Cascade Physics with the $HyperC^P$ Spectrometer at Fermilab

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Cascade Physics: A New Window on Baryon Spectroscopy
2 December 2005

Hyperon Physics at Fermilab

- Hyperon physics has a long and distinguished history at Fermilab.
  - Beginning with E8 and the Fermilab Neutral Hyperon Group at Fermilab's inception in the early 70s.
  - Continuing with E440, E441, E495, E361, E620, E497, E555, E619, E715, E761, E781, E756, E800, Selex, KTeV, *HyperCP*.
- Almost all the experiments focused on the static and decay properties of stable hyperons.
  - High energies allowed beams of hyperons to be made.
- Highlights of that program include:
  - The discovery of polarization in inclusive hyperon production in 1976, and subsequent measurements.
  - The precise measurement of the hyperon magnetic moments.
- Much other physics done:
  - Weak-radiative hyperon decays.
  - β-decays.
  - Measurements of masses, lifetimes, decay parameters.
  - Production cross sections.

Theory has Yet to Catch Up to Experiment

"We do *not* require more and better data. The issues are already clear. What we need is more and better theory!"

Barry Holstein
Hyperon Physics Symposium
Fermilab, 1999

- Longstanding problems in hyperon physics still remain.
  - $\Delta I = \frac{1}{2}$ rule.
  - Nonleptonic branching ratio enhancement.
  - S/P-wave problem.
  - Weak-radiative decays — Hara's theorem.
- Newer problems have appeared:
  - Hyperon polarization.
  - Hyperon magnetic moments.
- One glaring exception:

Caption: y7558 Cern, Dr. Louis Dick, physicist in pension from CERN his office. - Pensionierter P
No: BP_005-59 | © Photoagency Bilderberg / Russian Look

"Where we *do* need data involves the possibility of testing the standard model prediction of CP violation."

Barry Holstein
Hyperon Physics Symposium
Fermilab, 1999

HyperCP Physics Goals

Primary Goal:

- A search for exotic sources of CP violation in charged-Ξ and Λ decays.

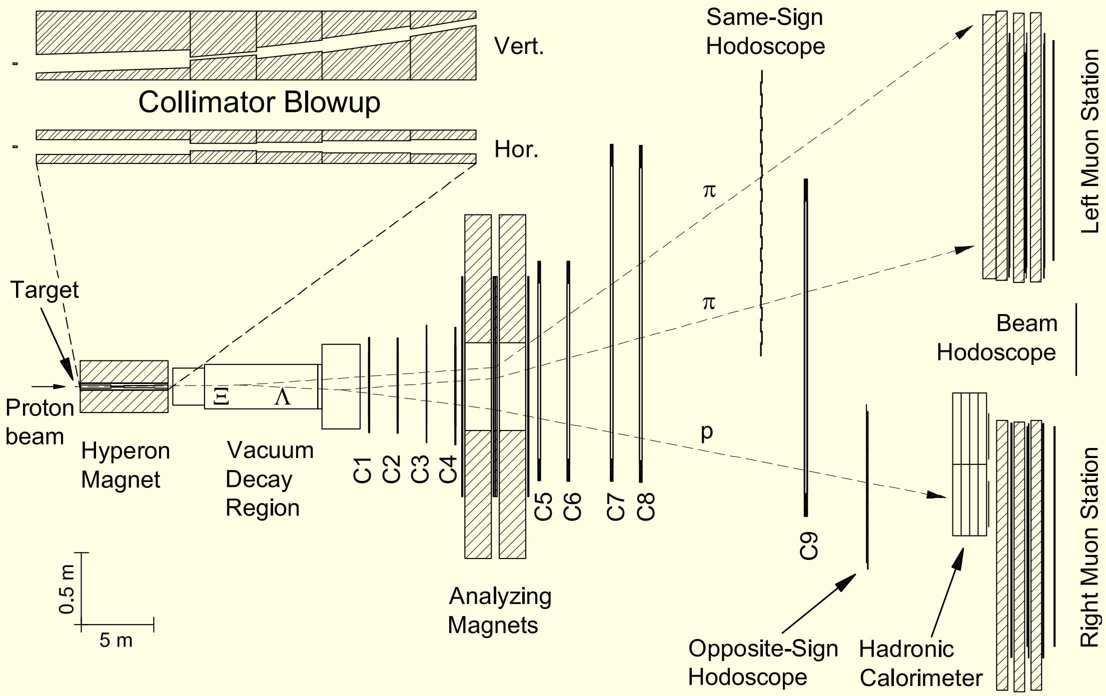
Secondary Goals:

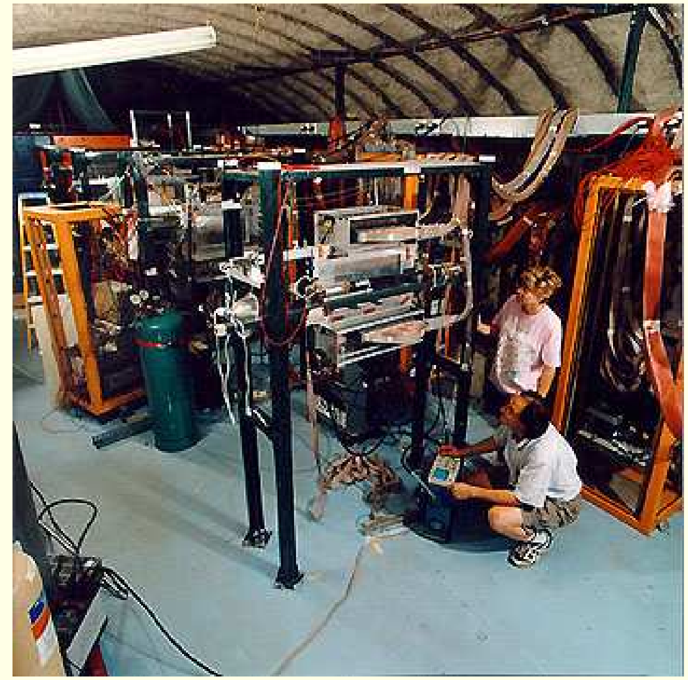
- Search for CP violation in $\Omega^{\pm} \to \Lambda K^{\pm}$ decays.
- Search for rare and forbidden hyperon and charged kaon decays:
  - Lepton number nonconservation in $\Xi^- \to p\mu^-\mu^-$.
  - Flavor changing neutral currents in hyperon and charged kaon decays: $\Omega^- \to \Xi^-\mu^+\mu^-$, $\Sigma^+ \to p\mu^+\mu^-$, $\Omega^- \to \Xi^-\mu^+\mu^-$, $K^{\pm} \to \pi^{\pm}\mu^+\mu^-$.
  - $\Delta S > 1$ 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.
  - α, β and γ parameters in Ξ^- decays.
  - α decay parameter in $\Omega^{\pm} \to \Lambda K^{\pm}$ decays.
  - Hyperon production cross sections.

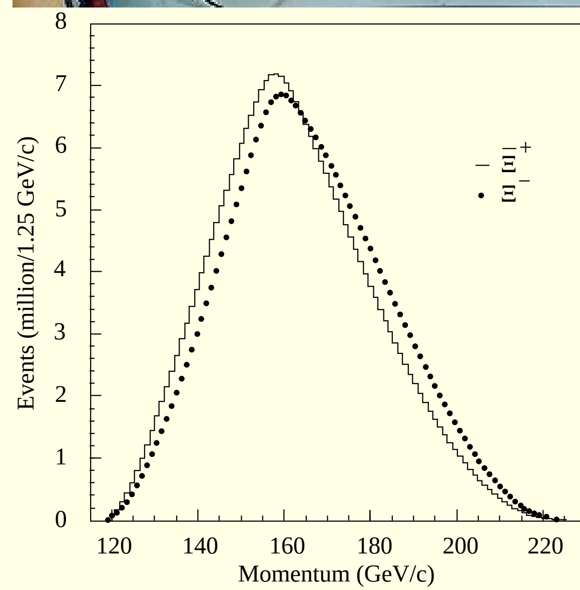
Note:

- Other Ξ^- physics, such as precision mass and lifetime measurements, could be done, but manpower for such analyses lacking.

New Hyperon Beam and Spectrometer Built

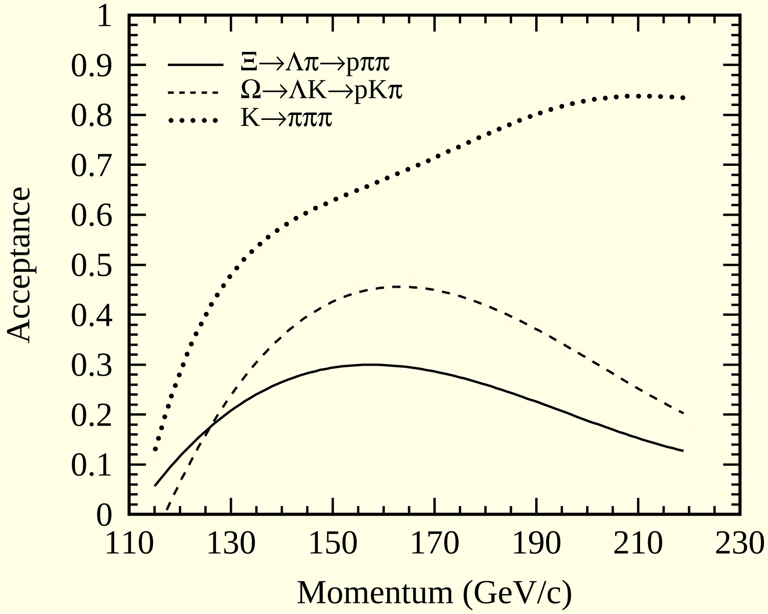




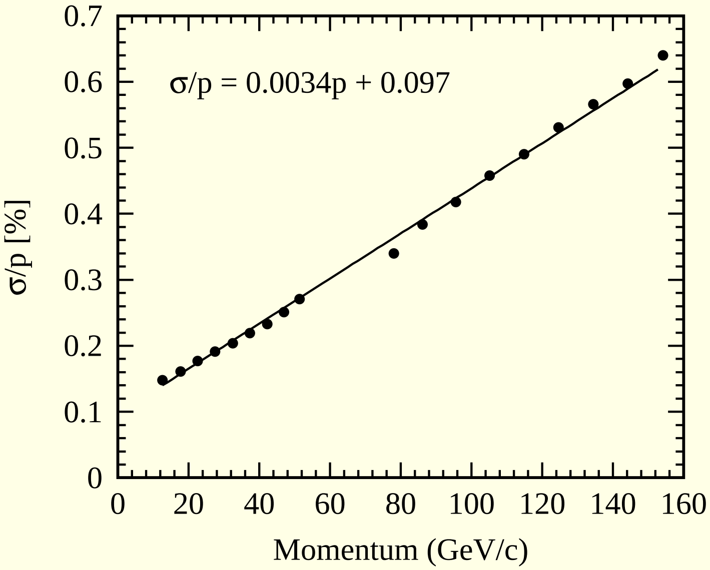


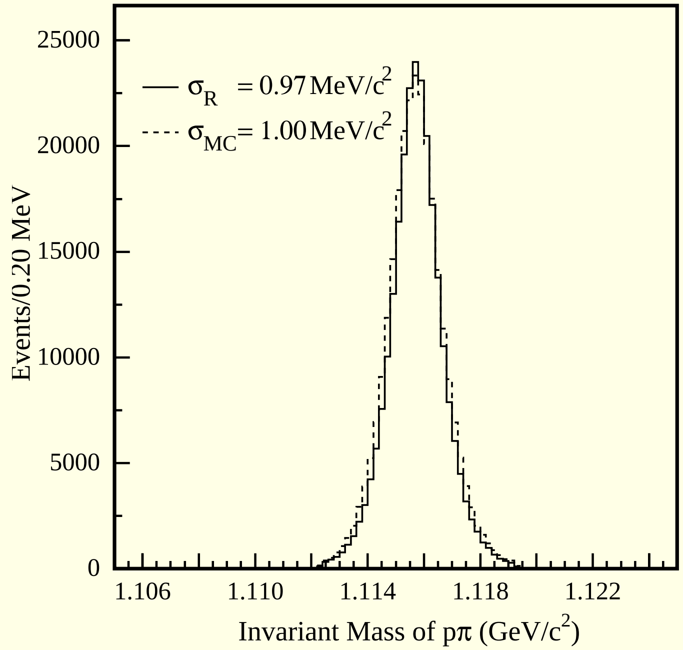
- New charged secondary beam built:
  - 800 GeV/c protons on $2\times2\,\mathrm{mm}^2$ Cu target
  - Mean momentum: 167 GeV/c
  - Rate: 10–15 MHz
- New high-rate spectrometer built:
  - 8 high-rate, narrow-pitch wire chambers
  - No particle ID except muon system
  - Simple, low-bias trigger.
  - Very high-rate DAQ

Spectrometer has Large Acceptance and Good Resolution



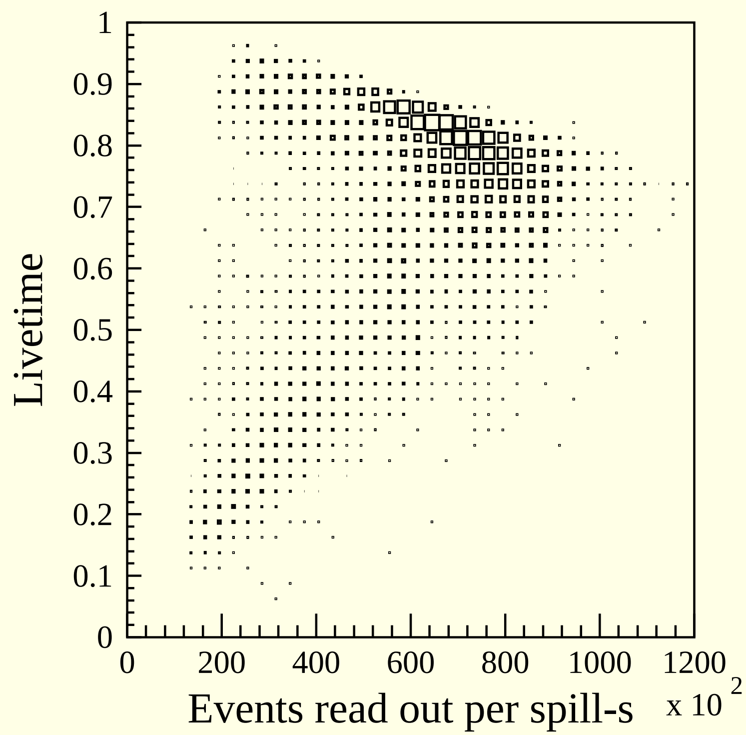
Acceptance for particles that decayed in the vacuum decay region.

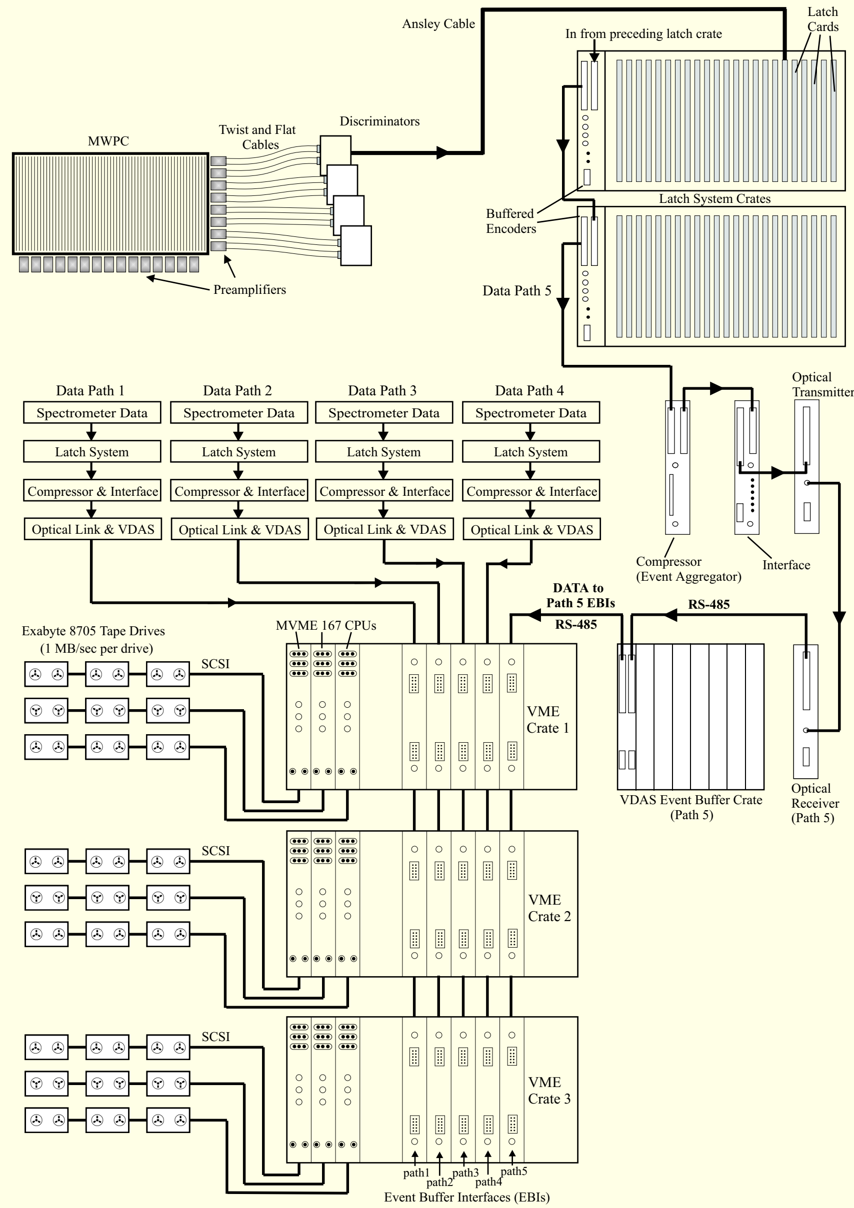




HyperCP Data Acquisition System

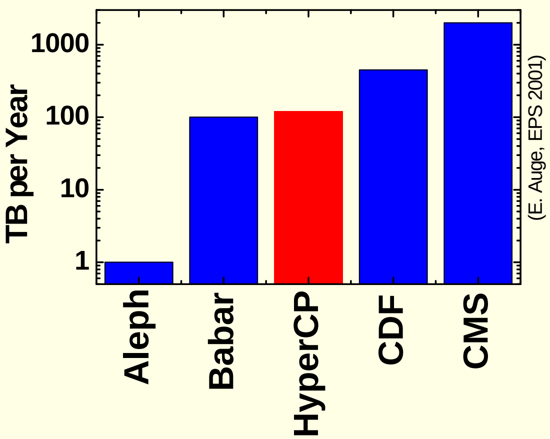
- All custom front ends: no CAMAC, Fastbus, or VME.
- Sustained data logging rate of 27 MB/s onto 27 Exabyte 8705 tapes.
- Maximum trigger rate of about 100,000 events per second:

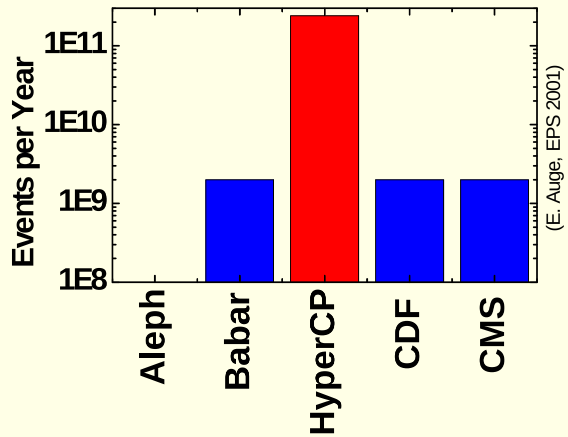




HyperCP Yields

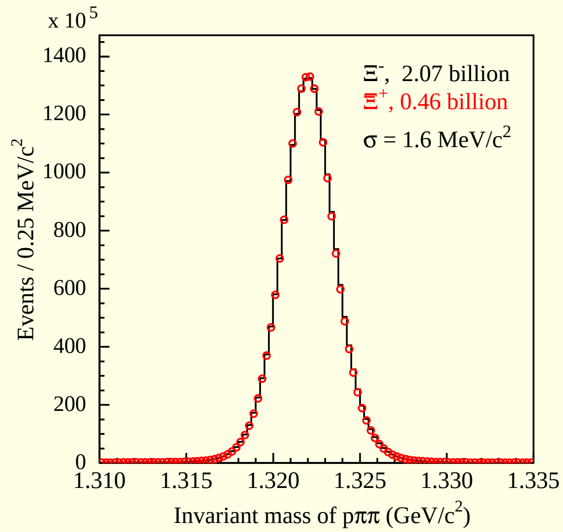
- In 12 months of data taking *HyperCP* recorded one the largest data samples ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.



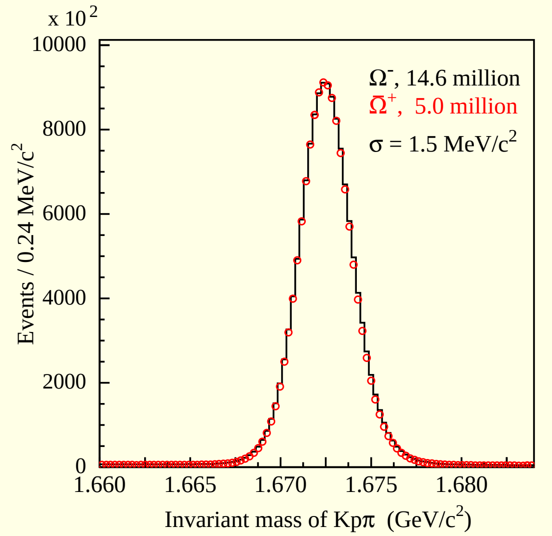


Entire WWW on 9/11/01 was 5 TB!

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



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



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

Short Primer on Nonleptonic Hyperon Decays

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

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

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

- **The magnitude of the parity violation is given by α_p**

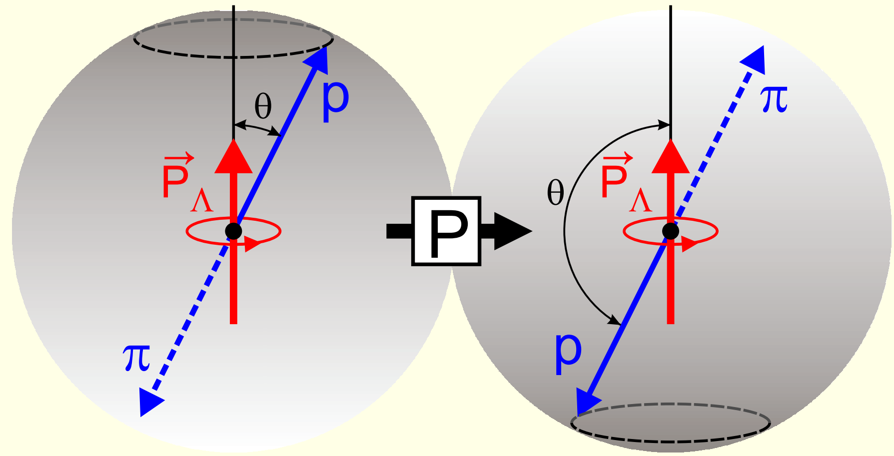
$$\alpha = \frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2}$$

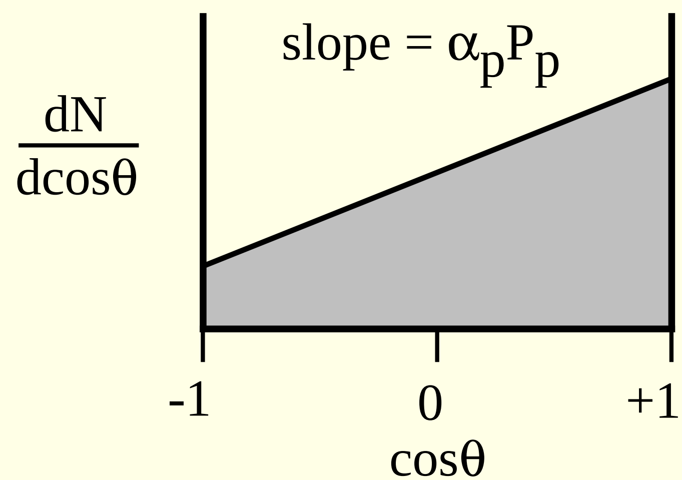
S: parity violating amplitude
P: parity conserving amplitude

- The slope of the daughter baryon $\cos\theta$ distribution is given by:

$$\alpha_p P_p$$

- **Hyperon alpha parameters large!**





Short Primer on Nonleptonic Hyperon Decays

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

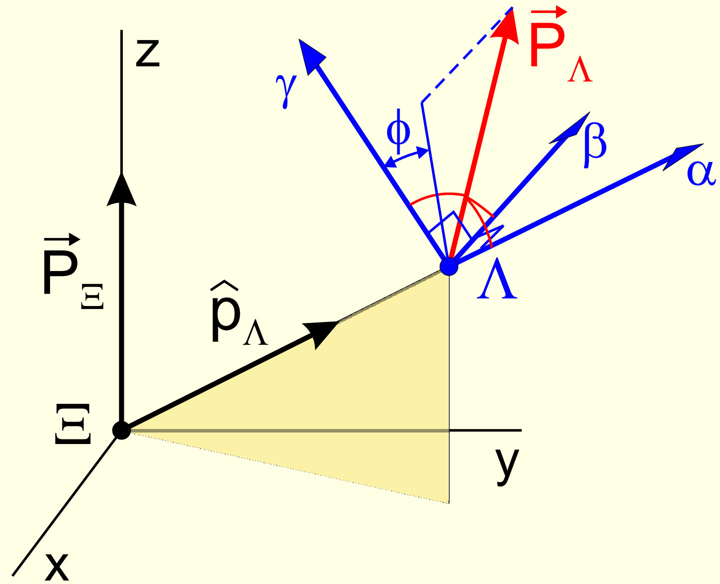
Daughter Λ baryon is polarized

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

where:

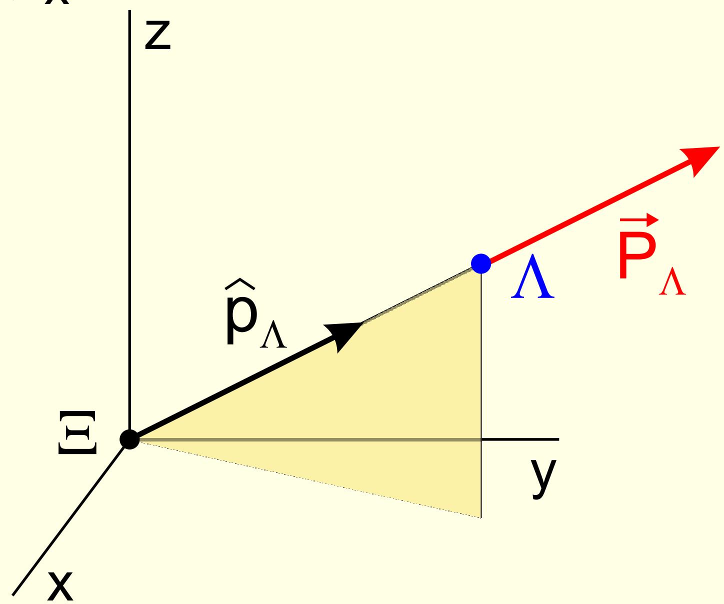
$$\alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2} \quad \beta = \frac{2\mathrm{Im}(S^*P)}{|S|^2+|P|^2} \quad \gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

$$\beta = \sqrt{1-\alpha^2}\sin\phi \qquad \gamma = \sqrt{1-\alpha^2}\cos\phi$$



If parent Ξ^- is **unpolarized** the Λ is produced in a helicity state:

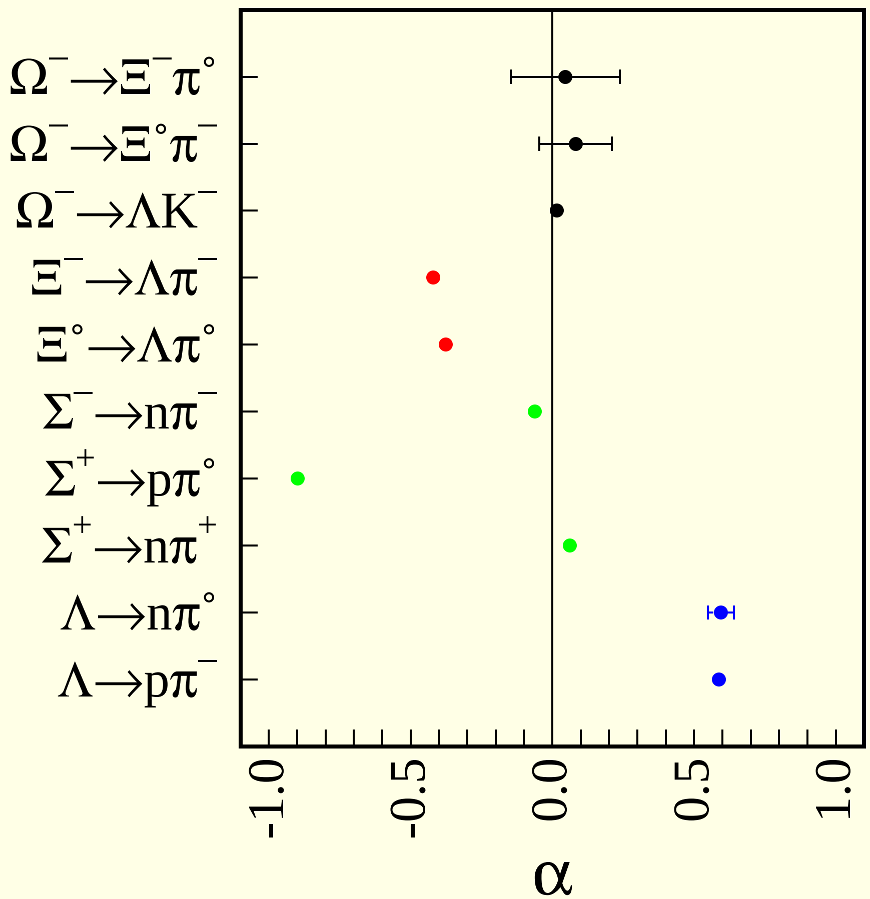
$$\boxed{\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda}$$

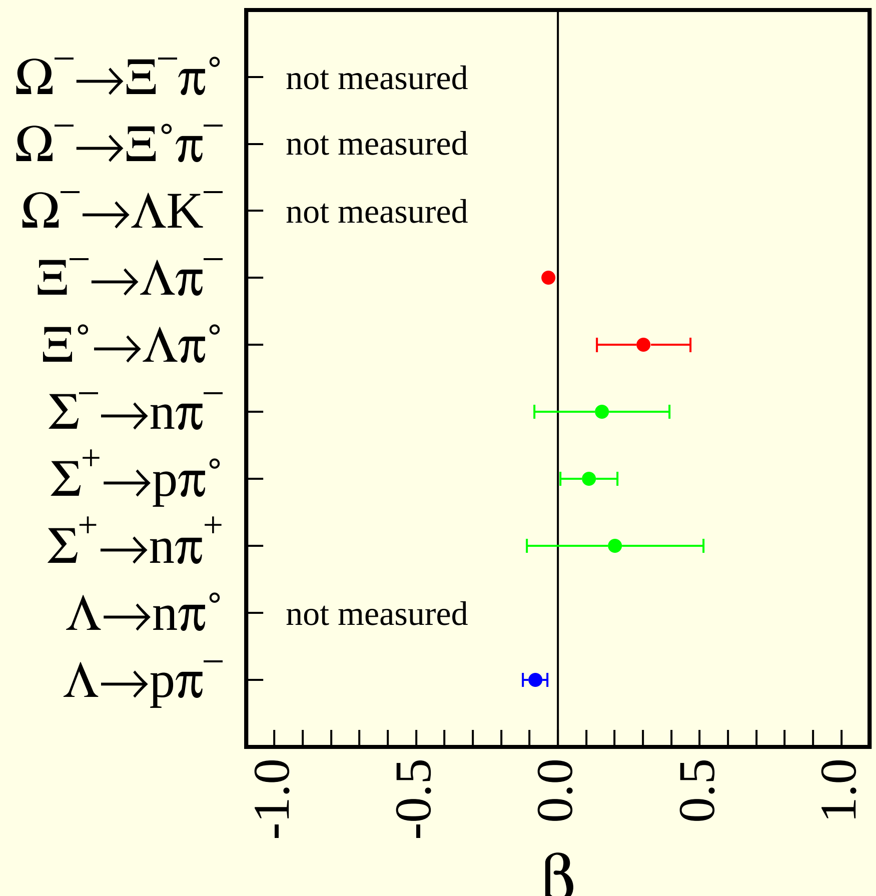


Hyperon α and β Parameters

- Alpha parameters can be large!
- Most are well measured.
- Until recently all known to be non-zero except for the three in Ω^- decays.

- Beta parameters zero or very small.
- Difficult to measure: need a polarized parent hyperon.



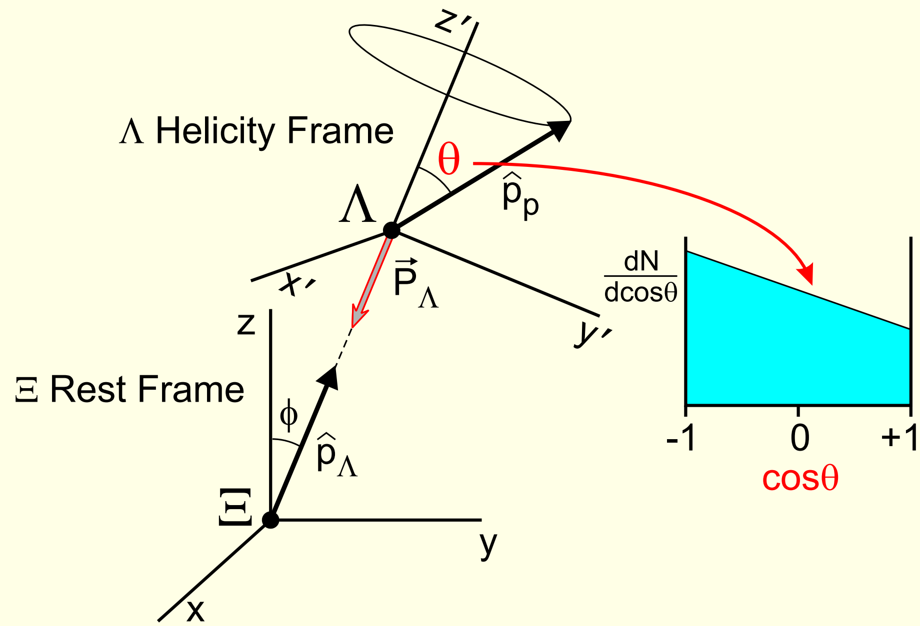


Calculating α and β Parameters Difficult

- S/P-wave problem longstanding
- Standard approach using contact term for parity-violating S-wave amplitude and pole model for parity-conserving P-wave amplitude gives good S-wave fit, but very poor P-wave fit.
- One can fit the P waves, but the S-wave amplitudes are bad: simultaneously fitting both S- and P-waves has been difficult.
- Solution: Include $(70,1^-)$ intermediate states (Le Youaunc).
- Solution: Include intermediate $\frac{1}{2}^-$ and $\frac{1}{2}^+$ resonances (Borasoy and Holstein).
- These approaches are promising, but ball remains in theorists court.

Measuring the Cascade α Decay Parameter

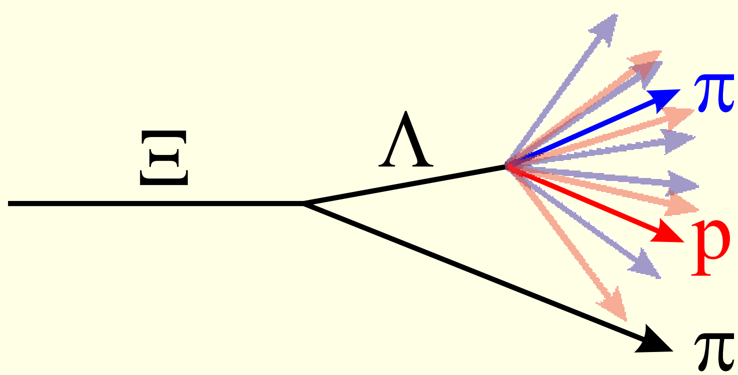
- Use unpolarized Ξ^- events $\Rightarrow \Lambda$ is produced in a helicity state with helicity α_Ξ.
- Find Λ polarization via its parity-violating decay distribution: $\alpha_\Xi \alpha_\Lambda$.
- The proton angular distribution is found in the **Lambda Helicity Frame**.



Use Hybrid Monte Carlo method:

- Take a real $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$ event, discard proton and pion, generate 10 new unpolarized Λ decays.
- Generate isotropic Λ decay HMC events and then weight by

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

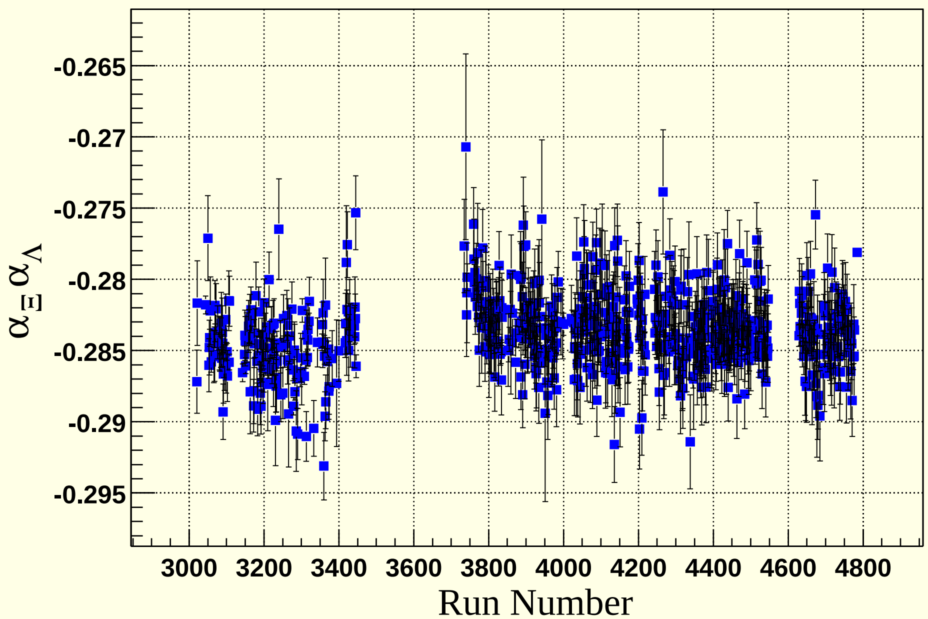


- Vary $\alpha_\Lambda \alpha_\Xi$ until best fit between data and MC is obtained.
- Requires:
  - Very good Monte Carlo description of the apparatus and decay.
  - Very fast Monte Carlo: $\sim$10 billion events.

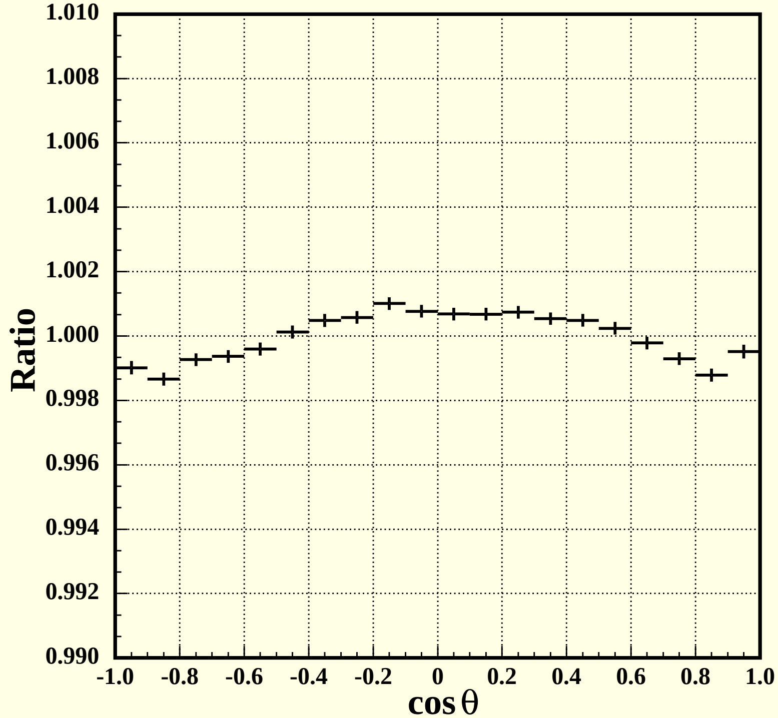
Measuring the Cascade α Decay Parameter

- Beating down systematic errors difficult and a work still in progress.
- Preliminary result: from 1.555 billion events:

$$\begin{aligned}\alpha_\Xi \alpha_\Lambda &= (-0.2850 \pm 0.00009)\ HyperC^P \\ &= (-0.294 \pm 0.005)\ \mathrm{PDG}\end{aligned}$$



- Agreement between HMC events and data good, but has systematic errors.



Ratio of real to weighted HMC events.

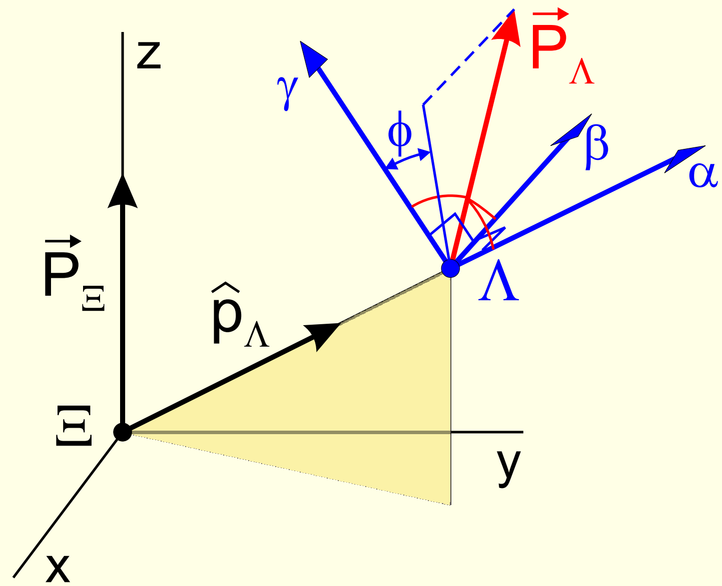
Measuring the Cascade β Parameter

$$\beta = \frac{2\mathrm{Im}(S^* P)}{|S|^2 + |P|^2}$$

- β gives the transverse component of the daughter Λ polarization "out-of-plane" for the polarized Ξ^- decay.

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

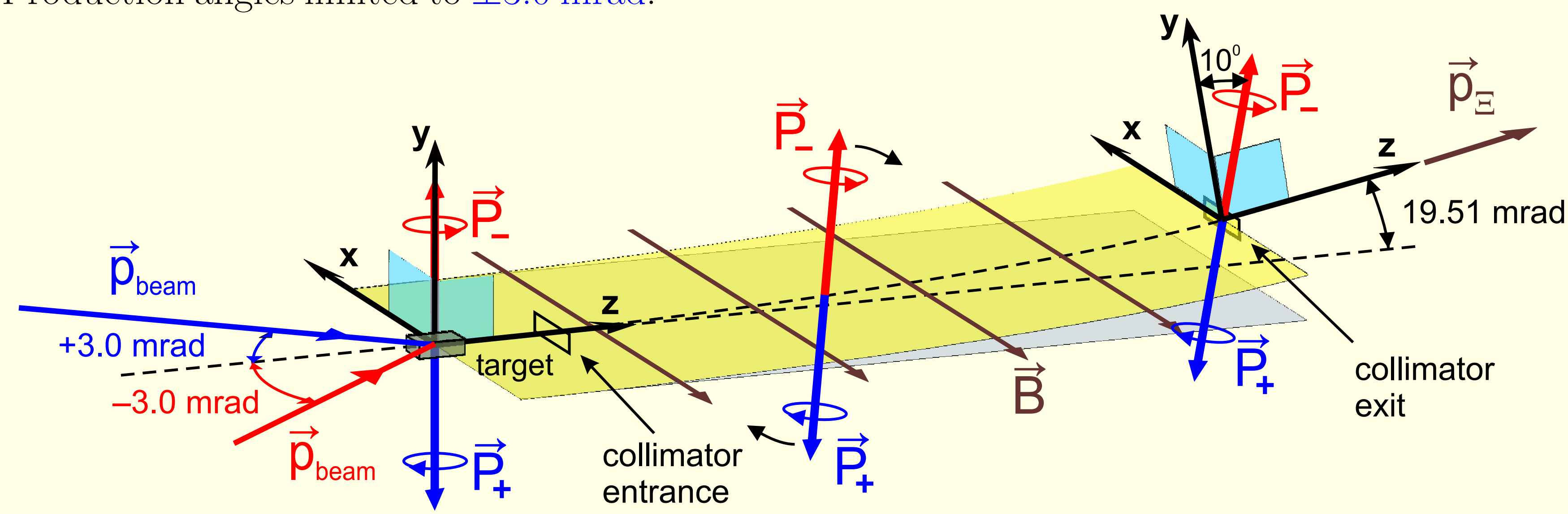
- It is known to be small.
- To determine β the Λ polarization must be measured from a polarized sample of Ξ decays.
- Procedure:
  - First find the direction and magnitude of the Ξ^- polarization.
  - Find the Λ polarization components in the transverse plane through the asymmetry in the Λ decay distribution: $P_\beta = \alpha_\Lambda \beta_\Xi P_\Xi$ and $P_\gamma = \alpha_\Lambda \gamma_\Xi P_\Xi$.



$$\boxed{\tan\phi = \frac{P_\beta}{P_\gamma} = \frac{\beta}{\gamma}}$$

Producing Polarized Cascades

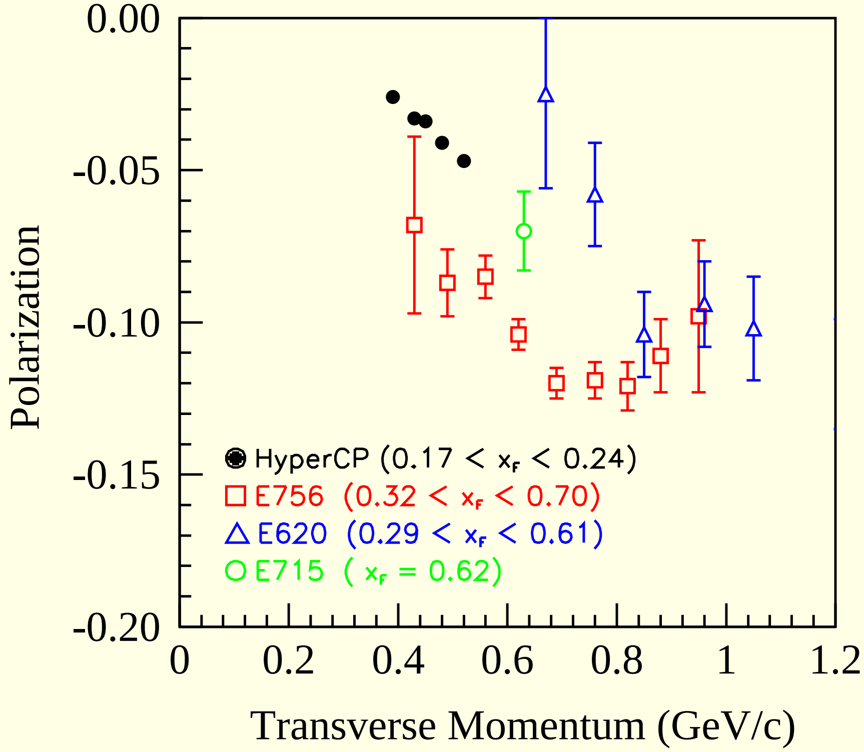
- Polarization in inclusive high-energy hyperon production was discovered at Fermilab in 1976.
- A series of experiments have found that all hyperons are produced polarized, with polarization increasing with p_t and x_F.
- Special polarization sample taken by targeting at non-zero production angles.
- Production angles limited to ± 3.0 mrad.
- Polarization extracted from the asymmetry in the Λ decay using a Hybrid Monte Carlo method.
- Bias canceled by subtracting $+3.0$ mrad from -3.0 mrad asymmetry.



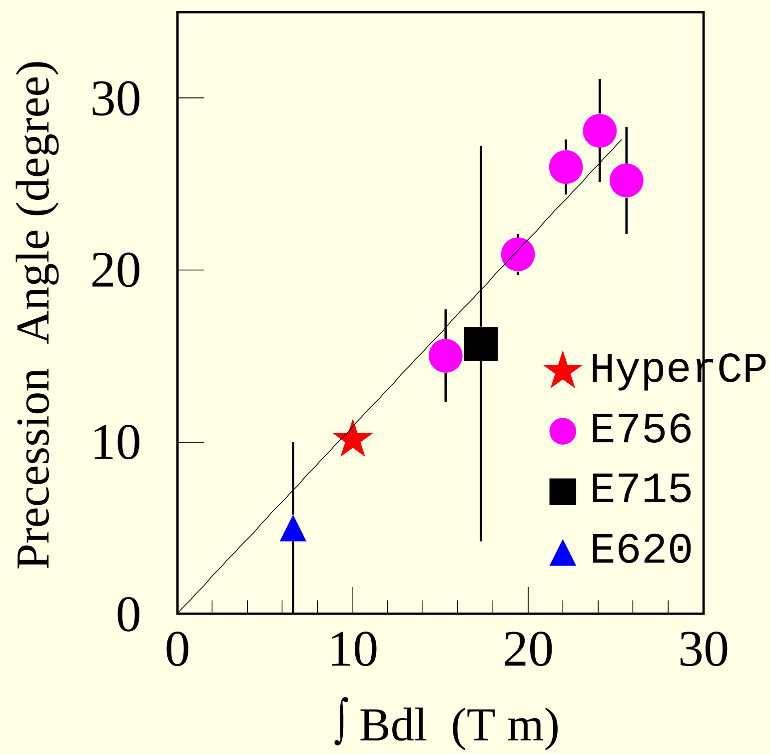
Ξ^- Polarization and Magnetic Moment

- Small polarization makes extracting β particularly difficult.
- Polarized data sample polarization poor: Mean polarization: $\sim 3.7\%$.

$$\langle p_t \rangle = 0.48 \text{ GeV}/c$$
$$\langle x_F \rangle = 0.2$$



- $\mu_\Xi = (-0.6562 \pm 0.0051)\mu_N$ consistent with PDG value of $\mu_\Xi = (-0.6507 \pm 0.0025)\mu_N$.
- Small field integral precludes competitive measurement of μ_Ξ.

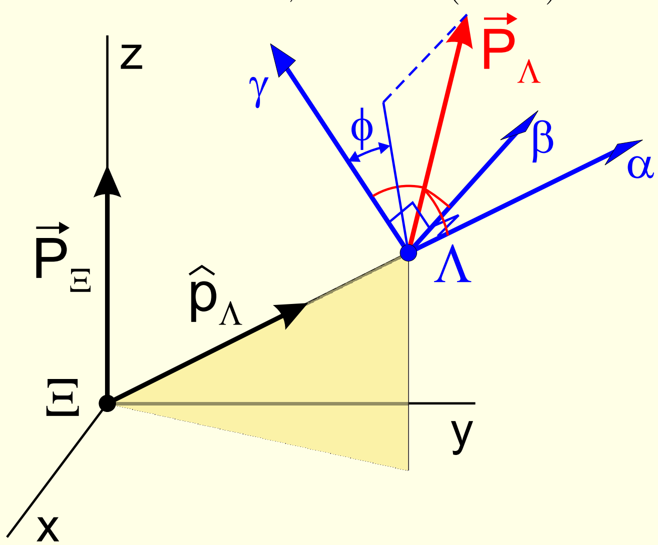


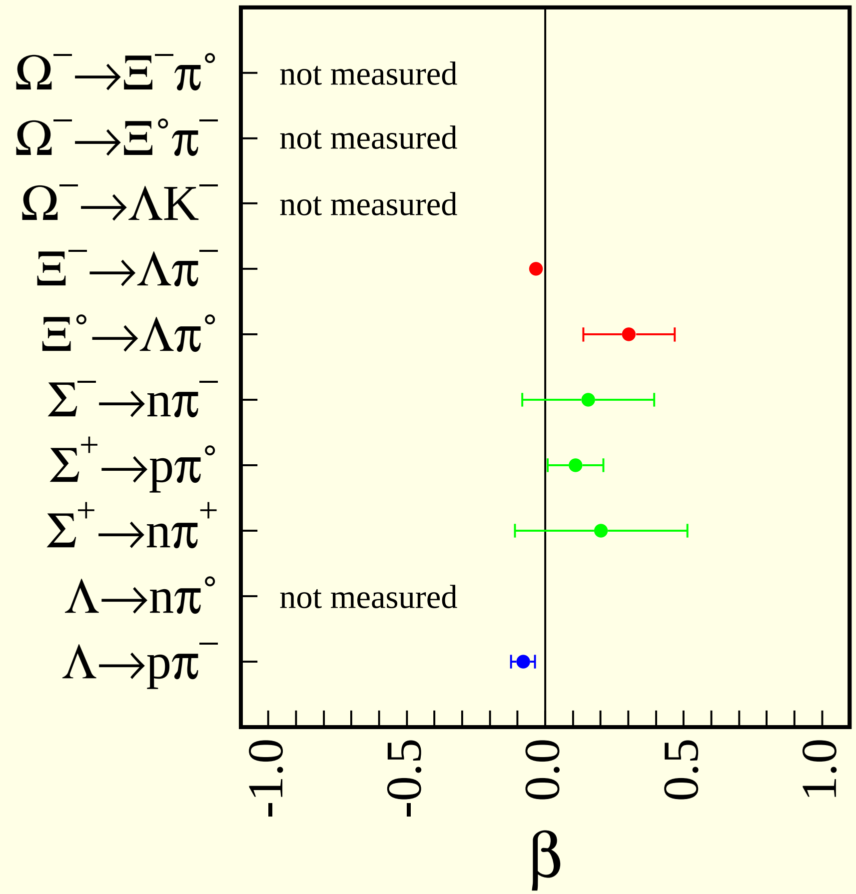
Cascade β and γ Decay Parameters

- From 144 million polarized Ξ^- decays:

$$\begin{aligned} \phi &= -2.39^\circ \pm 0.64^\circ(\mathrm{stat}) \pm 0.64^\circ(\mathrm{syst}) \\ \beta_\Xi &= -0.037 \pm 0.011(\mathrm{stat}) \pm 0.010(\mathrm{syst}) \\ \gamma_\Xi &= 0.888 \pm 0.0004(\mathrm{stat}) \pm 0.006(\mathrm{syst}) \end{aligned}$$

- At $2.5\,\sigma$ from zero best evidence of a non-zero β parameter in any hyperon decay.
- Has implications on CP-violation measurement.
- Published: PRL **93**, 011802 (2004).



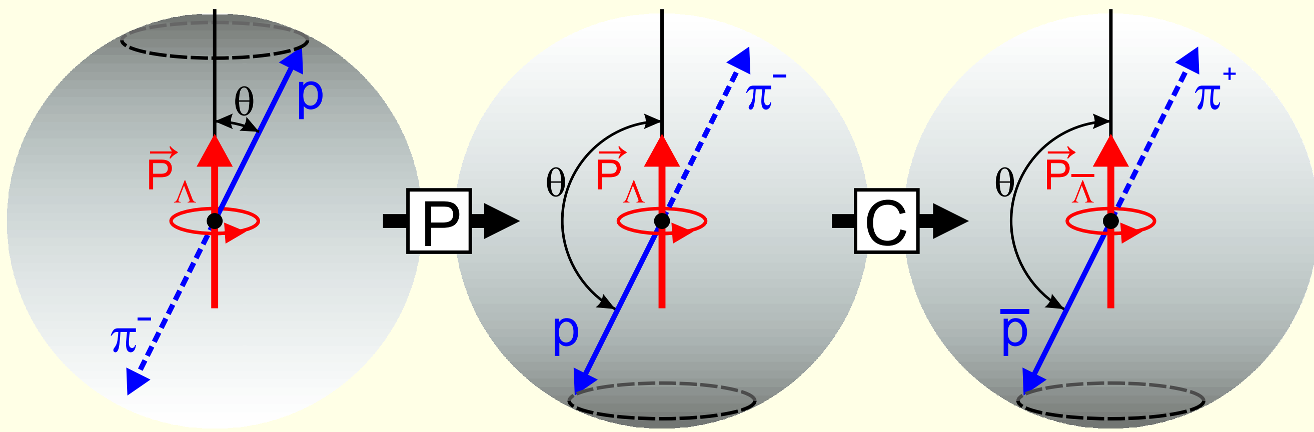


How to Search for *CP* Violation in Hyperon Decays

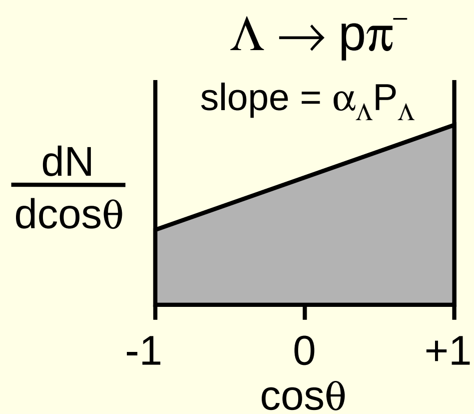
Due to parity violation the proton likes to go in the direction of the Λ spin:

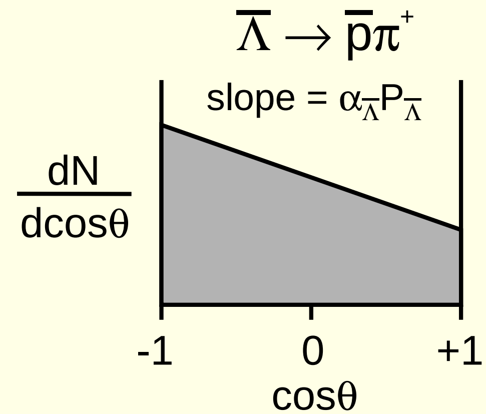
$$\Lambda \rightarrow p\pi^-: \qquad \frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1+\alpha_\Lambda P_\Lambda \cos\theta) \qquad \alpha = \frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2} = 0.642$$

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



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





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:

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

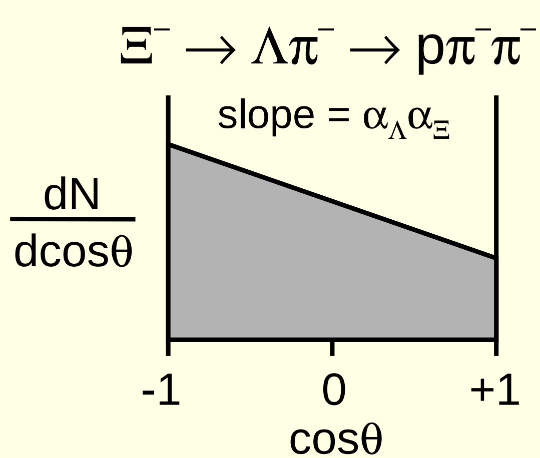
If the Ξ is produced unpolarized — which can simply be done by targeting at 0 degrees — then the Λ is found in a helicity state, with a large polarization ($\alpha_\Xi = -0.458$):

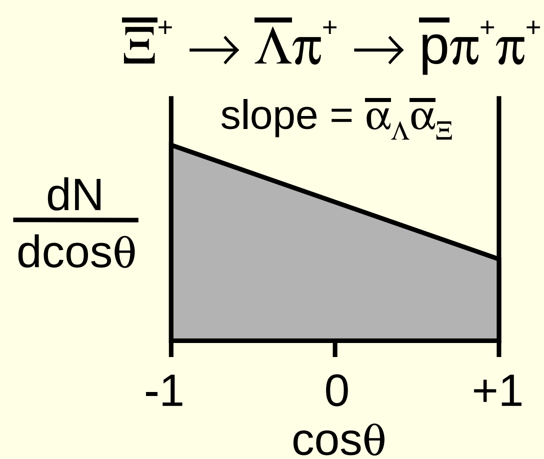
$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad\qquad \vec{P}_{\overline{\Lambda}} = \overline{\alpha}_\Xi \hat{p}_{\overline{\Lambda}}$$

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

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

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



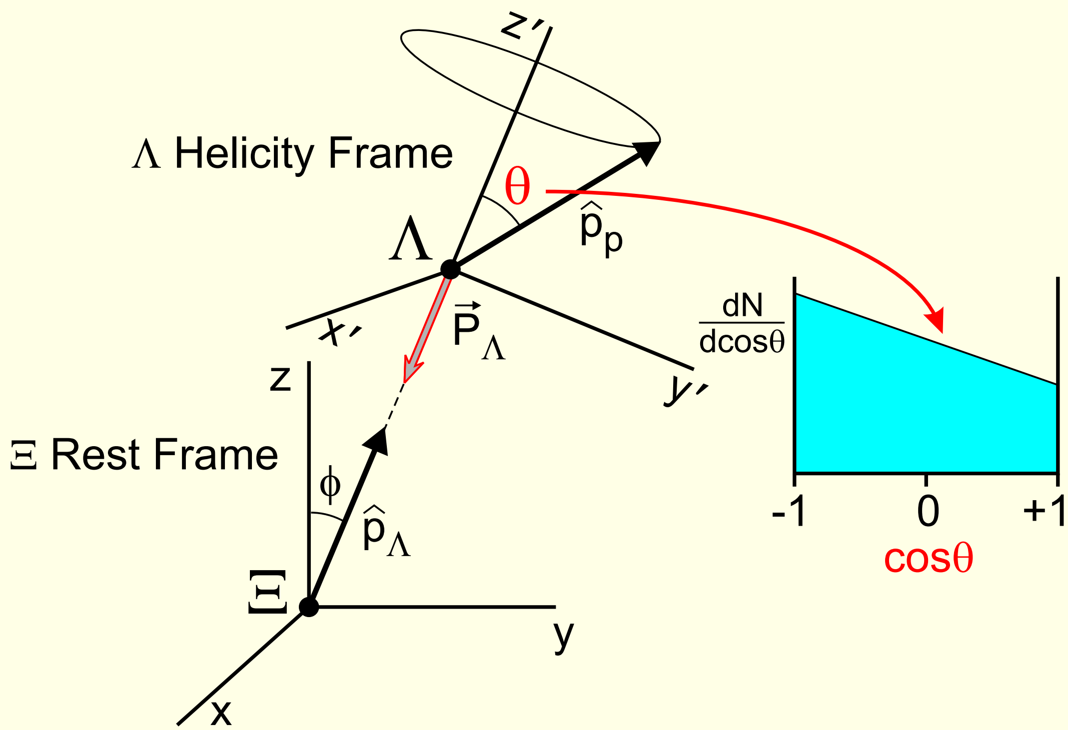


HyperCP technique is sensitive to both Ξ and Λ *CP* violation

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

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.

What is the experimental situation?

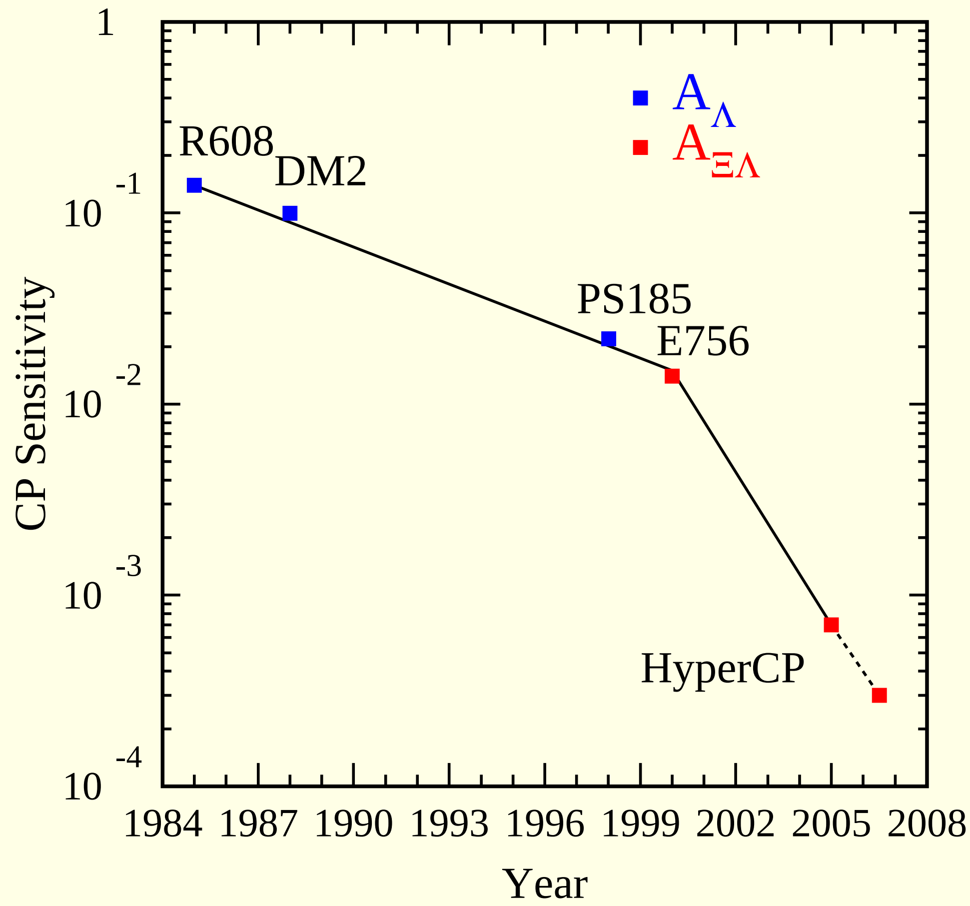
- To date there are only upper limits on the asymmetries.
- A_Λ has been measured to 2×10^{-2}:

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

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:

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

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

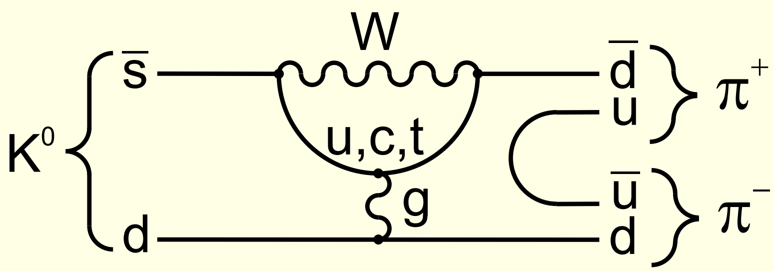
$$
\Xi^- \left\{ \begin{array}{rcr} \delta_P &=& -2.7^\circ \\ \delta_S &=& -18.7^\circ \end{array} \right\} 1965 \qquad \begin{array}{cr} = & -1^\circ \\ = & 0^\circ \end{array} \Bigg\} \text{recent}\chi PT
$$

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

Comparison of ϵ'/ϵ and A_Ξ, A_Λ

ϵ'/ϵ

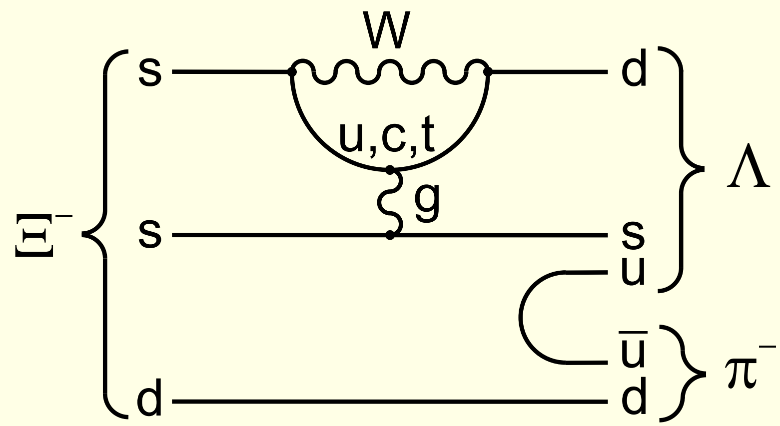
- Thought to be due to the Penguin diagram in the Standard Model.



- 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.

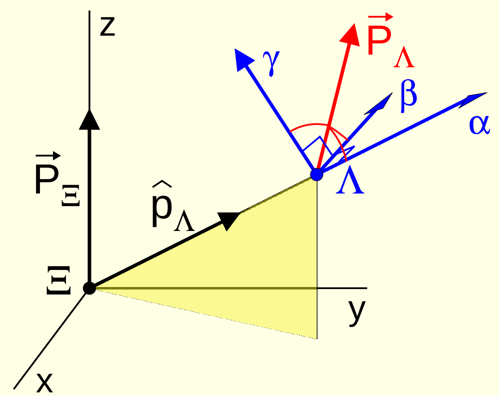
"Our results suggest that this measurement is complementary to the measurement of ϵ'/ϵ, in that it probes potential sources of CP *violation at a level that has not been probed by the kaon experiments."*

He and Valencia, PRD52 (1995) 5257.

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:

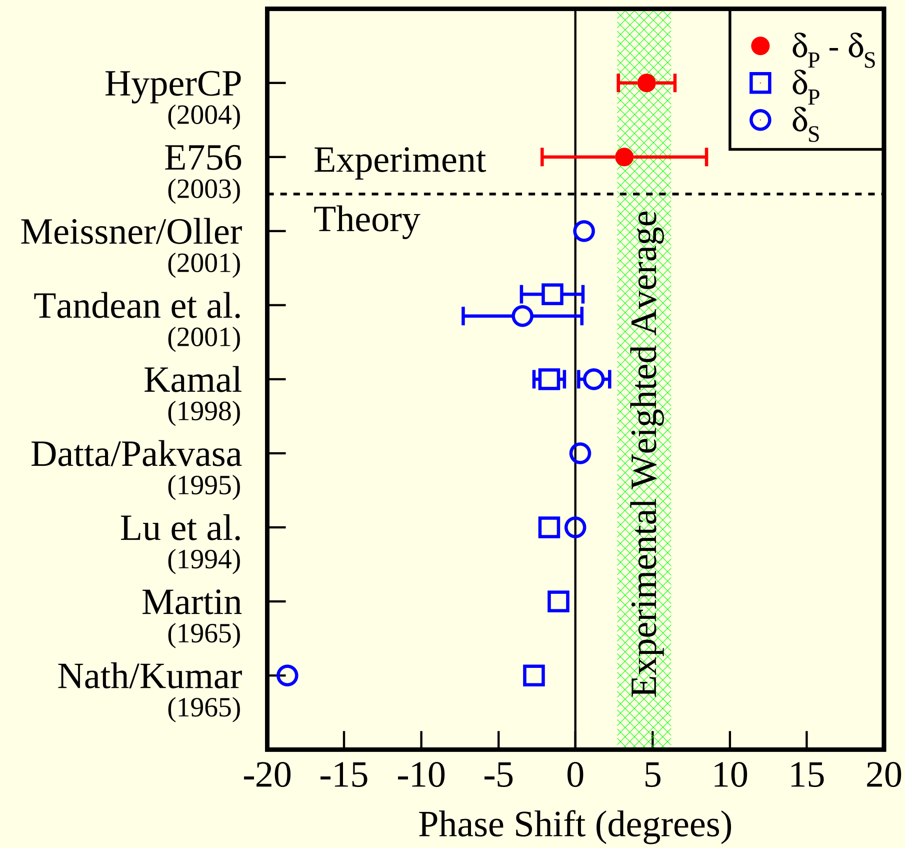
$$\vec{P}_\Lambda = \frac{(\alpha_\Xi + \vec{P}_\Xi \cdot \hat{p}_\Lambda)\hat{p}_\Lambda + \beta_\Xi(\vec{P}_\Xi \times \hat{p}_\Lambda) + \gamma_\Xi(\hat{p}_\Lambda \times (\vec{P}_\Xi \times \hat{p}_\Lambda))}{(1+\alpha_\Xi \vec{P}_\Xi \cdot \hat{p}_\Lambda)}$$



$$\beta_\Xi = -0.037\pm0.011(\text{stat}) \pm0.010(\text{syst})$$
$$\gamma_\Xi = 0.888\pm0.0004(\text{stat})\pm0.006(\text{syst})$$

- Using the known value of α_Ξ:

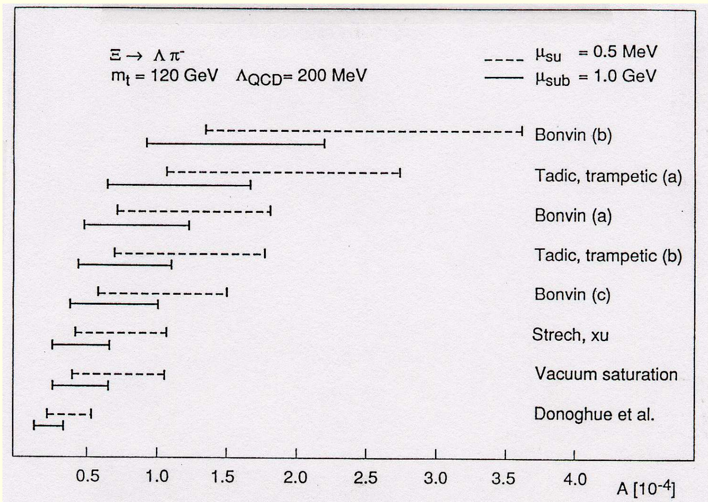
$$\boxed{\delta_P - \delta_S = \tan^{-1}\left(\frac{\beta_\Xi}{\alpha_\Xi}\right) = (4.6\pm1.4\pm1.2)^\circ}$$



- First non-zero measurement of phase shift.
- 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?

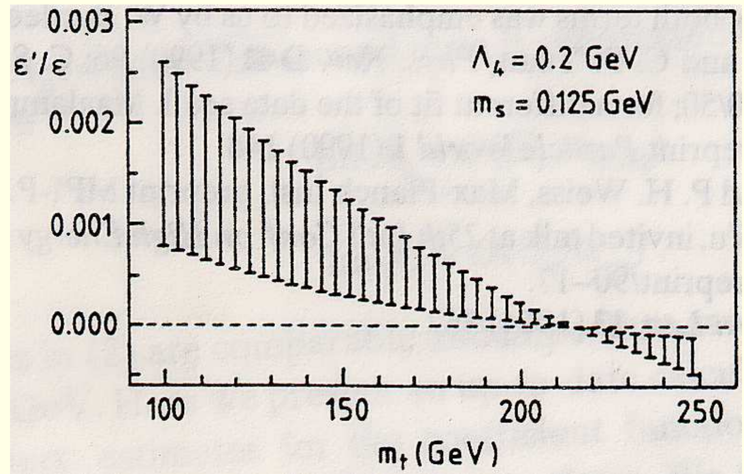
Bad News: Standard Model Theory Predictions Small

- 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:

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

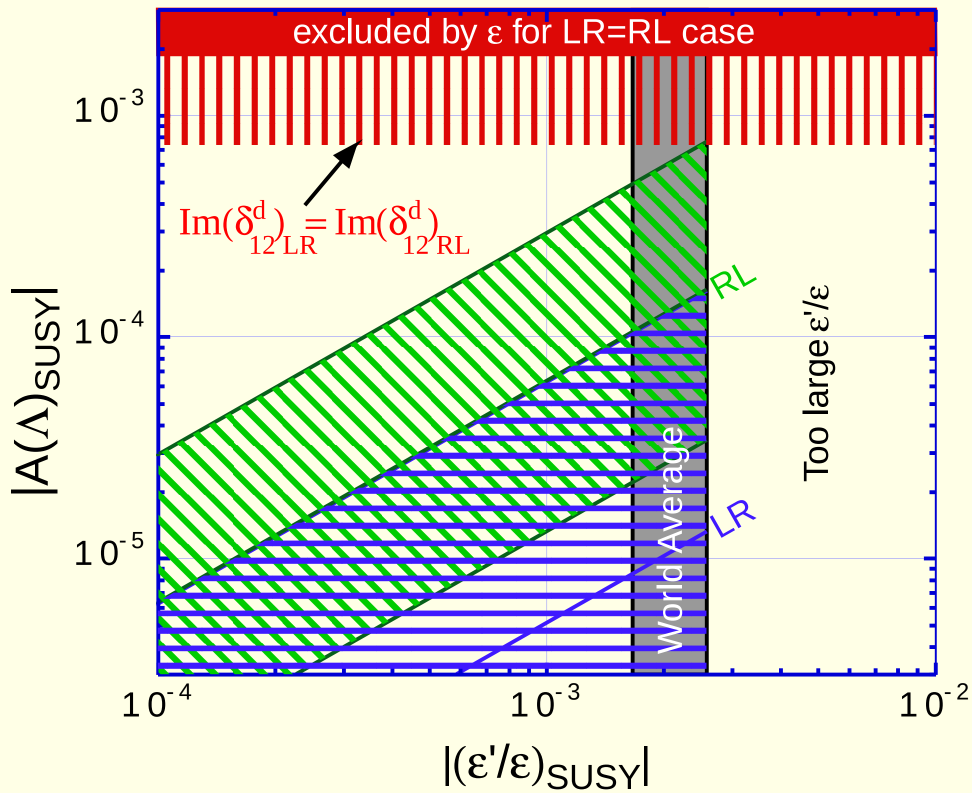
(Tandean & Valencia, 2003)

- 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

- Most beyond-the-standard-model theories predict new and large CP-violating phases.
- These beyond-the-standard-model predictions are often 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.

Extracting the CP Asymmetry

- If CP is a good symmetry proton and antiproton $\cos\theta$ distributions identical.

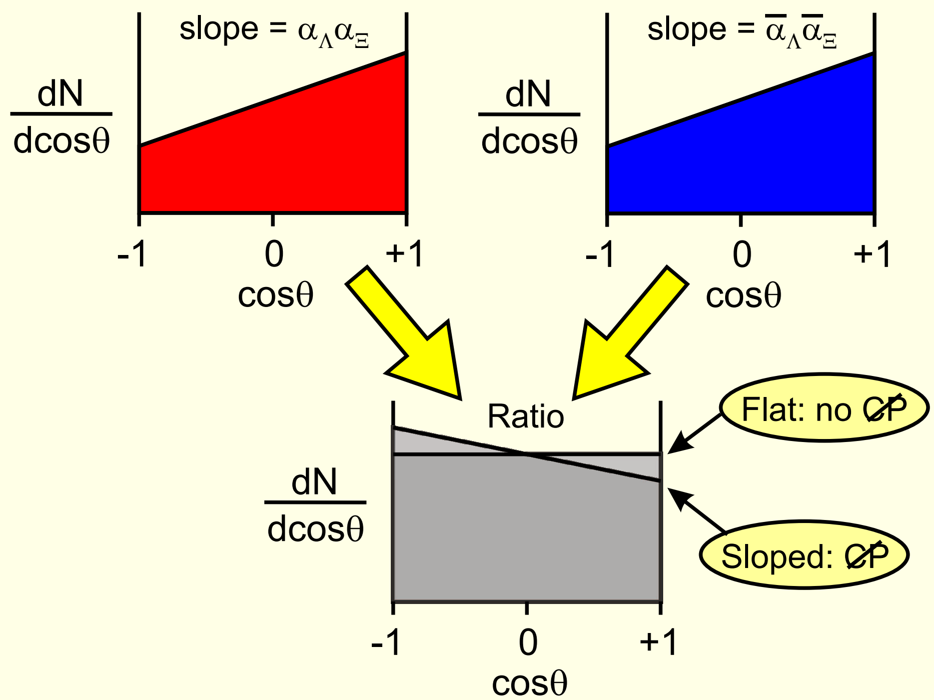
$$\frac{dN_-}{d\cos\theta_-} = A_-\frac{N_-}{2}(1+\alpha_\Xi\alpha_\Lambda\cos\theta_-) \qquad \frac{dN_+}{d\cos\theta_+} = A_+\frac{N_+}{2}(1+\overline{\alpha}_\Xi\overline{\alpha}_\Lambda\cos\theta_+)$$

- Take the ratio of the 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:

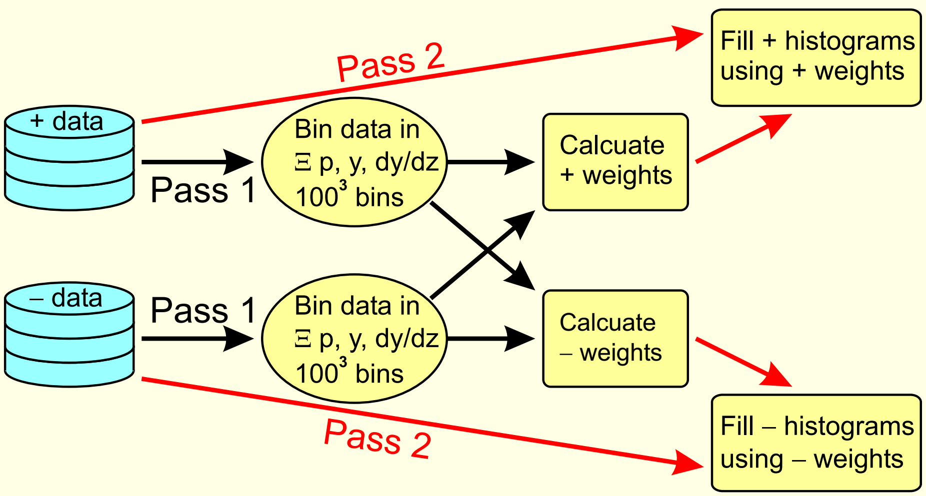
$$\begin{aligned}\delta &= \alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda \\ A_{\Xi\Lambda} &= \frac{\delta}{\alpha_\Xi\alpha_\Lambda+\overline{\alpha}_\Xi\overline{\alpha}_\Lambda} = \frac{\delta}{2\alpha_\Xi\alpha_\Lambda} \\ &= 1.71\,\delta\end{aligned}$$

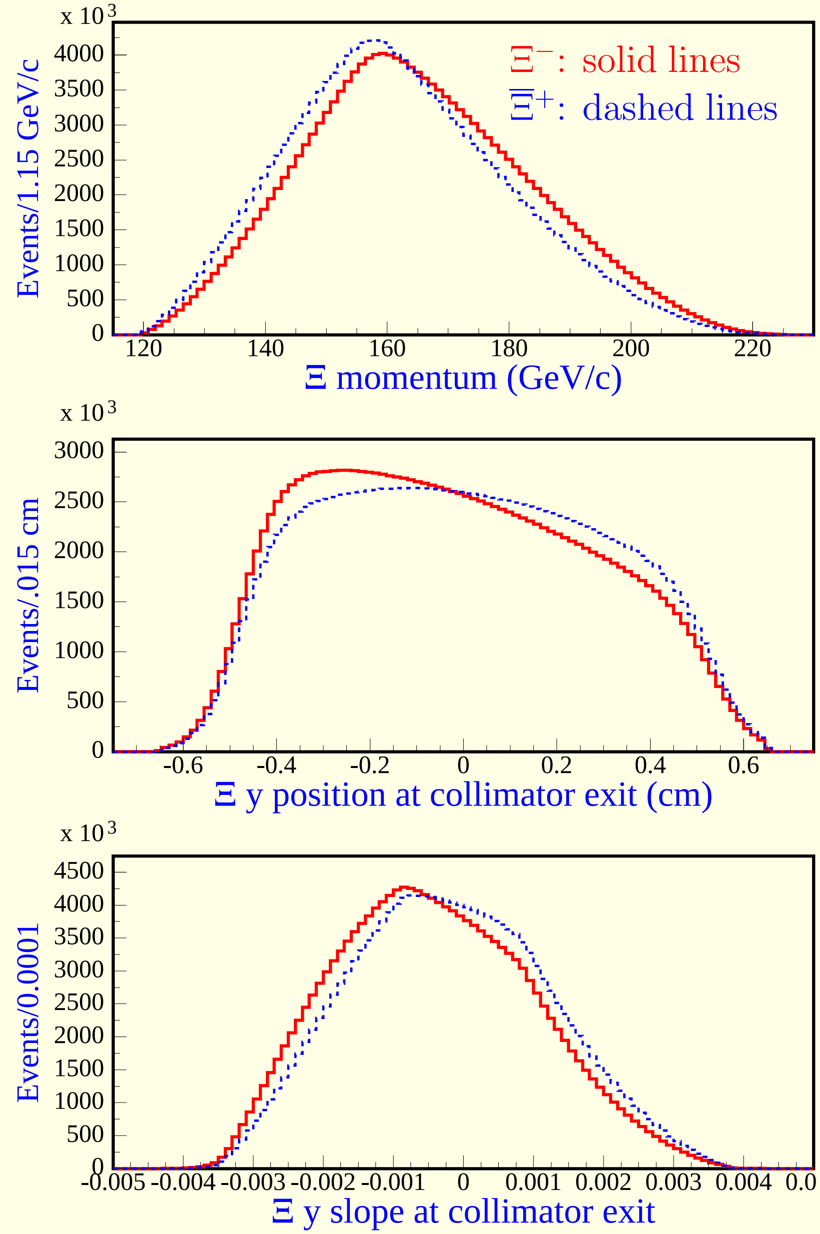


- **Note: No Monte Carlo needed to measure apparatus acceptance.**

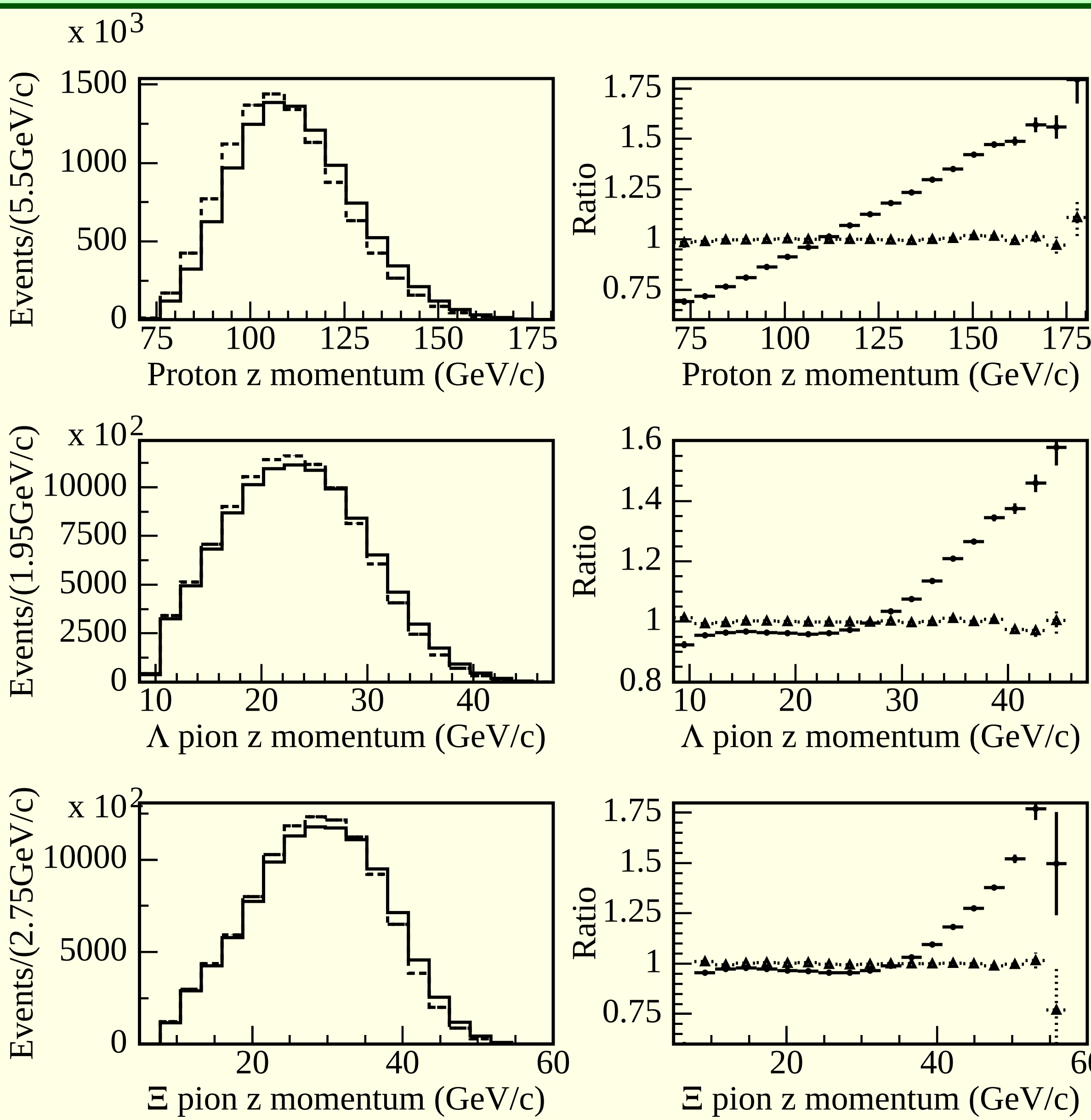
Equalize Ξ^- and $\overline{\Xi}^+$ Acceptances by Weighting Technique

- Problem: Geometrical 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.





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

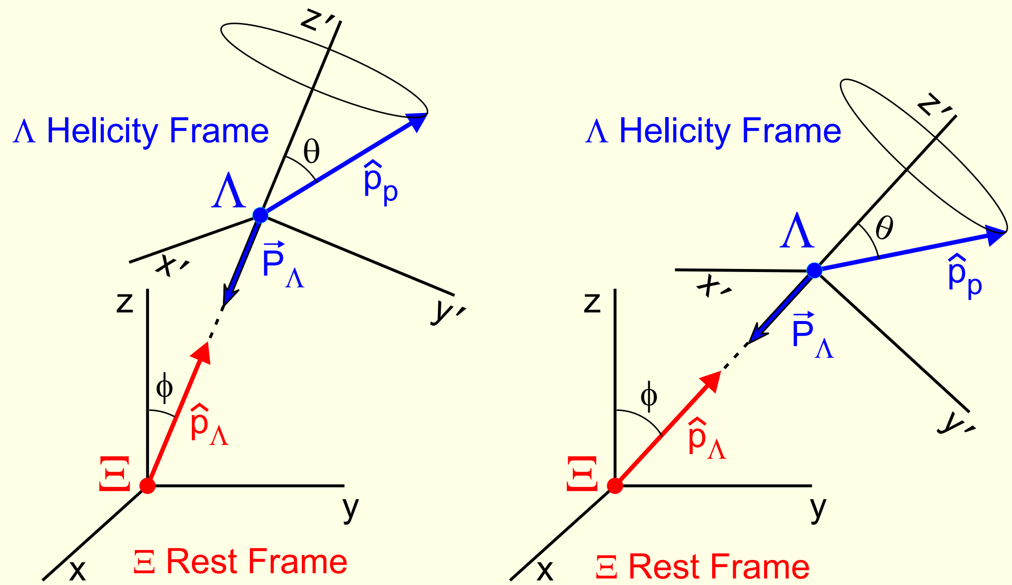


– Solid lines
+ dashed lines

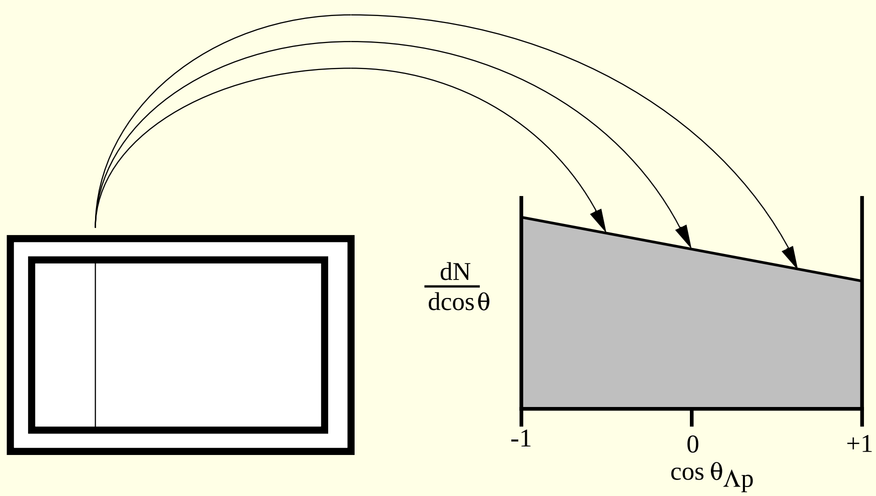
○: before weighting
△ after weighting

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.



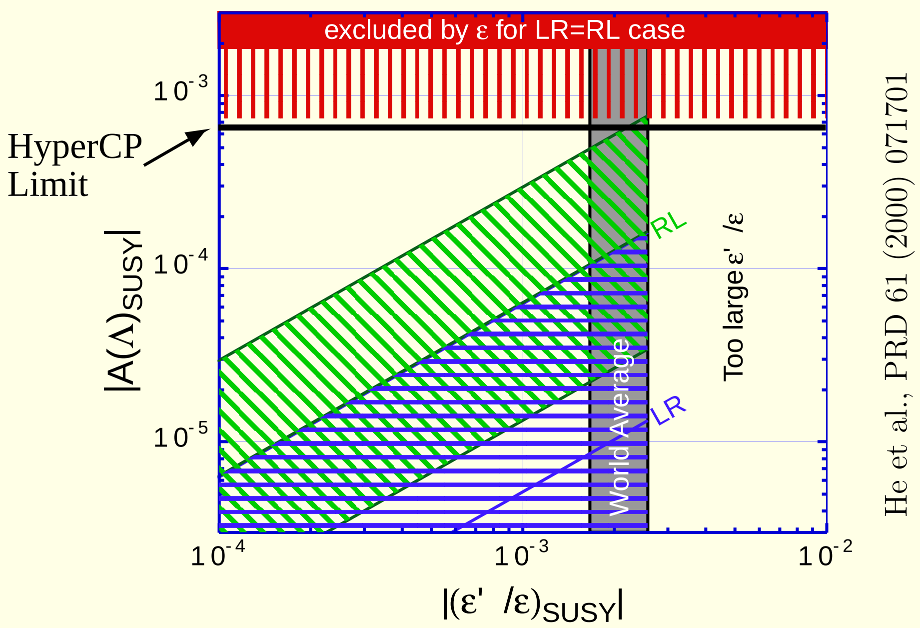
Important! Overall acceptance differences do not cause any biases.

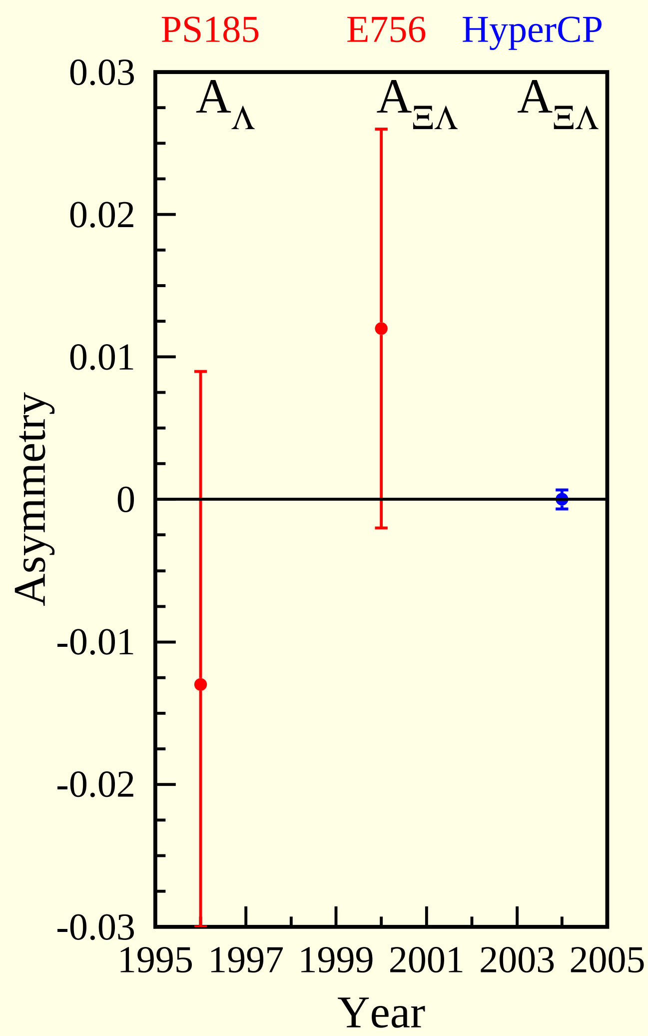
Result from CP Violation Search

- $\sim$10% total data sample.
- 118.6 million Ξ^-, 41.9 million $\overline{\Xi}^+$.

$$A_{\Xi\Lambda} = \frac{\alpha_\Xi\alpha_\Lambda - \overline{\alpha}_\Xi\overline{\alpha}_\Lambda}{\alpha_\Xi\alpha_\Lambda + \overline{\alpha}_\Xi\overline{\alpha}_\Lambda} = [0.0\pm5.1(\text{stat})\pm4.4(\text{syst})]\times10^{-4}$$

- Constraining beyond-the-standard-model predictions which are not well constrained by kaon CP measurements as hyperons probe both parity conserving and parity violating amplitudes.

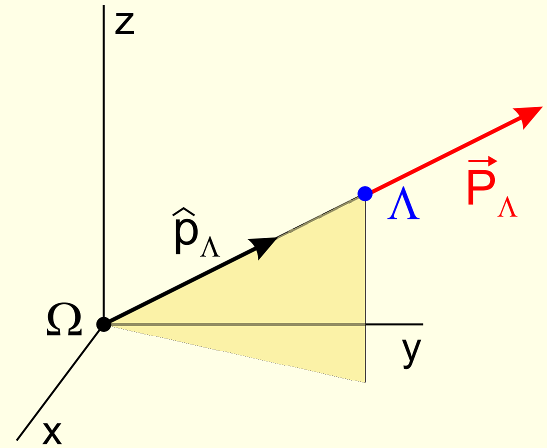




- PRL **93**, 262001 (2004).
- Expect 3× improvement with full dataset.

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

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



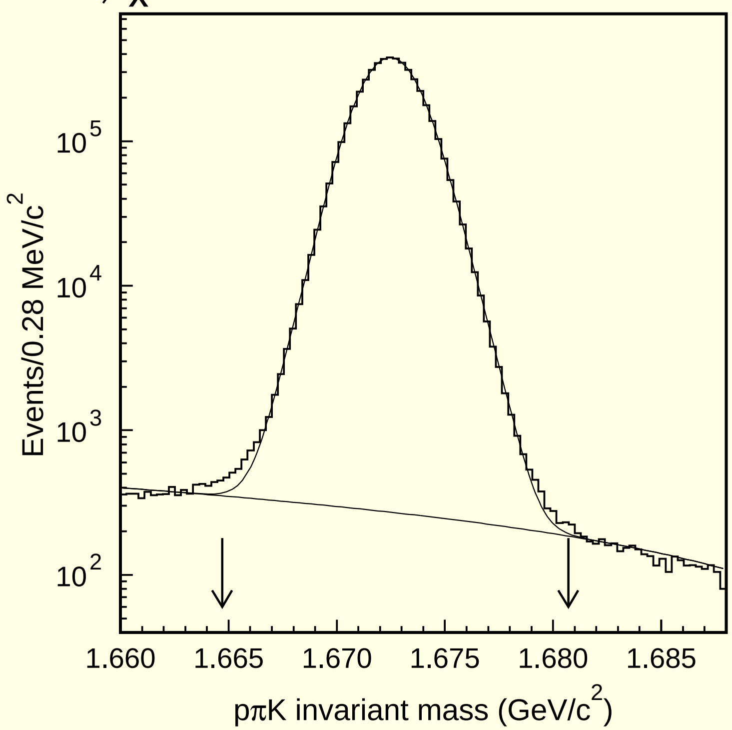
- Although spin-3/2, the unpolarized $\Omega^- \to \Lambda K^-$ decay goes much like the other hyperon two-body decays.
- The Λ decay asymmetry is:

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

- Here:

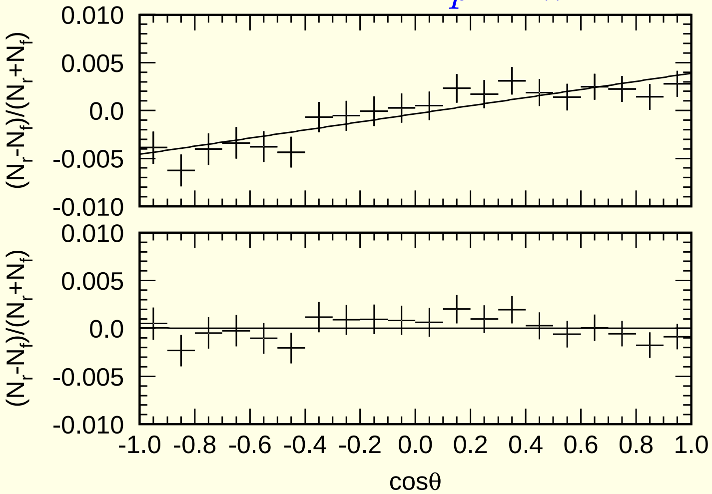
$$\alpha_\Omega = \frac{2\mathrm{Re}(P^* D)}{|P|^2 + |D|^2}$$

- 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.
- Large data sample, little background.



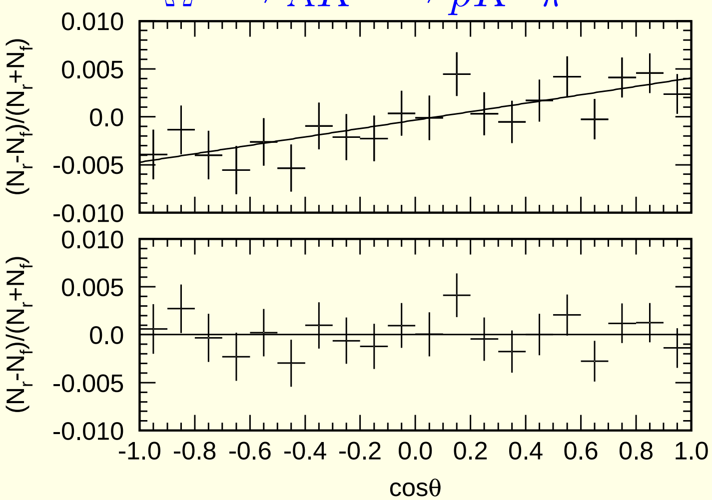
First Observation of Parity Violation in $\Omega^- \to \Lambda K^-$ Decays

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

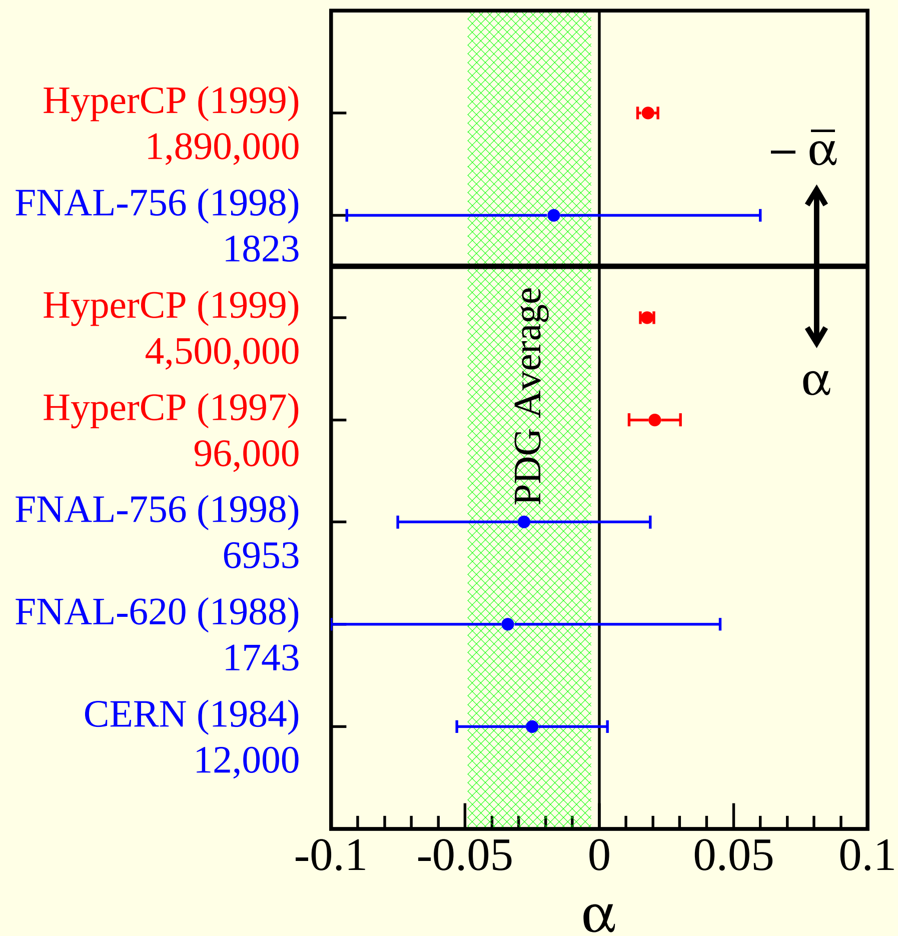


$\alpha_\Omega = [-1.78 \pm 0.19(\text{stat}) \pm 0.16(\text{syst})] \times 10^{-2}$

$\overline{\Omega}^+ \to \overline{\Lambda} K^+ \to \overline{p} K^+ \pi^+$



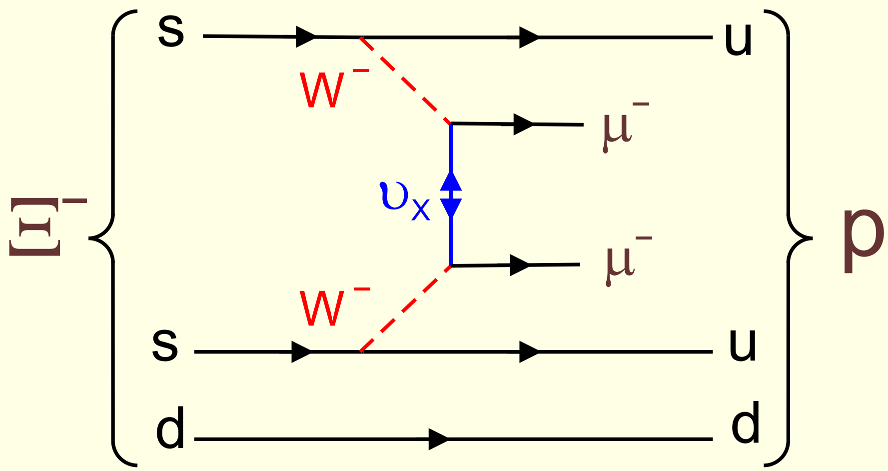
$\overline{\alpha}_\Omega = [+1.81 \pm 0.28(\text{stat}) \pm 0.25(\text{syst})] \times 10^{-2}$



- No evidence of *CP* violation in $\Omega^-/\overline{\Omega}^+$ decays.
- Most precisely know alpha parameter.
- 97: PRD **71**, 051102(R) (2005)
- 99: PLB **617**, 11 (2005)

Search for Lepton Number Violation

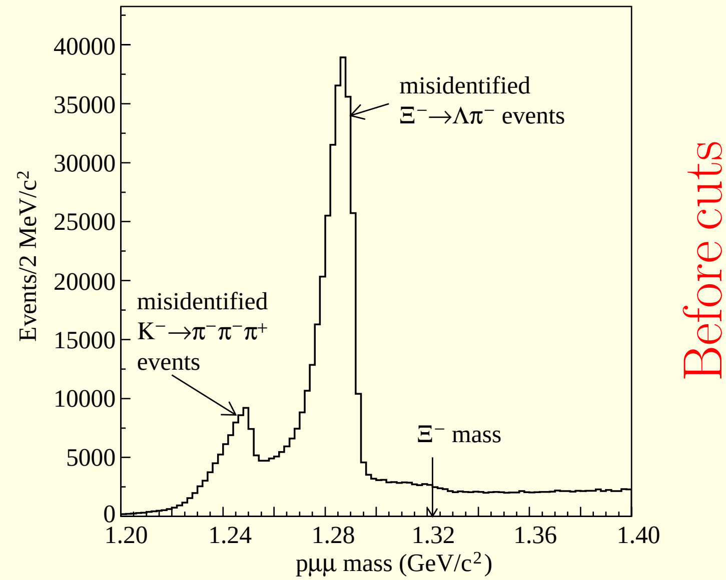
$\Xi^- \rightarrow p\mu^-\mu^-$

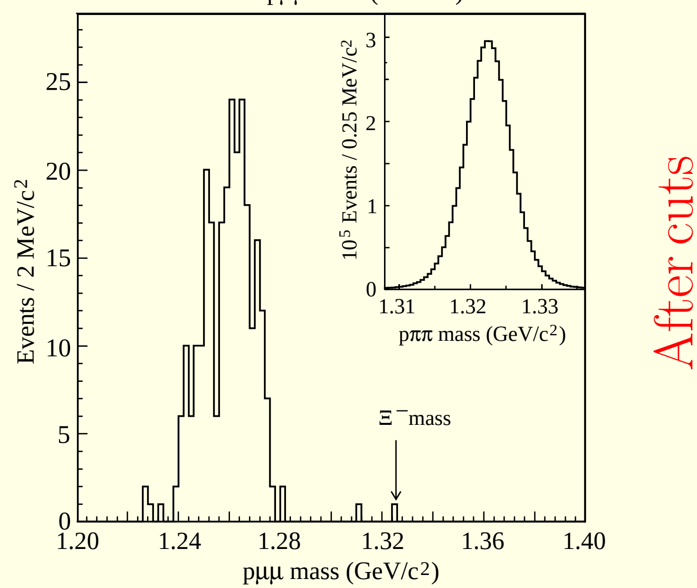


- Lepton number violating decay could imply existence of Majorana type neutrino.
- Not constrained by limits on neutrinoless double β decay.

$$\frac{B(\Xi^- \rightarrow p\mu^-\mu^-)}{B(\Xi^- \rightarrow all)} < 4.0\times10^{-8} \text{ @ 90\% CL}$$

- PDG limit :$< 3.7\times10^{-4}$ @ 90% CL (Littenberg and Shrock)
- to appear in PRL





Search for $\Delta S = 2$ Hyperon Decays

- SM branching ratios $< 10^{-12}$
  $\Rightarrow$ window for new physics

$$B(\Xi^0 \to p\pi^-) = 0.9 \left(\frac{\alpha_{\text{new}}}{\alpha_{\text{EW}}}\right)^2$$

- Important: 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^0-$\overline{K}^0$ mixing."

  He and Valencia, PL B409 (1997) 469.

- Look for two decays:

$$\Omega^- \to \Lambda\pi^- \qquad \Omega^- \to \Xi^0\pi^-$$
$$\hookrightarrow p\pi^- \qquad\qquad \hookrightarrow p\pi^-$$

- Nothing found: limits improved by large amounts.

	Limits (90% CL)	
Mode	***HyperCP***	**PDG**
$\Omega^- \to \Lambda\pi^-$	$< 2.9\times10^{-6}$	$< 1.9\times10^{-4}$
$\Xi^0 \to p\pi^-$	$< 8.2\times10^{-6}$	$< 3.6\times10^{-5}$

- PRL **94**, 101804 (2005)

Study of $\Omega^- \to \Xi^-\pi^+\pi^-$ Decay

- Decay can proceed two ways:

$$\Omega^- \to \Xi^-\pi^+\pi^- \quad \hookrightarrow \Lambda\pi^- \quad \hookrightarrow p\pi^-$$

$$\Omega^- \to \Xi^{*0}(1530)\pi^- \quad \hookrightarrow \Xi^-\pi^+ \quad \hookrightarrow \Lambda\pi^- \quad \hookrightarrow p\pi^-$$

- The current PDG branching ratios:

$$\left.\begin{aligned} \mathrm{BR}(\Omega^- \to \Xi^-\pi^+\pi^-) &= (4.3^{+3.4}_{-1.3})\times 10^{-4} \\ \mathrm{BR}(\Omega^- \to \Xi^{*0}(1530)\pi^- \to \Xi^-\pi^+\pi^-) &= (6.4^{+5.1}_{-2.0})\times 10^{-4} \end{aligned}\right\}$$

Based on 4 events from Bourquin et al. NPB 241, 1 (1984).

- Theory favors resonance mode.
- Hence Bourquin et al. assumed that their four events were all from the resonance mode, although the evidence is not compelling.
- *HyperCP* observes 137 events, giving a preliminary BR of:

$$\mathrm{BR}(\Omega^- \to \Xi^-\pi^+\pi^-) = [3.6\pm 0.3(\mathrm{stat})\pm 0.45(\mathrm{syst})]\times 10^{-4}$$

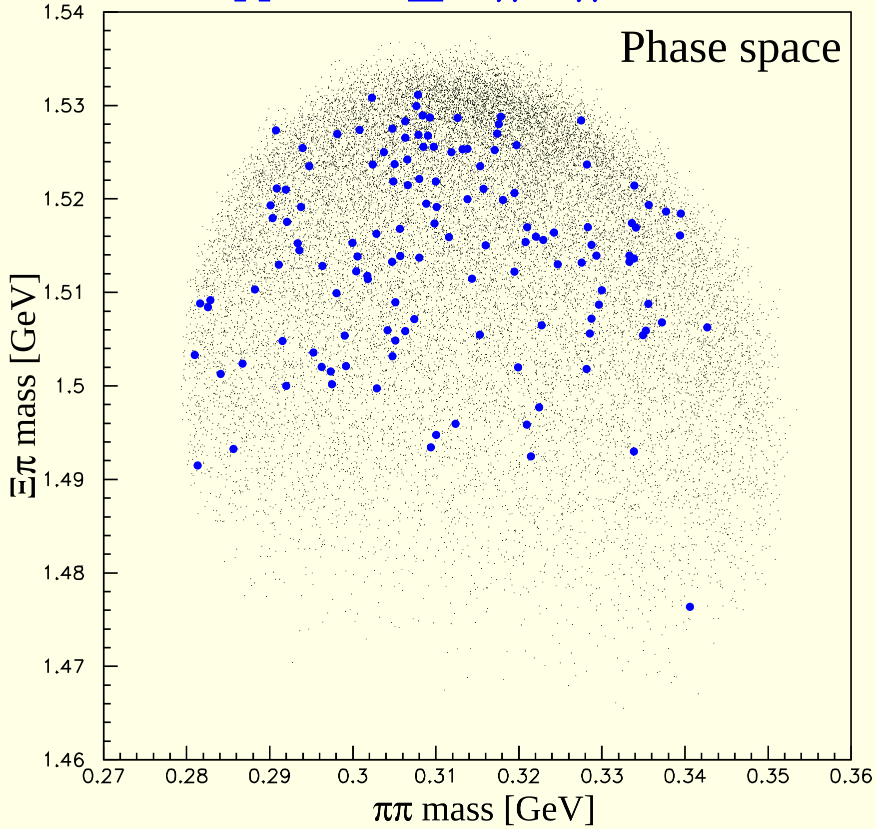
NPB (Proc. Suppl.) 115, 54 (2003).

- What fraction of these events come from the resonance decay?

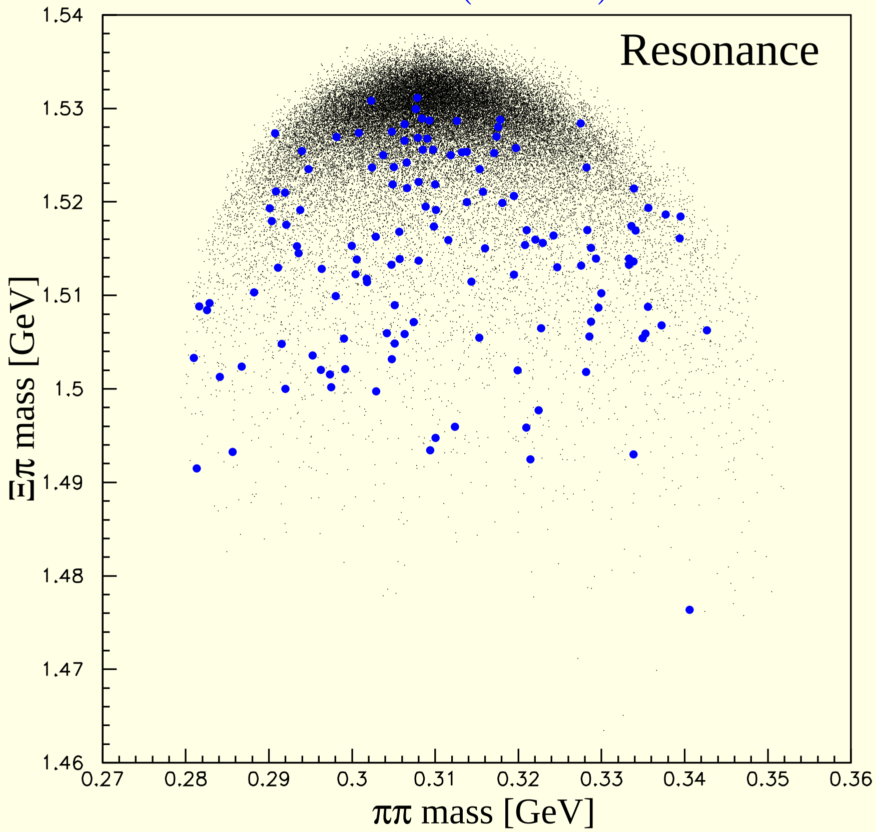
Dalitz Plot: Phasespace vs Resonance

- Big blue dots: data.
- **Small black dots**: Monte Carlo.

$\Omega^- \rightarrow \Xi^- \pi^+ \pi^-$



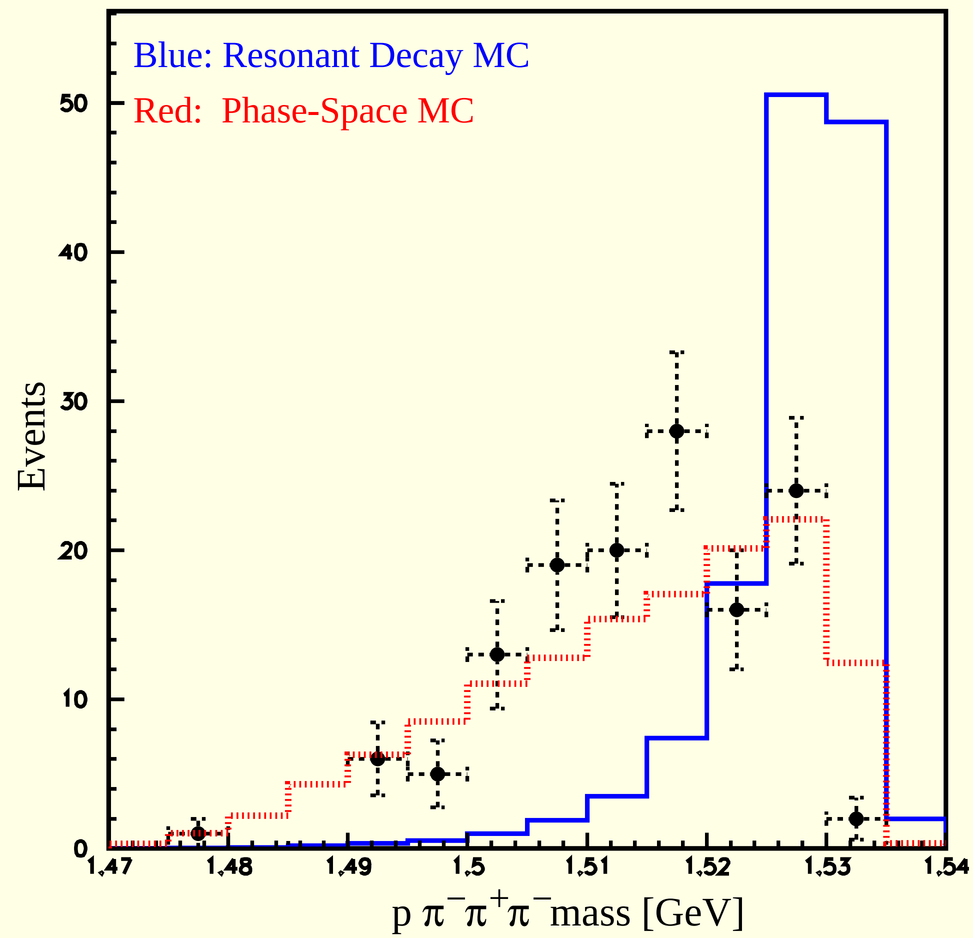
$\Omega^- \rightarrow \Xi^{*0}(1530)\pi^-$



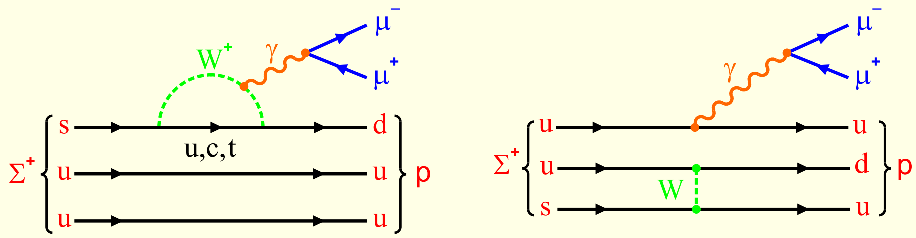
- The data are more consistent with the 3-body phase-space decay than with the resonance mode.

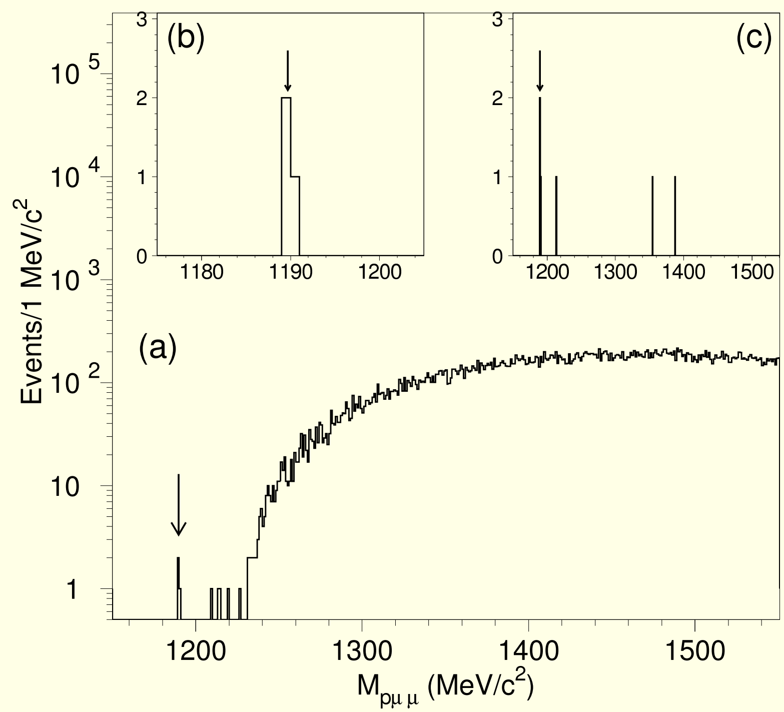
The $p\pi^-\pi^+\pi^-$ Invariant Mass

- Data is inconsistent with the $\Omega^- \to \Xi^{*0}(1530)\pi^-$ decay.
- Data more consistent with $\Omega^- \to \Xi^-\pi^+\pi^-$ uniform phase-space decay.
- Agreement with $\Omega^- \to \Xi^-\pi^+\pi^-$ decay not perfect.
- Linear superposition of both decays improves fit, **but only if coefficient for $\Omega^- \to \Xi^{*0}(1530)\pi^-$ decay is negative!**
- **Preliminary!**



Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$





- Three events represent the rarest decay of a baryon ever observed:

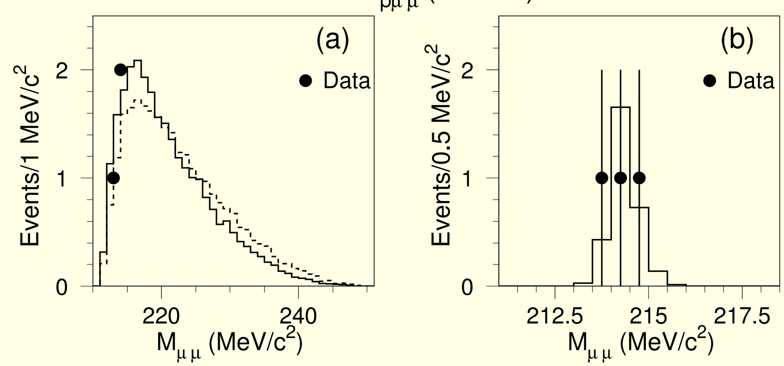
$$\frac{B(\Sigma^+ \rightarrow p\mu^+\mu^-)}{B(\Sigma^+ \rightarrow \mathrm{all})} = [8.6^{+6.6}_{-5.4}(\mathrm{stat}) \pm 5.5(\mathrm{syst})] \times 10^{-8}$$

- Narrow dimuon mass, $\mathrm{m} = 214.3 \pm 0.5\,\mathrm{MeV}$, suggests decay proceeds via hitherto unknown particle: could it be the pseudoscalar sgoldstino of Gorbunov and Rubakov?

$$\Sigma^+ \rightarrow pP^0 \rightarrow p\mu^+\mu^-$$

- PRL **94**, 021801 (2005)

This needs to be confirmed!



Conclusions and Outlook

- Very high-statistics hyperon data samples can be easily obtained at high-energy accelerators like Fermilab.
- With present technology the ∼1 billion event *HyperCP* data sets can be easily increased to ∼10 billion events, if not more.
- These data sets allow very high-precision measurements and sensitive rare-decay searches to be made in the hyperon sector.
- These limits are often not constrained by measurements in the kaon system.
- *HyperCP*'s hyperon *CP*-violation measurements are 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)

- **Unfortunately, after some thirty years of impressive experimental work, hyperon physics, indeed non-neutrino fixed-target physics, is finished at Fermilab.**