Lepton Number Violation





Before cuts



After cuts

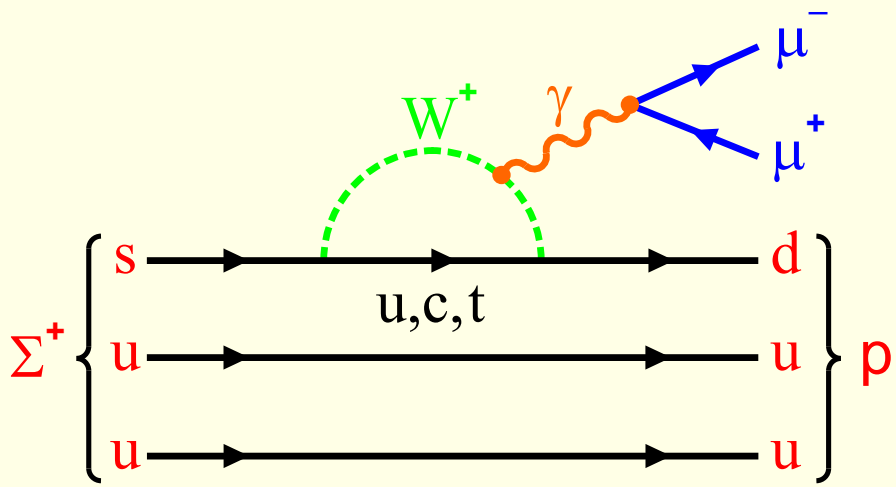
- Lepton number violating decay could imply existence of Majorana type neutrino.
- Not constrained by limits on neutrinoless double β decay.

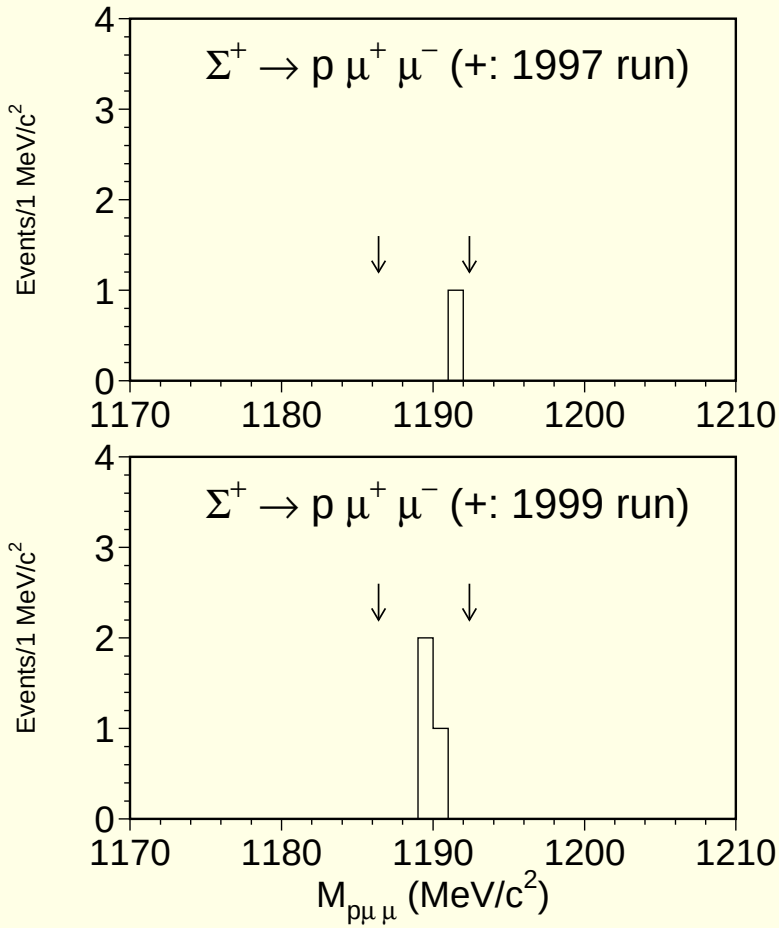
$$\frac{B(\Xi^- \to p\mu^-\mu^-)}{B(\Xi^- \to \Lambda\pi^-)} < 1.06\times10^{-7} \text{ @ } 90\% \text{ CL}$$

- PDG limit : $< 4\times10^{-4}$ @ 90% CL
  (Littenberg and Shrock)
- Preliminary result.

Search for FCNC in Hyperon Decays

$\Sigma^+ \to p\mu^+\mu^-$





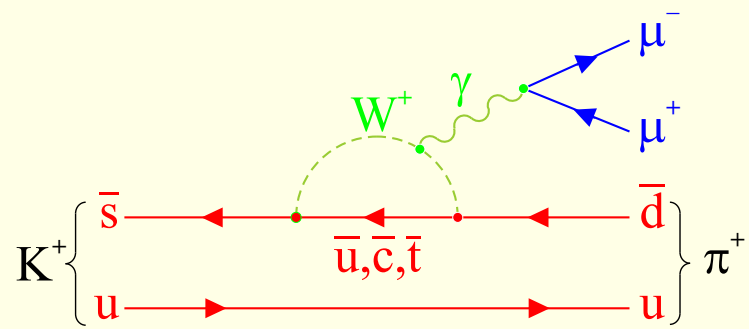
- No observation to date of FCNC in Baryon sector.
- $B(\Sigma^+ \to pe^+e^-) < 7\times10^{-6}$ (PDG)
- Theory: $\Sigma^+ \to p\mu^+\mu^- / pe^+e^- < 1/100$.

$$\frac{B(\Sigma^+ \to p\mu^+\mu^-)}{B(\Sigma^+ \to \text{all})} \approx 3\times10^{-8}$$

- Very Preliminary!

Measurement of the Branching Ratio $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$

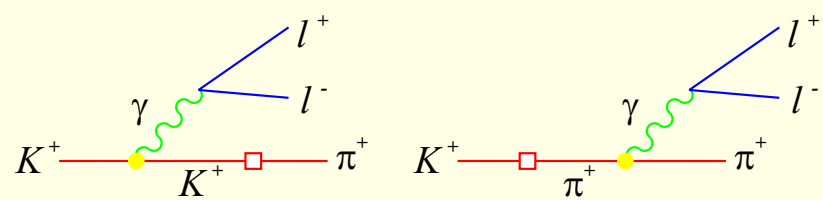
- FCNC decay.



- Test of Chiral Perturbation theory.

- $K^{+} \to \pi^{+}l^{+}l^{-}$ also gives an estimate of the indirect CP-violating amplitude in $K_{\rm L} \to \pi^{\circ}e^{+}e^{-}$.

- In the Standard Model this FCNC decay is dominated by long-distance one-photon exchange:



- Recent Chiral Perturbation theory calculations unambiguously relate $K^{+} \to \pi^{+}\mu^{+}\mu^{-}$ to $K^{+} \to \pi^{+}e^{+}e^{-}$:

$$R = \frac{(K^{+} \to \pi^{+}\mu^{+}\mu^{-})}{(K^{+} \to \pi^{+}e^{+}e^{-})} > 0.23$$

Experimental Problems

- BR($K^+ \to \pi^+ e^+ e^-$) well measured:

(2.6 ± 0.5)	$\times 10^{-7}$	(CERN)
$(2.75 \pm 0.23 \pm 0.13)$	$\times 10^{-7}$	(BNL-777)
$(2.94 \pm 0.05 \pm 0.13 \pm 0.05)$	$\times 10^{-7}$	(BNL-865)
(2.88 ± 0.13)	$\times 10^{-7}$	(PDG)

- BR($K^+ \to \pi^+ \mu^+ \mu^-$) not so well measured!

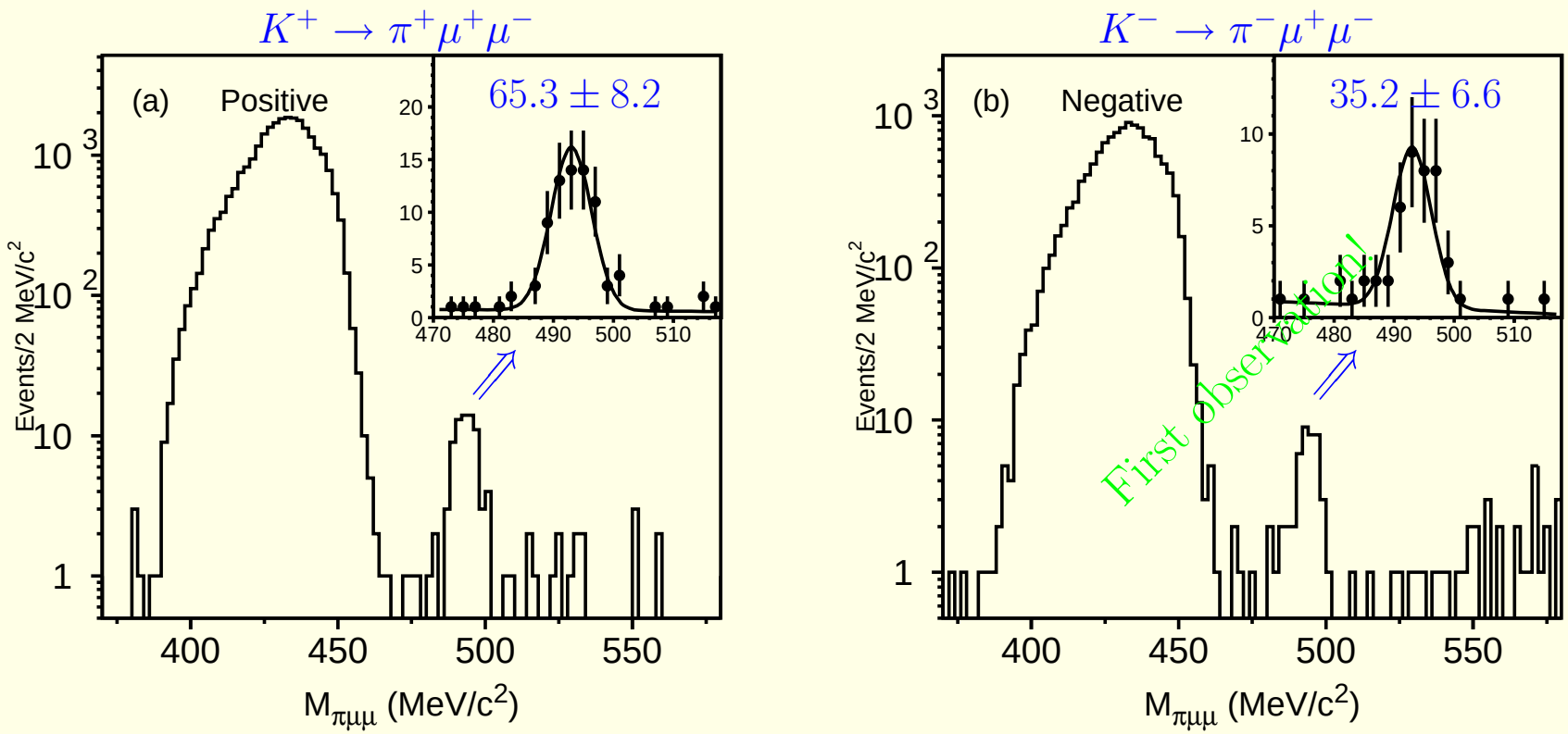
$(5.0 \pm 0.4 \pm 0.7 \pm 0.6)$	$\times 10^{-8}$	BNL-787
$(9.22 \pm 0.60 \pm 0.49)$	$\times 10^{-8}$	BNL-865

$\Rightarrow 3.3\sigma$ discrepancy!

- The BNL-E787 result on R is too low:

$R = 0.17 \pm 0.03$	BNL-787
$R = 0.32 \pm 0.03$	BNL-865

Measuring the Number of $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ Events



- Signal is clean with minimum of cuts.
- Large peak to the left of the signal is from $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays reconstructed with the $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ hypothesis.
- First observation of $K^{-} \to \pi^{-}\mu^{+}\mu^{-}$!

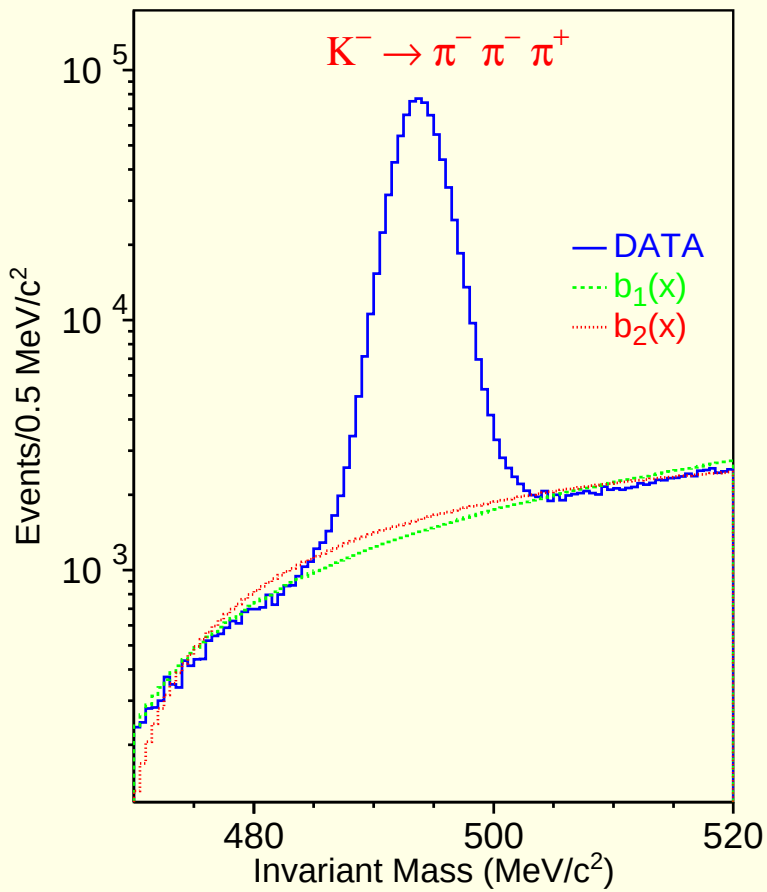
Counting the Number of $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ Events

- Try linear and quadratic fits to the background in the side-bands:

$$b_1(m) = c_1 + c_2 m$$
$$b_2(m) = c_1 + c_2 m + c_3 m^2$$

- Estimated number of events in the 1997 run:

$$N(K^{+} \to \pi^{+}\pi^{+}\pi^{-}) = (4.446 \pm 0.010)\times 10^5$$
$$N(K^{-} \to \pi^{-}\pi^{+}\pi^{-}) = (2.318 \pm 0.008)\times 10^5$$



HyperCP $K^\pm \to \pi^\pm\mu^+\mu^-$ Results

- Separate branching ratios:

$$B(K^+ \to \pi^+\mu^+\mu^-) = [9.7 \pm 1.2(\text{stat}) \pm 0.4(\text{syst})]\times 10^{-8}$$

$$B(K^- \to \pi^-\mu^+\mu^-) = [10.0 \pm 1.9(\text{stat}) \pm 0.7(\text{syst})]\times 10^{-8}$$

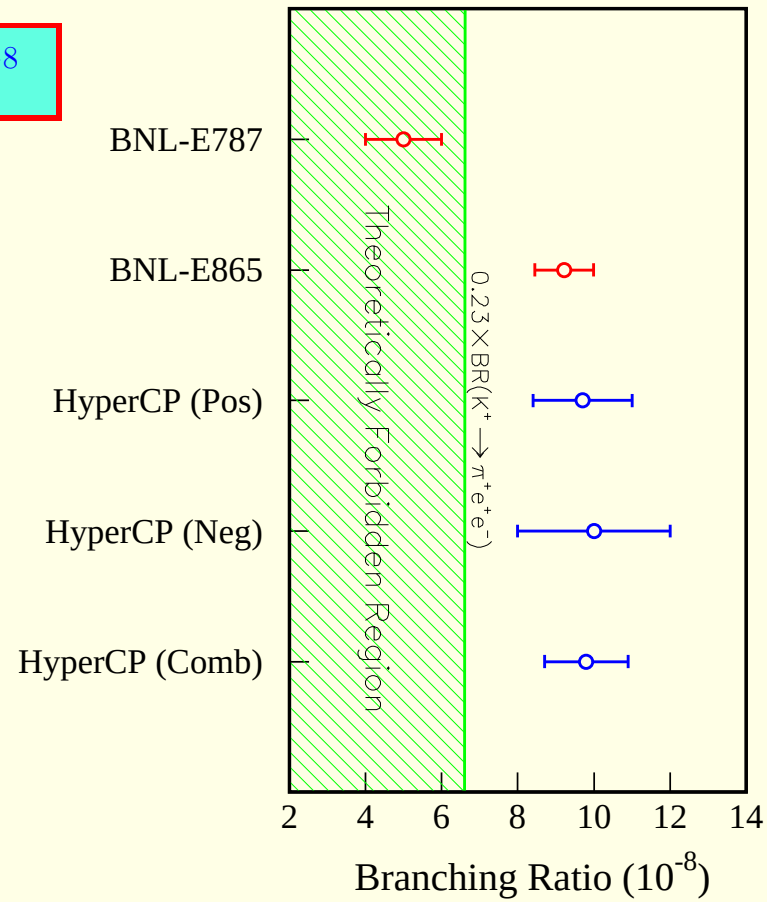
- Combined result:

$$\boxed{B(K^\pm \to \pi^\pm\mu^+\mu^-) = (9.8 \pm 1.0 \pm 0.5)\times 10^{-8}}$$

- CP asymmetry:

$$\Delta(K^\pm_{\pi\mu\mu}) = \frac{\Gamma(K^+_{\pi\mu\mu}) - \Gamma(K^-_{\pi\mu\mu})}{\Gamma(K^+_{\pi\mu\mu}) + \Gamma(K^-_{\pi\mu\mu})} = -0.02 \pm 0.11(\text{stat}) \pm 0.04(\text{syst})$$

- Our result is consistent with the Chiral Perturbation theory calculation of $R = (K^+ \to \pi^+\mu^+\mu^-)/(K^+ \to \pi^+e^+e^-)$.
- $3\times$ more events with 1999 data.



Search for $\Delta S = 2$ Hyperon Decays

- SM branching ratios $< 10^{-12}$
  $\Rightarrow$ window for new physics
- Limits from K decays do not preclude an observable effect.

  "...it is possible for new $\Delta S = 2$ interactions to induce hyperon decays at an observable level while evading the bounds from K°-$\overline{K}^\circ$ mixing."

  He and Valencia, PL B409 (1997) 469.
- Preliminary results:

Mode	***HyperCP*** **(90% CL)**	**PDG limits**
$\Omega^- \to \Lambda\pi^-$	$< 2.7\times10^{-6}$	$< 1.9\times10^{-4}$
$\Xi^\circ \to p\pi^-$	$< 7.8\times10^{-6}$	$< 3.6\times10^{-5}$

Conclusions and Outlook

- *HyperCP* has amassed by far the largest data sample ever recorded, with which a rich program of charged hyperon and kaon physics is in progress.
- We find no evidence of CP violation in $\Xi^{\pm}$ and Λ decays, with two independent analyses of the data:

$$\delta A_{\Xi\Lambda} = (1.5 \pm 5.1 \pm 4.5)\times 10^{-4}$$
$$\delta A_{\Xi\Lambda} = (7 \pm 12 \pm 6.2)\times 10^{-4}$$

- We will be able to push our limit to

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

  two orders of magnitude better than the present limit — assaulting CP violation from a different direction than the kaon and B experiments.
- We have the first evidence of parity violation in $\Omega^- \to \Lambda K^-$ decays.
- We are breaking new ground with our unique program of searches for rare and forbidden hyperon decays.
- Our $K^{\pm} \to \pi^{\pm}\mu^+\mu^-$ branching ratio result is consistent with Chiral Perturbation theory and favors the BNL-865 result.