Report from the Fermilab HyperCP Experiment: Search for CP Violation in Hyperon Decays

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The HyperCP Experiment took data at the Fermi National Accelerator Laboratory.

- The experiment has took data in the 1997 fixed target run at Fermilab.
- Results presented here are PRELIMINARY .
- The HyperCP Experiment's primary Physics goal is to look for CP violation in the decays of Ξ hyperons.

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

- Other Physics to be explored by the HyperCP Experiment include:
  - Search for rare decays:
    * $\mathrm{K}^\pm \rightarrow \pi^\pm\mu^+\mu^-$.
    * $\mathrm{K}^- \rightarrow \pi^+\mu^-\mu^-$.
    * $\Xi^- \rightarrow \mathrm{p}\,\mu^-\mu-$
  - Search for CP violation in $\mathrm{K}^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decays.
- All Physics uses a "left-right" trigger for the spectrometer.
  - An event with at least one particle with the beam sign and at least one particle with opposite the beam sign.

Physics of CP Violation in Ξ decays

- The non-leptonic decay of the Ξ hyperon is described in terms of the Lee-Yang variables:

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

- Under CP operation, α and β change signs, γ is unchanged.
- The decay distribution for the daughter spin $\frac{1}{2}$ baryon in the rest frame of the parent hyperon is:

$$\frac{dP}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \vec{P}_p \cdot \hat{p}_d)$$

- Where in the rest frame of the parent:
  - $\vec{P}_p$ is the parent hyperon polarization.
  - $\hat{p}_d$ is the daughter baryon momentum direction.
- The daughter baryon is polarized according to:

$$\vec{P}_d = \frac{(\alpha + \vec{P}_p \cdot \hat{p}_d)\hat{p}_d + \beta(\vec{P}_p \times \hat{p}_d) + \gamma(\hat{p}_d \times (\vec{P}_p \times \hat{p}_d))}{(1 + \alpha \vec{P}_p \times \hat{p}_d)}$$

- Where:
  - α, β, γ are the Lee-Yang variables.

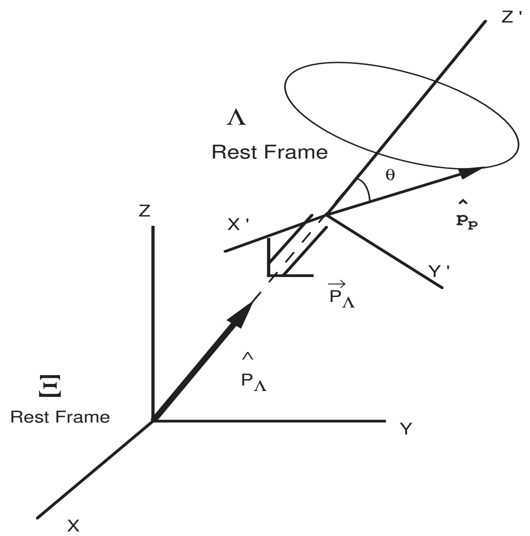
- The HyperCP Experiment uses unpolarized Ξ particles.
  - (Use 0^o production angle for Ξ.)
- As a result the daughter Λ polarization is:

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

- The polarization of the Λ may be measured by the decay asymmetry:

$$\frac{dP}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{p}_p)$$

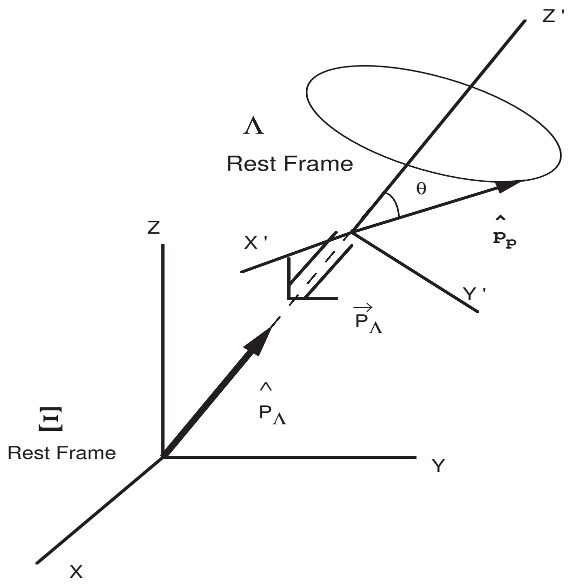
- Where
  - $\hat{p}_p$ is the direction of the proton (anti-proton) in the Λ ($\overline{\Lambda}$) rest frame.
  - Note the polarization of the Λ is : $\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda$



- The asymmetry in the proton (anti-proton) decay distribution is:
  - (After integrating over the azimuthal angle.)

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

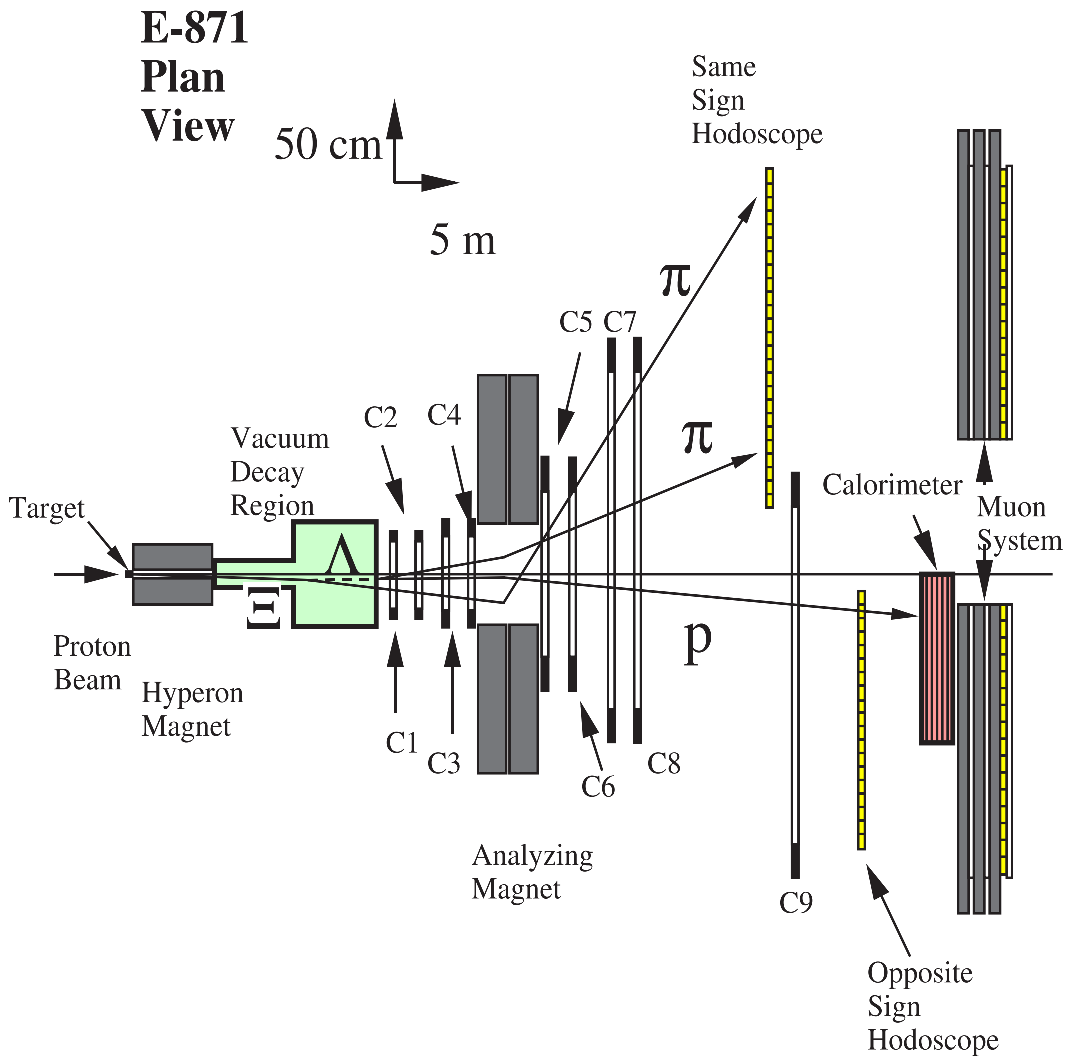
- Note the "Z" axis in the Λ rest frame is defined by the Λ direction in the Ξ rest frame.
- So the "θ" is the polar angle of the proton (or anti-proton) in the Λ rest frame.
- Any differences in the angular distributions of the proton from Ξ^- decays and anti-proton from $\overline{\Xi}^+$ decays is a signature of CP Violation.



- The combined asymmetry parameters for the Ξ and Λ will be determined from the angular distributions.
- A CP asymmetry may be constructed:

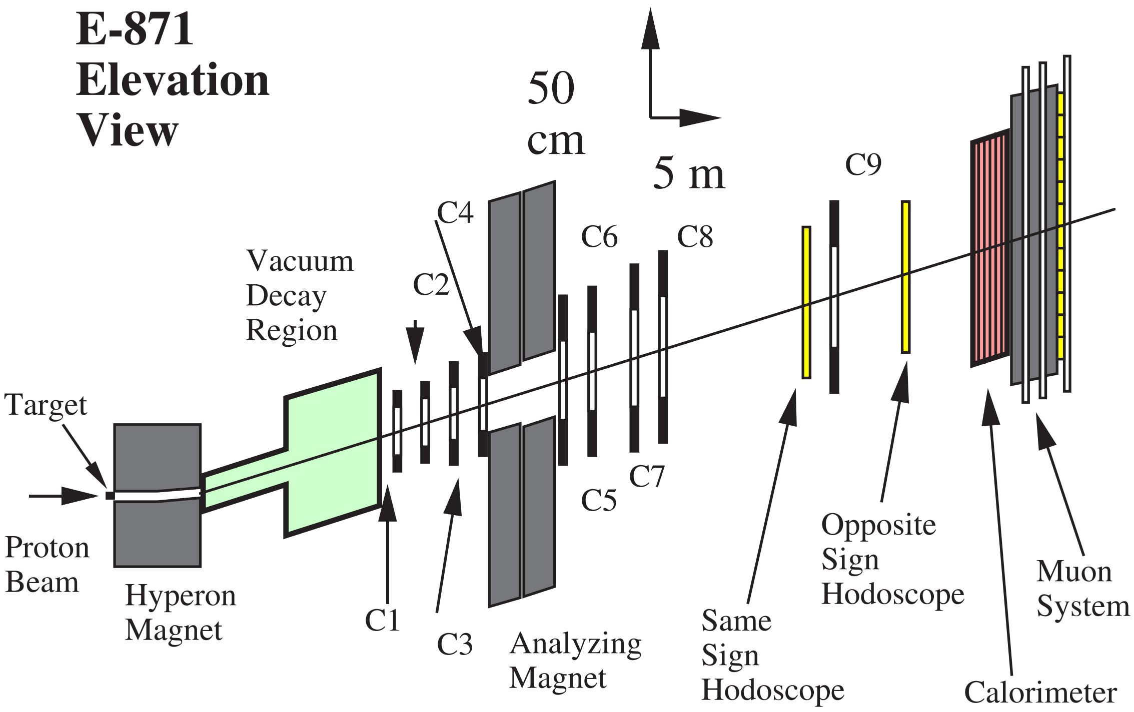
$$\mathcal{A} = \frac{\alpha_\Lambda \alpha_\Xi - \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}}}{\alpha_\Lambda \alpha_\Xi + \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}}}$$

- The HyperCP experiment collected 67×10^9 triggers to tape.
- This data should contain roughly 1.1×10^9 Ξ^- reconstructible decays and 4.5×10^8 $\overline{\Xi}^+$ reconstructible decays.
- This results in a overall sensitivity of 1.7×10^{-4} for the CP asymmetry $\mathcal{A}$.
- Theoretical predictions using the Standard Model predict a value for the CP asymmetry $\mathcal{A}$ of -0.7×10^{-4} to -8.8×10^{-4}.
  - Using other non-standard models will widen this range or even exclude CP violation in Ξ decays.

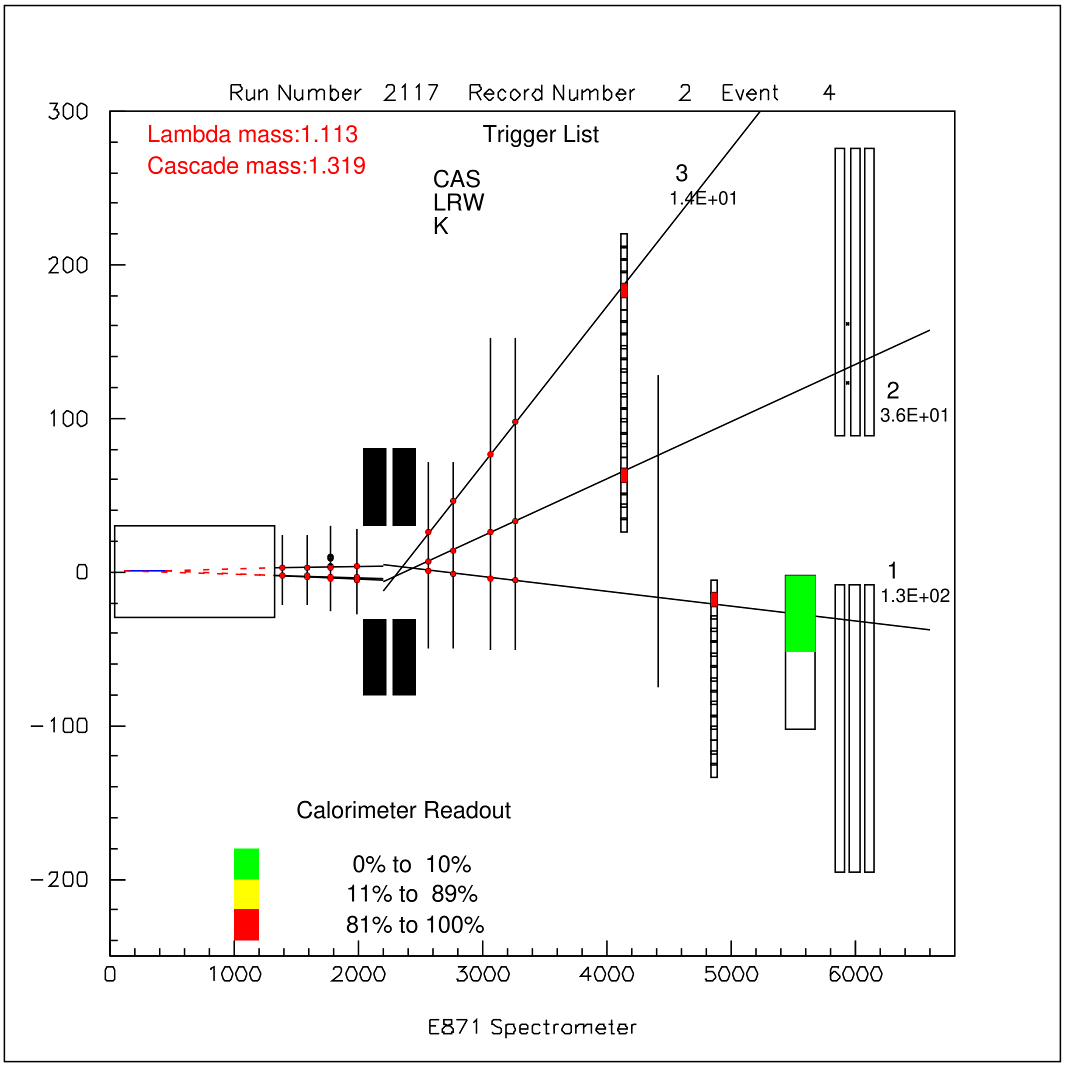


- HyperCP spectrometer: Plan View.
- 800 GeV/c primary proton beam hits target.
- 150 GeV/c secondaries exit the Hyperon magnet.
  - Negative mode secondary beam contains Ξ^-.
  - Positive mode secondary beam contains $\overline{\Xi}^+$.
- Four PWC's upstream an analysis magnet, Four PWC's downstream.

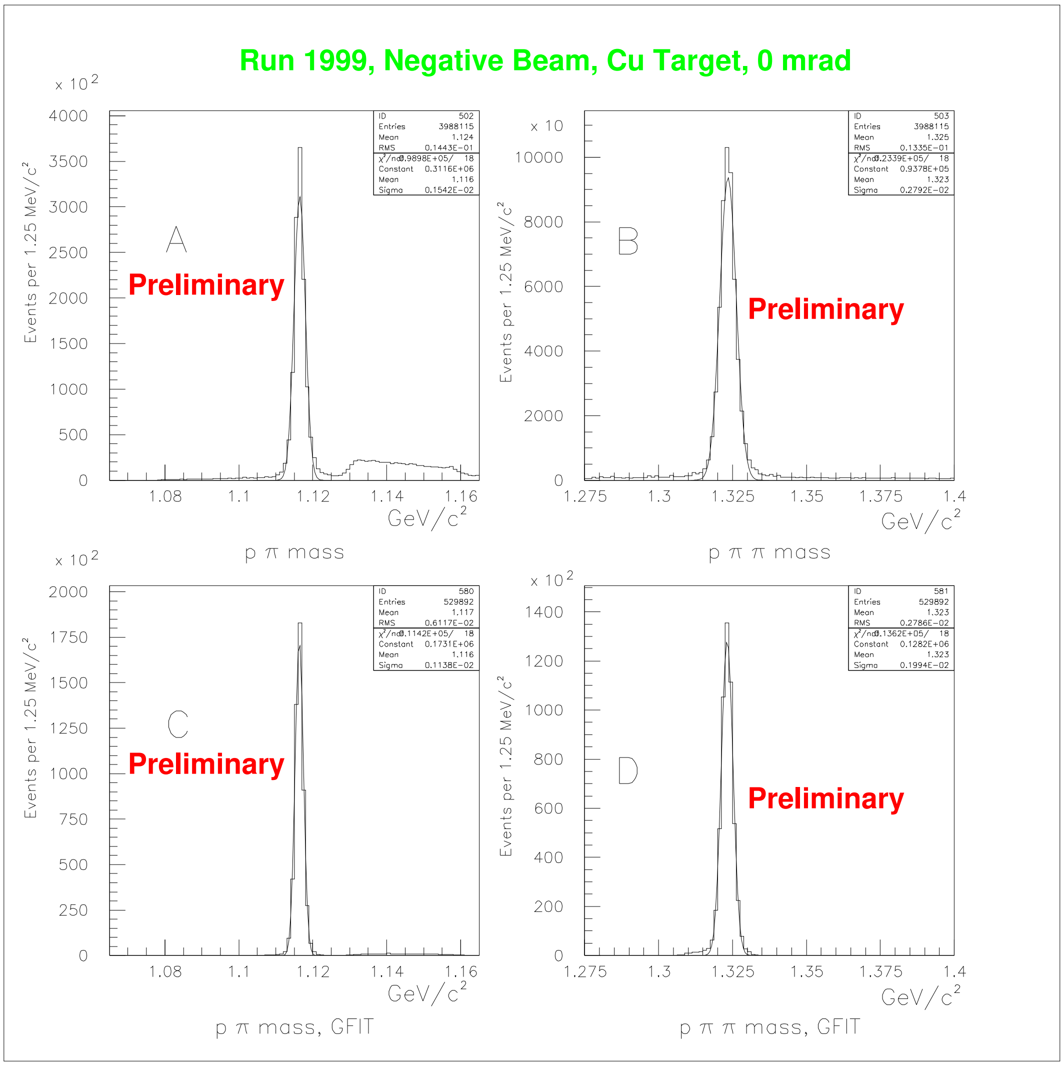
- Two trigger hodoscopes to form “left-right” trigger.
- Calorimeter used for halo muon rejection.
- Muon identification down stream used for rare decay trigger.



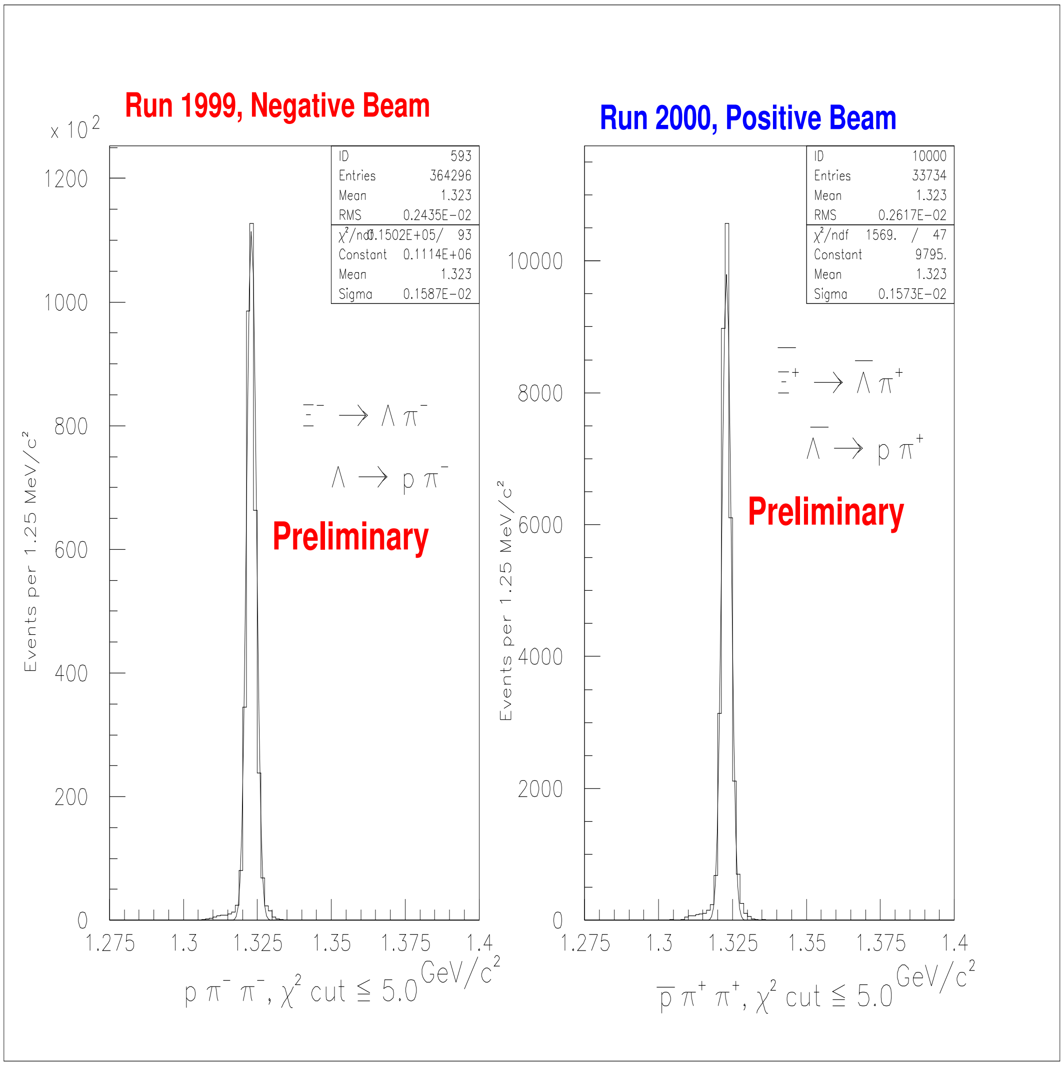
- HyperCP spectrometer: Elevation View.
- The secondaries are bent vertically.



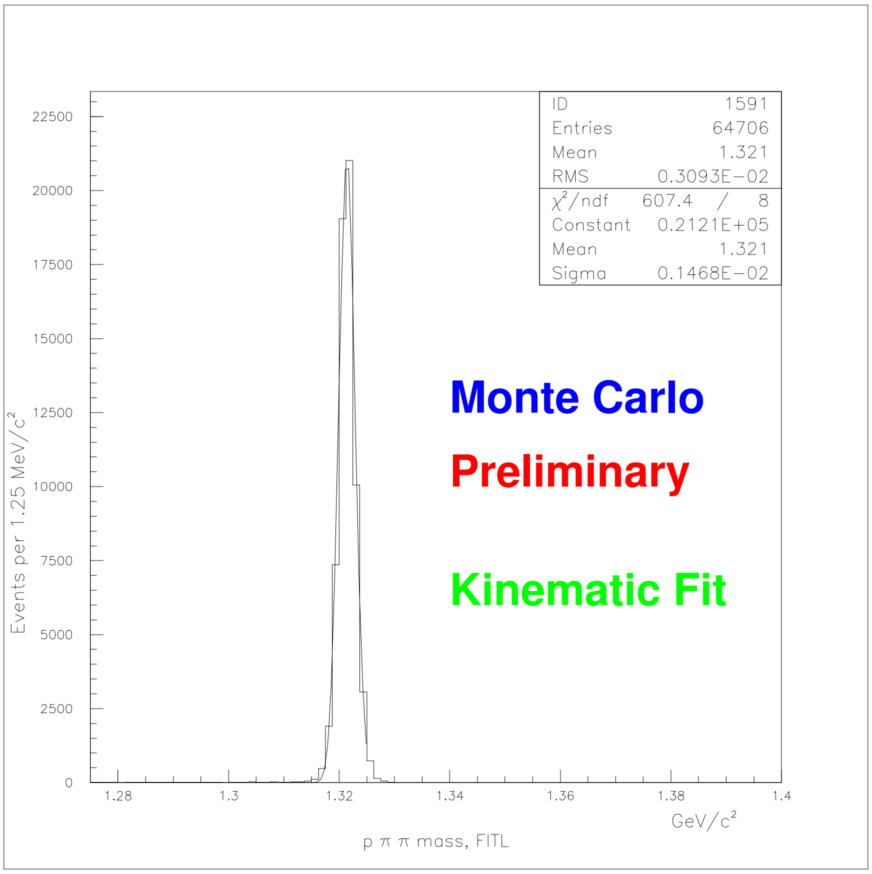
- Event display of a typical Ξ event.
- Tracking is used to draw tracks.
- Hits used by tracking are colored "red".
- Track number and total momentum are calculated.
- Hits in the trigger hodoscope are colored red.
- Calorimeter has percent dynamic range color coded.
- Ξ and Λ mass are calculated.



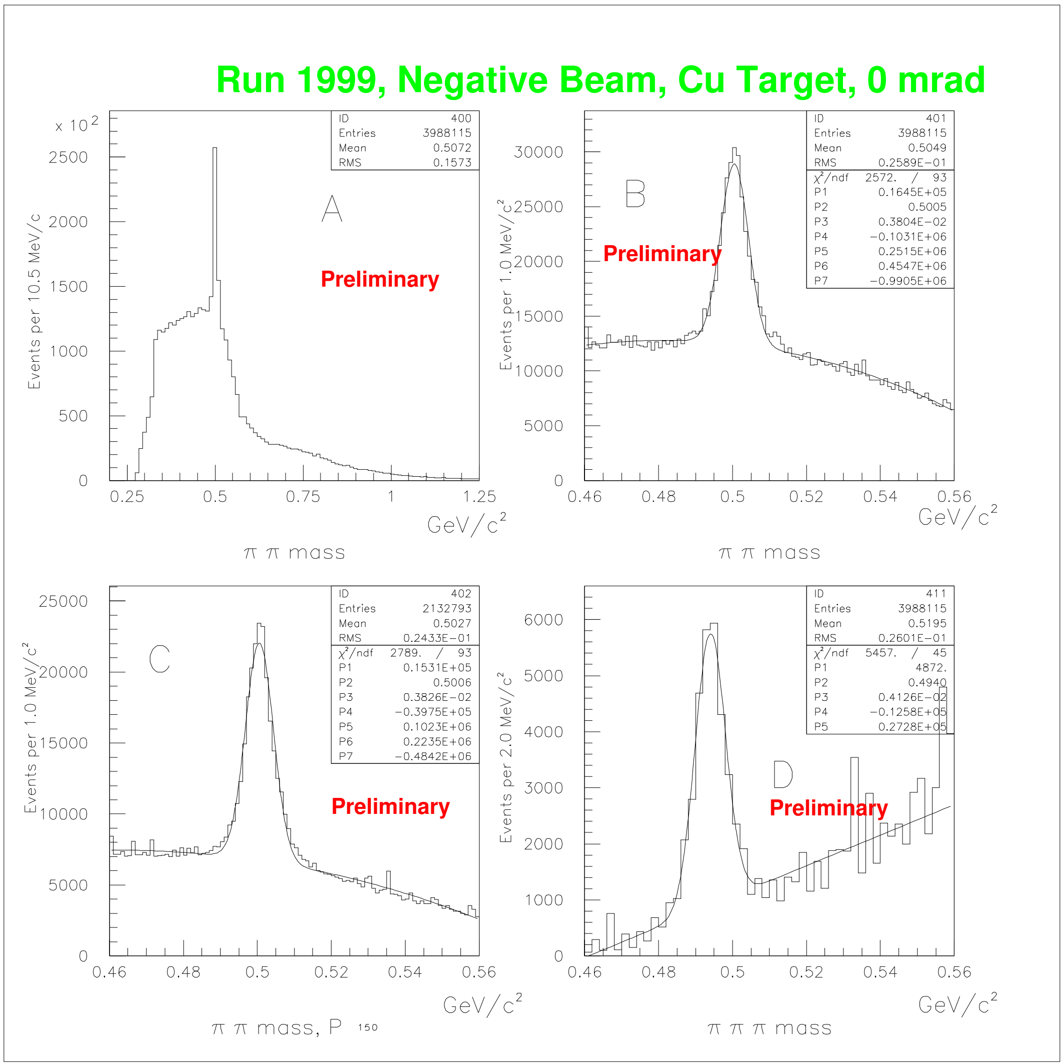
- Figure A is the invariant mass of Same-sign and Opposite-sign tracks.
  - Same-sign are tracks with same sign as secondary beam.
  - Pick pairs of tracks with distance of closest approach.
- Figure B is the invariant mass of two Same-sign and one Opposite-sign tracks.
- Figure C is the invariant mass for Same-sign and Opposite-sign tracks out of the Geometric Fit.
  - Geometric Fit fits to the geometry of a "kink" and neutral "vee".
- Figure D is the three track combination out of the Geometric fit.



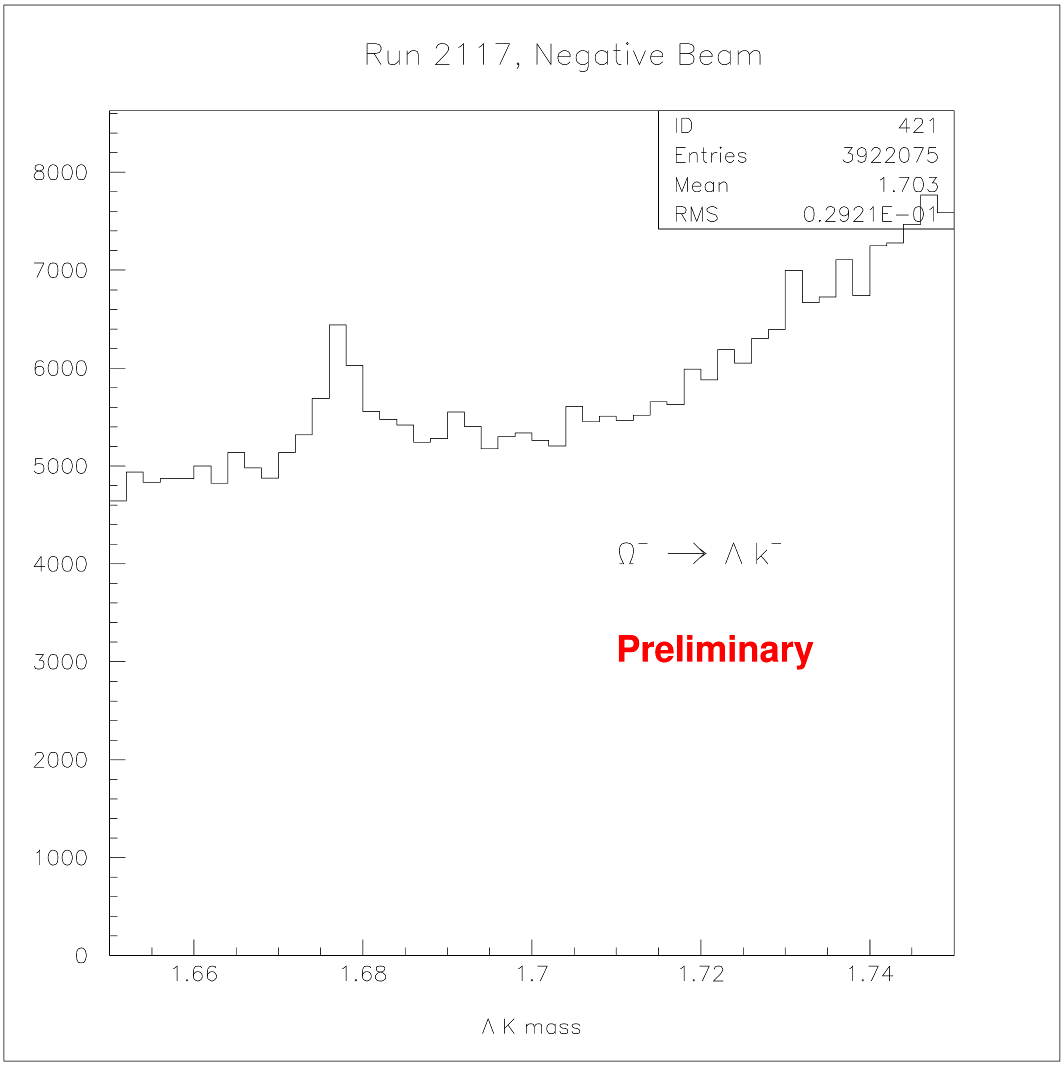
- Ξ^- and $\overline{\Xi}^+$ using the Kinematic Fit.
- Kinematic fit requires the neutral "vee" vertex to:
  - Have the mass of the Λ.
  - Momentum to be conserved in the Λ rest frame.
- These plots also have a χ^2 cut of 5.0.



- Monte Carlo of Ξ mass resolution.
- Ξ events are generated and are traced through the hyperon magnets.
- Ξ's are allowed to decay via $\Xi \to \Lambda\pi \to p\pi\pi$ mode.
- Events that satisfy the trigger are reconstructed with the same tracking, geometric and kinematic fitting programs as the data.
- This plot contains the invariant mass distribution as calculated from the kinematic fit.
- The resolution is 1.47 MeV/c^2 from the Monte Carlo
- The resolution from real data is about 1.6 MeV/c^2.



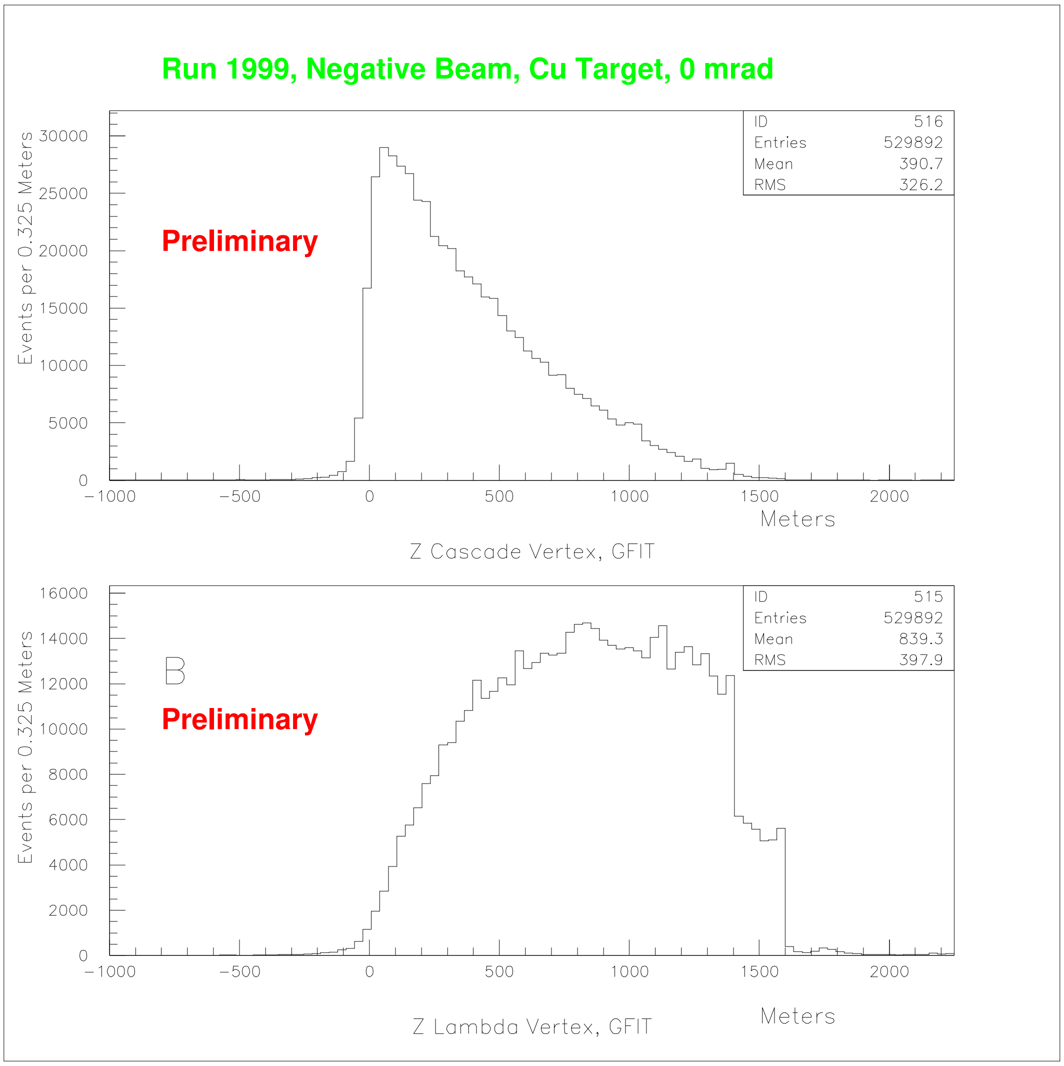
- K_{short}'s are produced at the collimator exit.
- Use Same-sign and Opposite-sign track pair that have distance of closest approach.
- Figure A



- $\Omega^- \to \Lambda K^- \to p\pi^- K^-$.
- This is the same topology as the $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$.
- Use the same geometric fit (for the decay geometry).
- And the same kinematic fit (for the Λ decay).
- The Ω^- has a mass of approximately 1.672 GeV/c^2.

Conclusions

- The HyperCP experiment has collected the largest Ξ^- and $\overline{\Xi}^+$ sample in the world.
  - The experiment recently concluded its first round of data collection at Fermilab (September 1997).
  - The experiment collected 67×10^9 triggers.
  - 1.1×10^9 reconstructible Ξ^-
  - 4.5×10^8 reconstructible $\overline{\Xi}^+$
  - The HyperCP experiment anticipates a sensitivity of the CP violating asymmetry $\mathcal{A}$ of 1.7×10^{-4}.
  - The experiment should have:
    * 2.2×10^7 reconstructible Ω^-.
    * 9.0×10^6 reconstructible $\overline{\Omega}^+$.
- The experiment is in the early analysis stage.
- The experiment anticipates analyzing approximately 10% of its data by January 1998.
- The HyperCP experiment is also applying for more beam time in the next fixed target run at Fermilab in 1998.



- Figure A: The Ξ vertex distribution.
- Figure B: The Λ vertex distribution.

CP Violation in the K^o System

- K^o and $\overline{K}^o$ are produced via the strong interaction.
- They decay via the weak interaction.
  - The weak (decay) states are not eigenvectors of the strong (production) states.
  - Results in quantum mechanical mixing.
- Assume that weak interaction is symmetric under CP.
- Expect two CP eigenstates:

$$\boxed{\begin{array}{ll} |K_1\rangle = \frac{1}{\sqrt{2}}(|K^o\rangle + |\overline{K}^0\rangle) & \text{CP even} \\ |K_2\rangle = \frac{1}{\sqrt{2}}(|K^o\rangle - |\overline{K}^0\rangle) & \text{CP odd} \end{array}}$$

- These are CP eigenstates, and decay in to CP eigenstates

$$\begin{array}{lll} CP|K_1\rangle = +1|K_1\rangle & |K_1\rangle \rightarrow 2\pi & \text{CP even} \\ CP|K_2\rangle = -1|K_2\rangle & |K_2\rangle \rightarrow 3\pi & \text{CP odd} \end{array}$$

- As a result, one expects to see only two types of decays:

Decay	Lifetime	
$k_{short} \rightarrow \pi^+\pi^-$	$\tau \rightarrow 0.892 \times 10^{-10}$ sec	CP even
$k_{long} \rightarrow \pi^+\pi^-\pi^o$	$\tau \rightarrow 5.17 \times 10^{-10}$ sec	CP odd

- In 1964 it was discovered that the long lived $|K_2\rangle$ state could decay into the 2π state!
  - The asymmetry is on the order of 3×10^{-3}.
  - The K^o system is the only system that CP violation has been observed in.

- CP violation in the K^o system has also been observed in the asymmetry in the decay rates of:

$$K_{long} \rightarrow e^+\nu_e\pi^- \; K_{long} \rightarrow e^-\overline{\nu_e}\pi^+$$

Experimental Upper Limits on CP Violations in Hyperon Decay

- Only experimental upper limits exist for CP violation in hyperon decays.
- Experiments have looked for CP violation in $\Lambda/\overline{\Lambda}$ decays.

$\overline{p}p \to \Lambda X, \overline{p}p \to \overline{\Lambda} X$	0.02	$\pm$	0.14	R608
$e^+e- \to J/\psi \to \Lambda\overline{\Lambda}$	0.01	$\pm$	0.10	DM2
$\overline{p}p \to \Lambda\overline{\Lambda}$	0.013	$\pm$	0.022	PS185
Recomputed World Average	0.013	$\pm$	0.021	

- The theoretically expected value for the CP asymmetry in the $\Lambda/\overline{\Lambda}$ system is $-0.3 \times 10{-}4$ to -4.0×10^{-4}.
- These experiments are not sensitive enough to see CP violation that is consistent with the Standard Model.

- R608: P. Chauvat et al., Phys. Lett **B163** (1985) 273.
- DM2: M. H. Tixier et al., Phys. Lett. **B212** (1988) 523.
- PS 185: P. D. Barnes et al., Phys. Lett. **B199** (1987) 147.

Λ and Ξ Hyperons

Λ

- Quark content: up, down, strange.
- Electric charge: 0 (neutral)
- Mass: 1.115684 ± 0.000006 GeV/c^2.
- Lifetime: $(2.632 \pm 0.020) \times 10^{-10}$ sec.
- Asymmetry: $\alpha = 0.642 \pm 0.013$.
- Major decay modes:
  - p π^-, Br = 0.639
  - n π^o, Br = 0.358

Particle Data Group, Phys. Rev. (**D54**)51.

Ξ^-

- Quark content: down, strange, strange.
- Electric charge: -1.
- Mass: 1.32132 ± 0.00013 GeV/c^2.
- Lifetime: $(1.639 \pm 0.015) \times 10^{-10}$ sec.
- Asymmetry: $\alpha = -0.456 \pm 0.014$.
- Major decay modes:
  - $\Lambda\pi^-$, Br = 0.99887

Particle Data Group, Phys. Rev. (**D54**)54.