CP Violation in Hyperon Decays

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NONLEPTONIC HYPERON DECAYS

- **Parity violating, ΔS = 1 decay of spin-$\frac{1}{2}$ strange baryon into spin-$\frac{1}{2}$ baryon and a pion, e.g.**

$$\Lambda \to \mathrm{p}\ \pi$$

- **The matrix element**

$$\mathcal{M}(\Lambda \to \mathrm{p}\ \pi) = S + P\,\vec{\sigma} \cdot \widehat{q}_p$$

where
S **- amplitude of the S-wave final state**
P **- amplitude of the P-wave final state**
$\widehat{q}_p$ **- unit direction of proton momentum**

NONLEPTONIC HYPERON DECAYS
continued

- **Total decay rate**

$$\Gamma = G_F^2 m_\pi^4 \frac{p_p(E_p + m_p)}{4\pi m_\Lambda}(|S|^2 + |P|^2)$$

- **Decay parameters**

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

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

$$\gamma_\Lambda = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2}$$

with

$$\alpha_\Lambda^2 + \beta_\Lambda^2 + \gamma_\Lambda^2 = 1$$

NONLEPTONIC HYPERON DECAYS
continued

In the rest frame of decaying Λ

- **The angular distribution of proton**

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{\mathcal{P}}_\Lambda \cdot \hat{q}_p) = \frac{1}{4\pi}(1 + \alpha_\Lambda \mathcal{P}_\Lambda \cos\theta_p)$$

where $\mathcal{P}_\Lambda$ - polarization of Λ
Thus α_Λ is related to angular distribution of proton from decay of polarized Λ

NONLEPTONIC HYPERON DECAYS
continued

- **The polarization of proton**

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

Thus β_Λ is related to proton polarization in direction perpendicular to the plane formed by $\vec{\mathcal{P}}_\Lambda$ and $\hat{q}_p$

- **For unpolarized Λ**

$$\vec{\mathcal{P}}_p = \alpha_\Lambda\, \hat{q}_p$$

so α_Λ is the magnitude of polarization of proton from unpolarized Λ decay

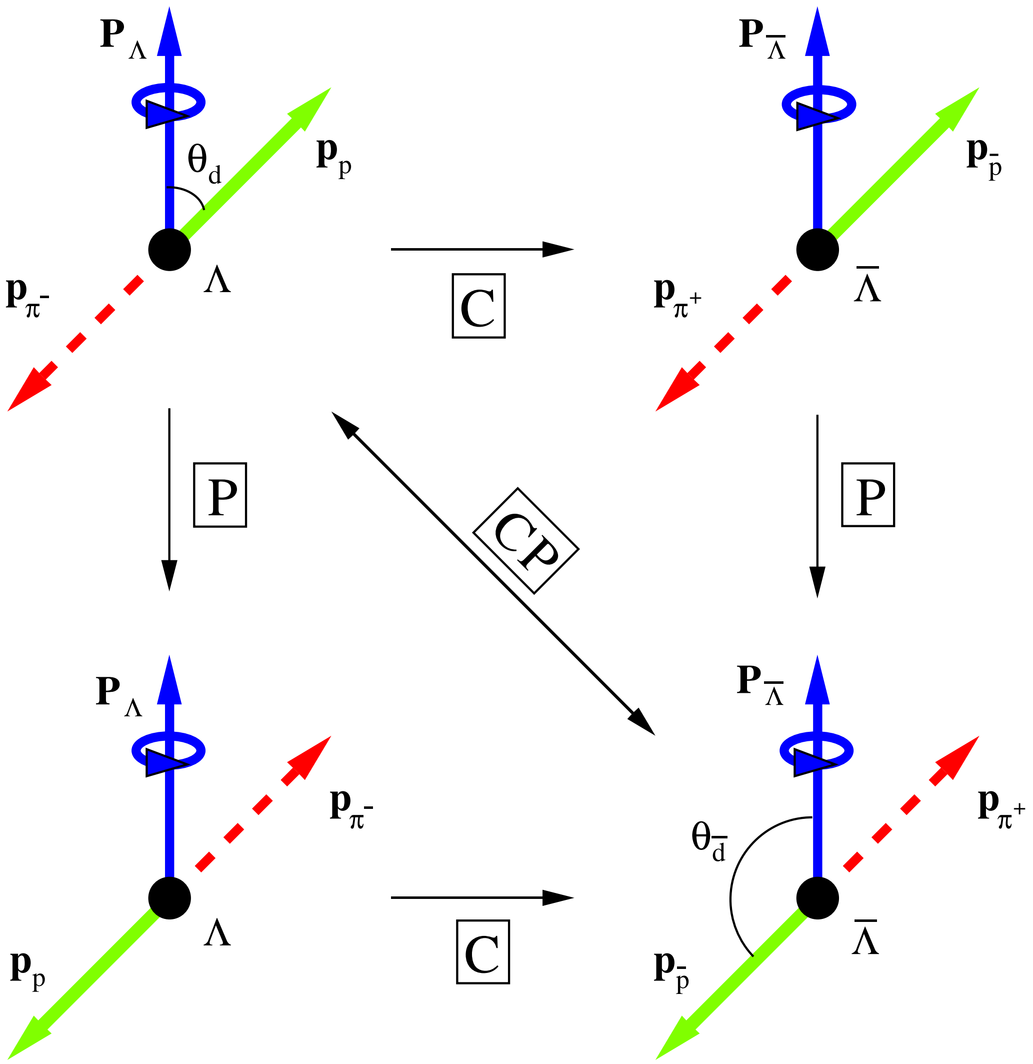
CP IN HYPERON DECAYS

- **If CP is conserved**

$$\begin{aligned}\bar{\Gamma} &= \Gamma \\ \overline{\alpha} &= -\alpha \\ \bar{\beta} &= -\beta\end{aligned}$$

- **Some CP violation observables**

$$\begin{aligned}\Delta &= \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \\ A &= \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \\ B &= \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}\end{aligned}$$



$$\boxed{\alpha_{\bar{\Lambda}} = -\,\alpha_\Lambda}$$

$\Lambda \rightarrow p\pi$ decay under CP transformation

SEARCH FOR DIRECT CP VIOLATION IN Λ DECAYS

Need to produce Λ, $\bar{\Lambda}$ with known polarizations

Experiment	Decay Mode	A_Λ
R608 at ISR	$pp \to \Lambda X$, $\bar{p}p \to \bar{\Lambda} X$	**-0.02 $\pm$ 0.14**
DM2 at Orsey	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	**0.01 $\pm$ 0.10**
PS185 at LEAR	$p\bar{p} \to \Lambda\bar{\Lambda}$	**-0.013 $\pm$ 0.022**

Hyper$\mathcal{CP}$ APPROACH

- **Produce unpolarized Ξs in the reactions**

$$p + Cu \rightarrow \Xi^{\pm} + X$$

- **Obtain polarized Λ's from Ξ decays**

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

identified via decays

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

- **Polarization of Λ in Ξ rest frame**

$$\vec{\mathcal{P}}_\Lambda = \alpha_\Xi \, \hat{q}_\Lambda$$

- **In Λ rest frame**

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \vec{\mathcal{P}}_\Lambda \cdot \hat{q}_p) = \frac{1}{4\pi}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_p)$$

- **Measure asymmetry**

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

with 1×10^{-4} precision

THEORETICAL PREDICTIONS

- **Superweak model predicts**

No ΔS=1 CP violation

- **For $\Lambda \to p\,\pi$ decay**

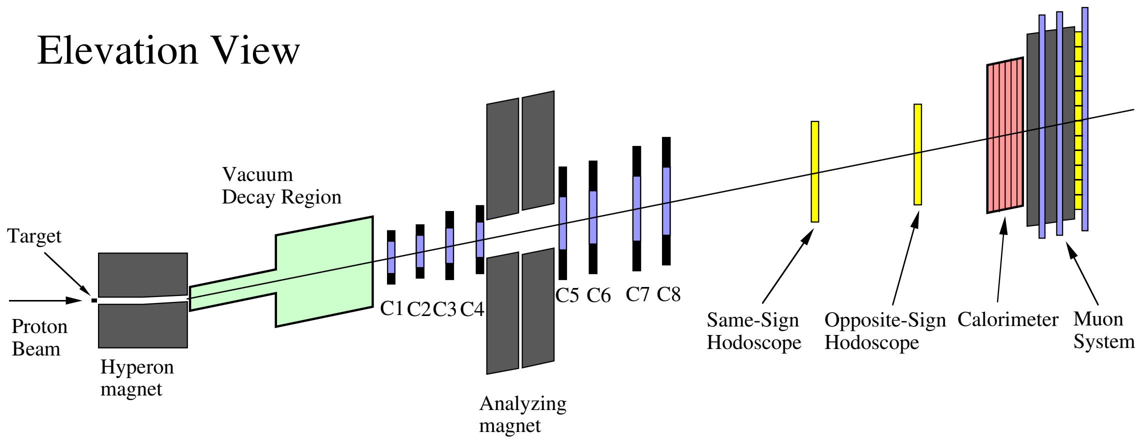
	Δ_Λ	A_Λ	B_Λ
CKM	$< 10^{-6}$	$(-5, -1) \times 10^{-5}$	$(0.6, 3) \times 10^{-4}$
Weinberg	-8×10^{-6}	-2.5×10^{-5}	1.6×10^{-3}
Left-Right	**0**	$(-0.1, 6) \times 10^{-4}$	7×10^{-4}

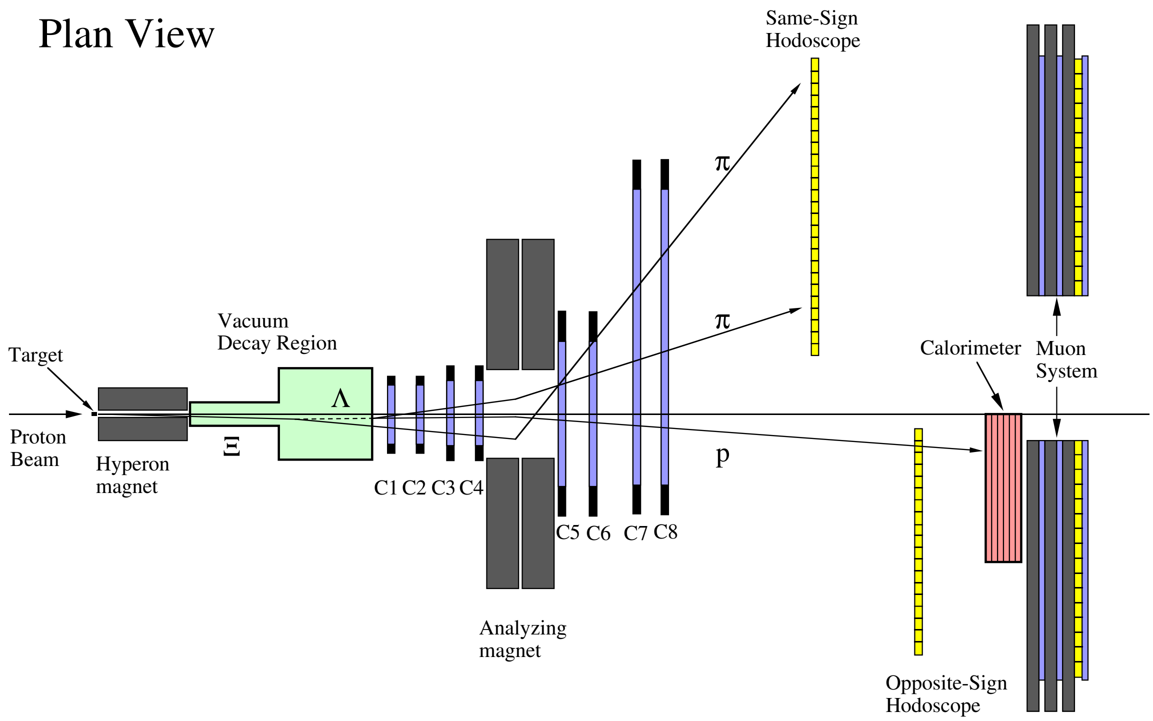
- **For $\Xi \to \Lambda\,\pi$ decay**

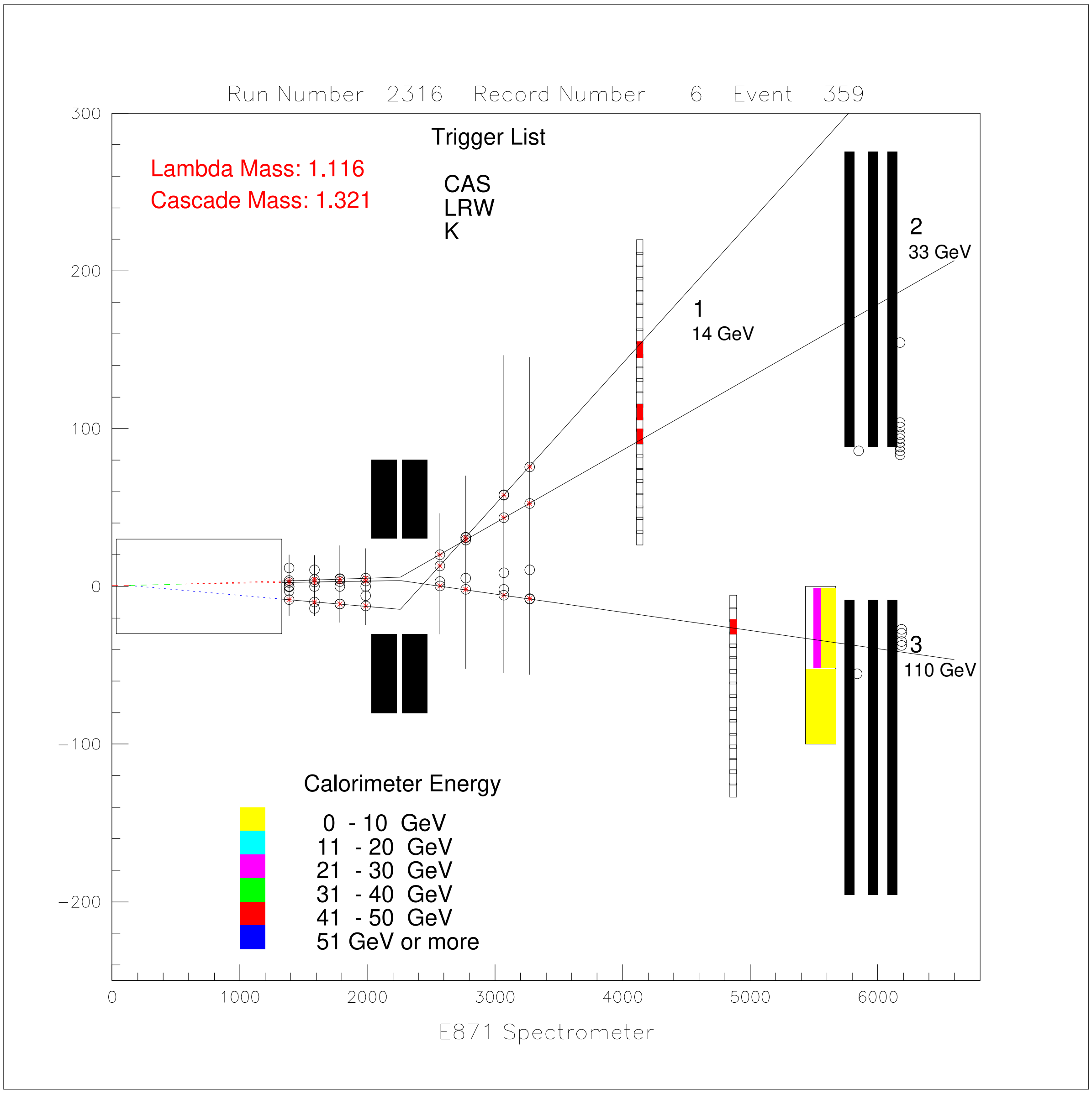
	Δ_Ξ	A_Ξ	B_Ξ
CKM	**0**	$(-10, -1) \times 10^{-5}$	$(10, 1) \times 10^{-3}$
Weinberg	**0**	-3.2×10^{-4}	3.8×10^{-3}
Left-Right	**0**	$(-2.5, 6) \times 10^{-5}$	-3.1×10^{-4}

DIRECT ΔS=1 CP VIOLATION IN KAON AND HYPERON DECAYS

$\epsilon^{'}/\epsilon$	$\mathbf{A}_{\Lambda\Xi}$
Large cancellation between electroweak and strong penguin diagrams at large top mass	**No such cancellation**
Large uncertainty in hadronic matrix elements	**Somewhat smaller uncertainty that could be narrowed by measurement of $\Lambda\pi$ phase shifts $(\delta_S - \delta_P)$ at E=M$_\Xi$**
Pure S-wave decay: probes only parity violating amplitudes	**Probes interference between parity violating and conserving amplitudes. Sensitive to new physics in parity conserving channel**


Elevation View
Vacuum
Decay Region
Target
Proton
Beam
Hyperon
magnet
C1 C2 C3 C4
C5 C6
C7 C8
Analyzing
magnet
Same-Sign
Hodoscope
Opposite-Sign
Hodoscope
Calorimeter
Muon
System


Plan View
Same-Sign
Hodoscope
Vacuum
Decay Region
Target
Proton
Beam
Hyperon
magnet
Λ
Ξ
π
π
p
C1 C2 C3 C4
C5 C6
C7 C8
Analyzing
magnet
Calorimeter
Muon
System
Opposite-Sign
Hodoscope



Run Number 2316 Record Number 6 Event 359
Trigger List
CAS
LRW
K
Lambda Mass: 1.116
Cascade Mass: 1.321
1
14 GeV
2
33 GeV
3
110 GeV
Calorimeter Energy
0 - 10 GeV
11 - 20 GeV
21 - 30 GeV
31 - 40 GeV
41 - 50 GeV
51 GeV or more
300
200
100
0
−100
−200
0
1000
2000
3000
4000
5000
6000
E871 Spectrometer

SUMMARY OF THE 1997 RUN

- **Between April and September of 1997 collected**

$$75 \times 10^9 \text{ triggers}$$

with

$$39 \times 10^9\ \Xi \text{ triggers}$$

on 10,000 5-Gb Exabyte tapes ($\sim$ 33 Tb)

- **This should yield**

$$1.2 \times 10^9 \text{ reconstructed } \Xi^-$$
$$0.3 \times 10^9 \text{ reconstructed } \overline{\Xi}^+$$

- **Overall sensitivity**

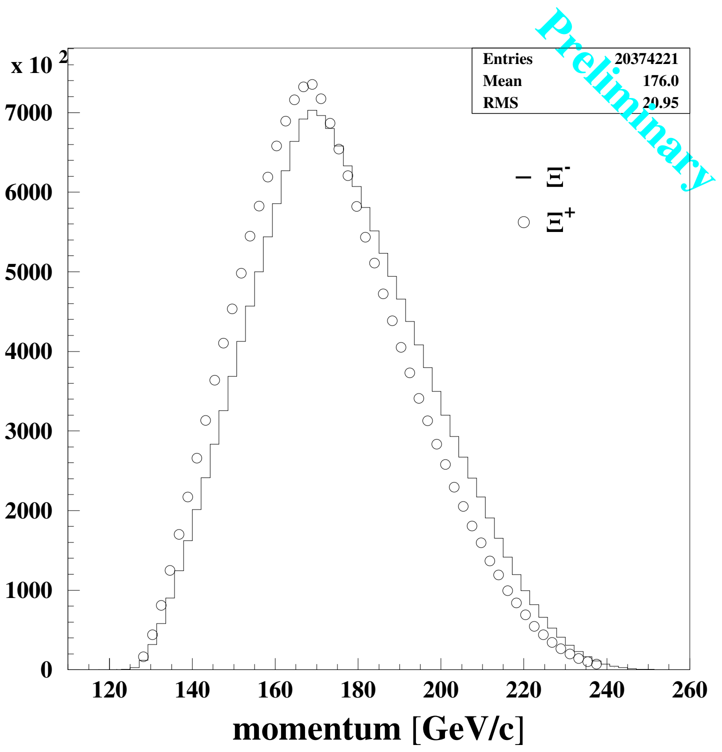
$$\delta A_{\Lambda\Xi} \approx 2 \times 10^{-4}$$

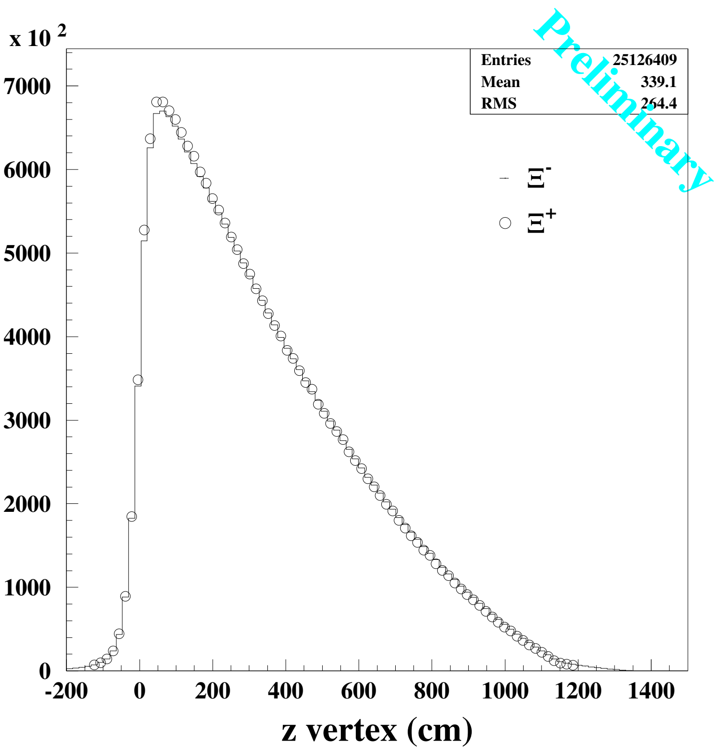
STATUS OF DATA ANALYSIS

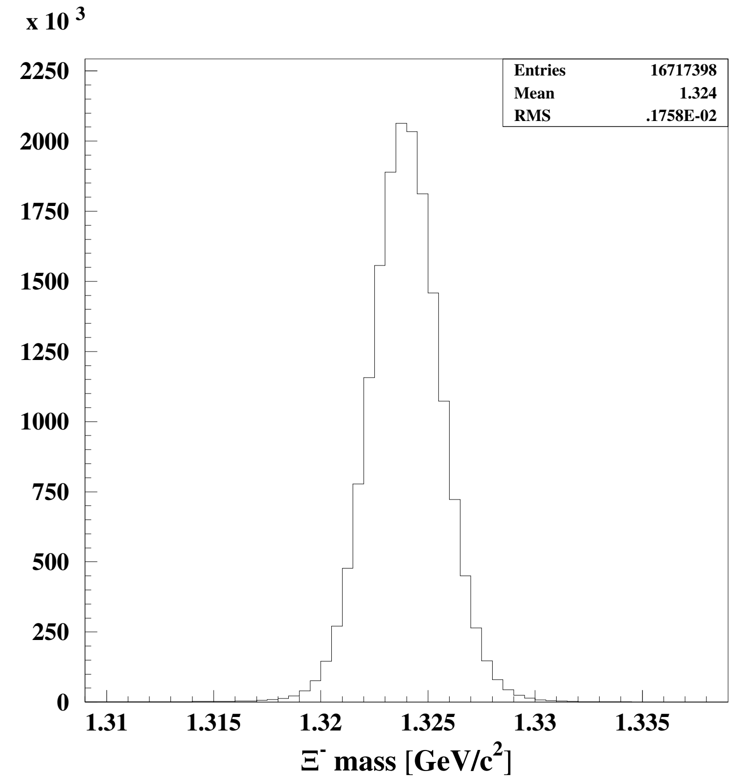
- Since the end of the run:
  - Study, optimize and decide on official reconstruction code;
  - Bring up farm-processing code;
  - Determine various run-dependent parameters such as alignment constants, magnetic field maps, efficiencies etc.

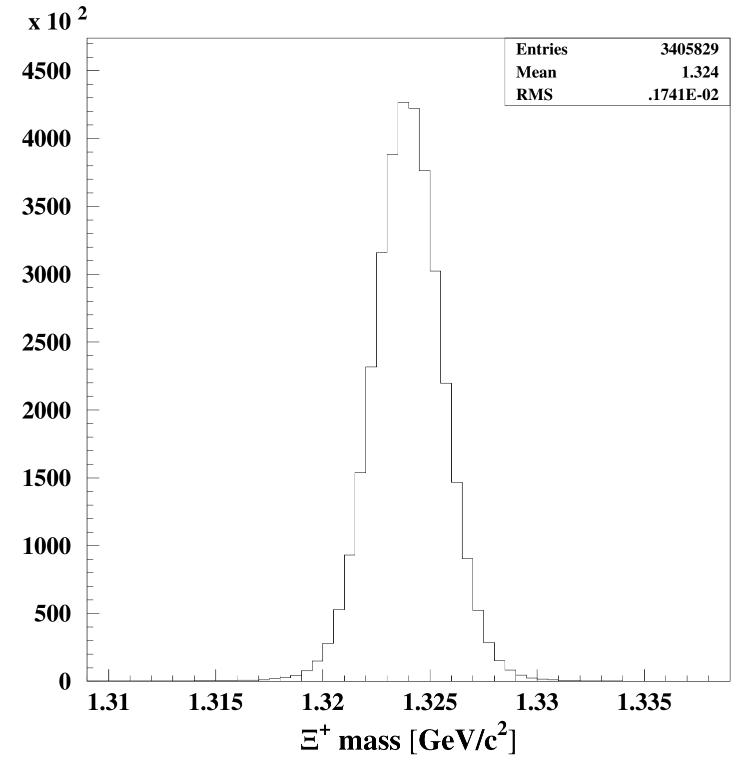
- Preliminary event reconstruction has been done on Fermilab farms. Processed about 10% of the data with a total of 7,000 MIPS

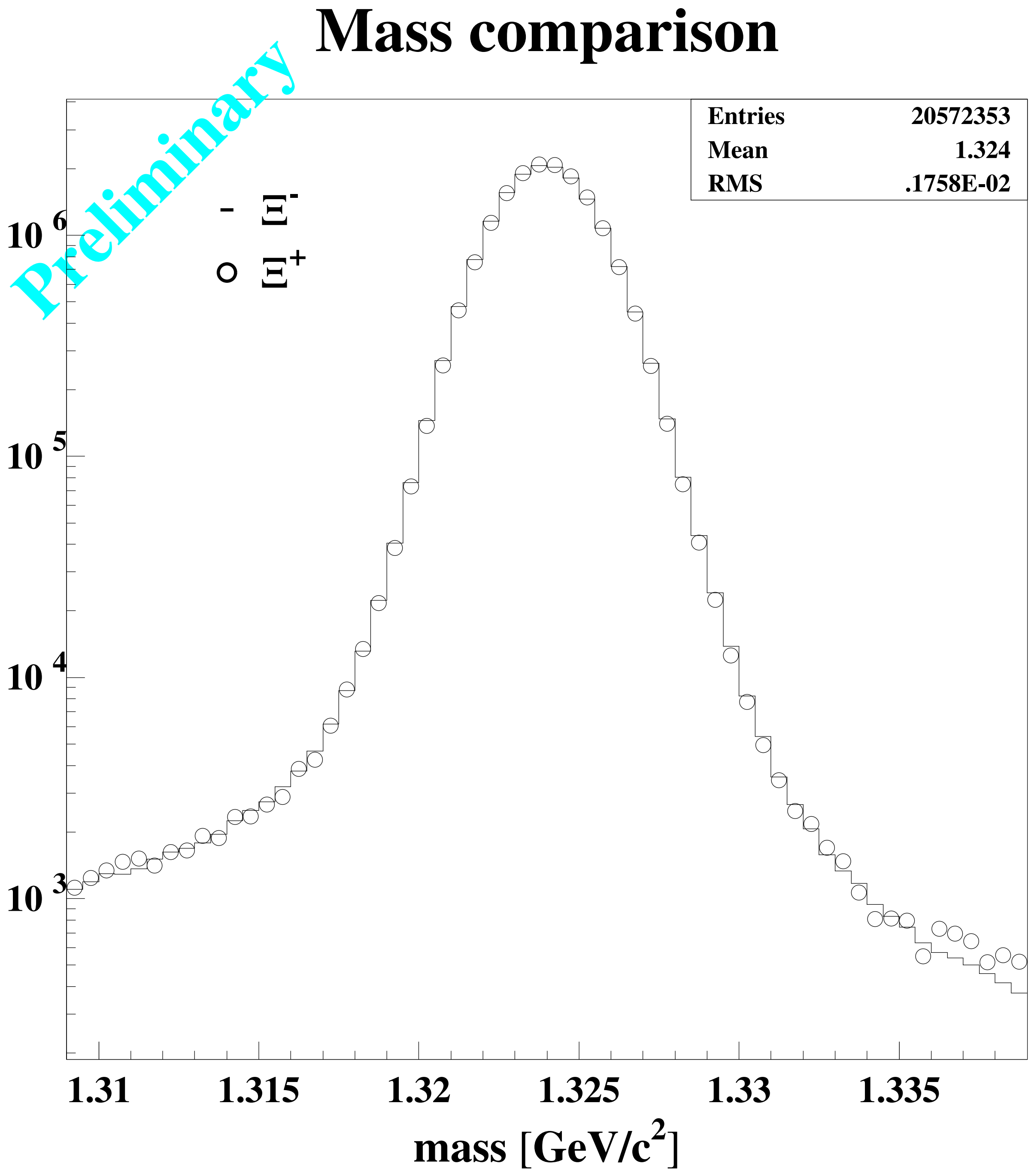
- Start processing with the new reconstruction package and 10,000 MIPS. The entire data set can be processed in about 250 days.


x 10 2
Entries 20374221
Mean 176.0
RMS 20.95
Preliminary
Ξ-
Ξ+
0
1000
2000
3000
4000
5000
6000
7000
120
140
160
180
200
220
240
260
momentum [GeV/c]

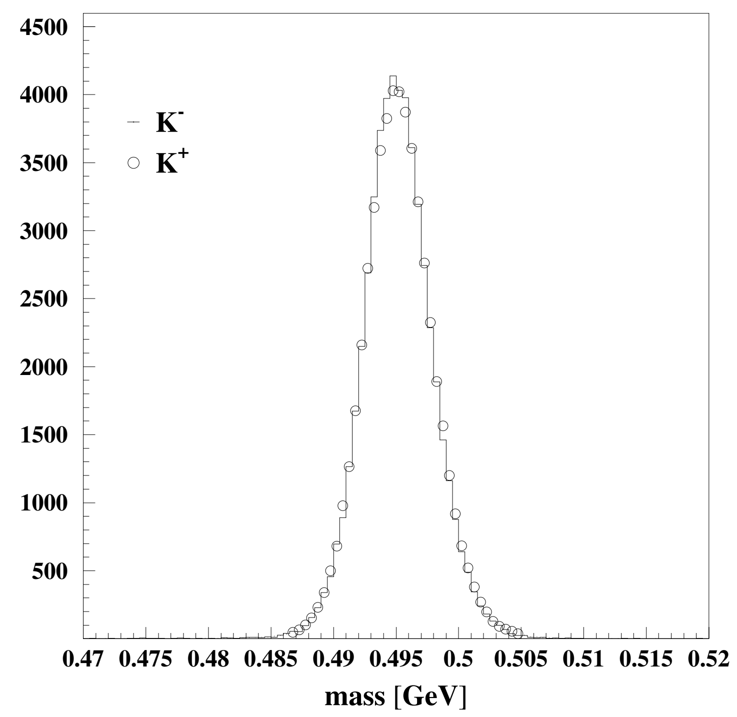

x 10 2
Entries 25126409
Mean 339.1
RMS 264.4
Preliminary
Ξ-
Ξ+
0
1000
2000
3000
4000
5000
6000
7000
-200
0
200
400
600
800
1000
1200
1400
z vertex (cm)


x 10 3
Entries 16717398
Mean 1.324
RMS .1758E-02
2250
2000
1750
1500
1250
1000
750
500
250
0
1.31
1.315
1.32
1.325
1.33
1.335
Ξ- mass [GeV/c2]

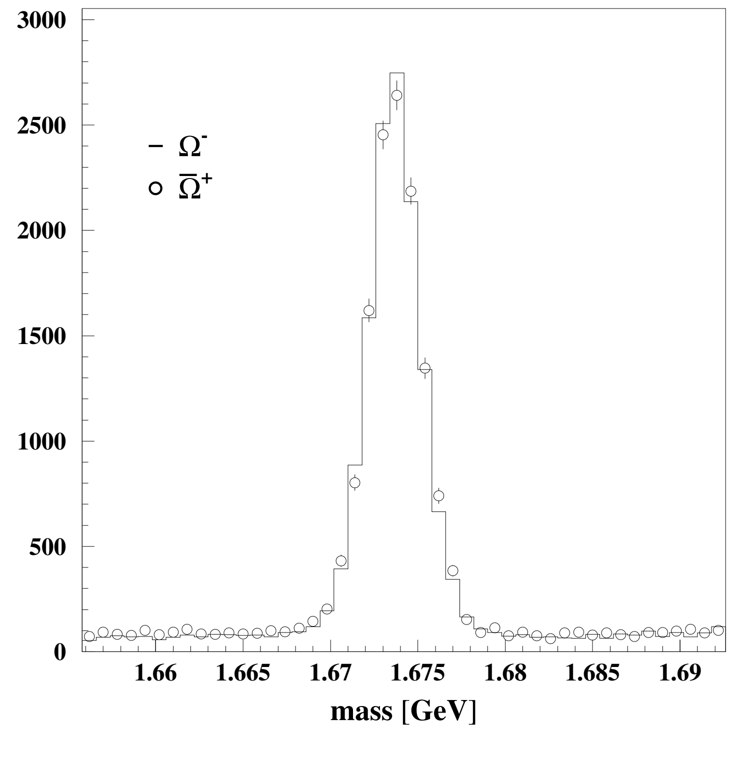

x 10 2
Entries 3405829
Mean 1.324
RMS .1741E-02
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1.31
1.315
1.32
1.325
1.33
1.335
Ξ+ mass [GeV/c2]



Mass comparison
Preliminary
Entries 20572353
Mean 1.324
RMS .1758E-02
Ξ⁻
Ξ⁺
10 6
10 5
10 4
10 3
1.31
1.315
1.32
1.325
1.33
1.335
mass [GeV/c2]



4500
4000
3500
3000
2500
2000
1500
1000
500
K-
K+
0.47
0.475
0.48
0.485
0.49
0.495
0.5
0.505
0.51
0.515
0.52
mass [GeV]



3000
2500
2000
1500
1000
500
0
Ω-
Ω̄+
1.66
1.665
1.67
1.675
1.68
1.685
1.69
mass [GeV]

SYSTEMATICS

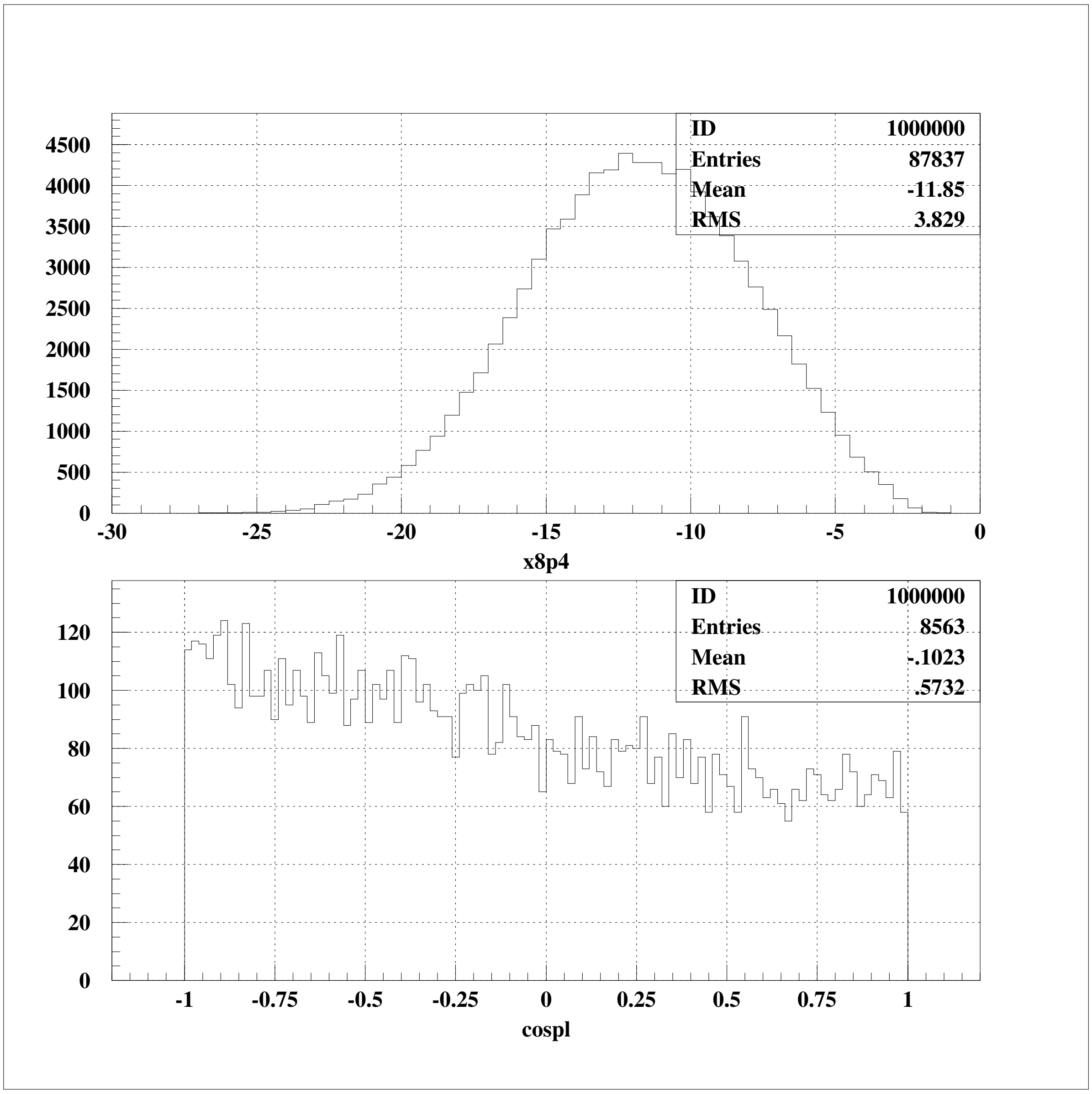
If not corrected for will cause false asymmetries between Ξ^- and $\overline{\Xi}^+$ decays

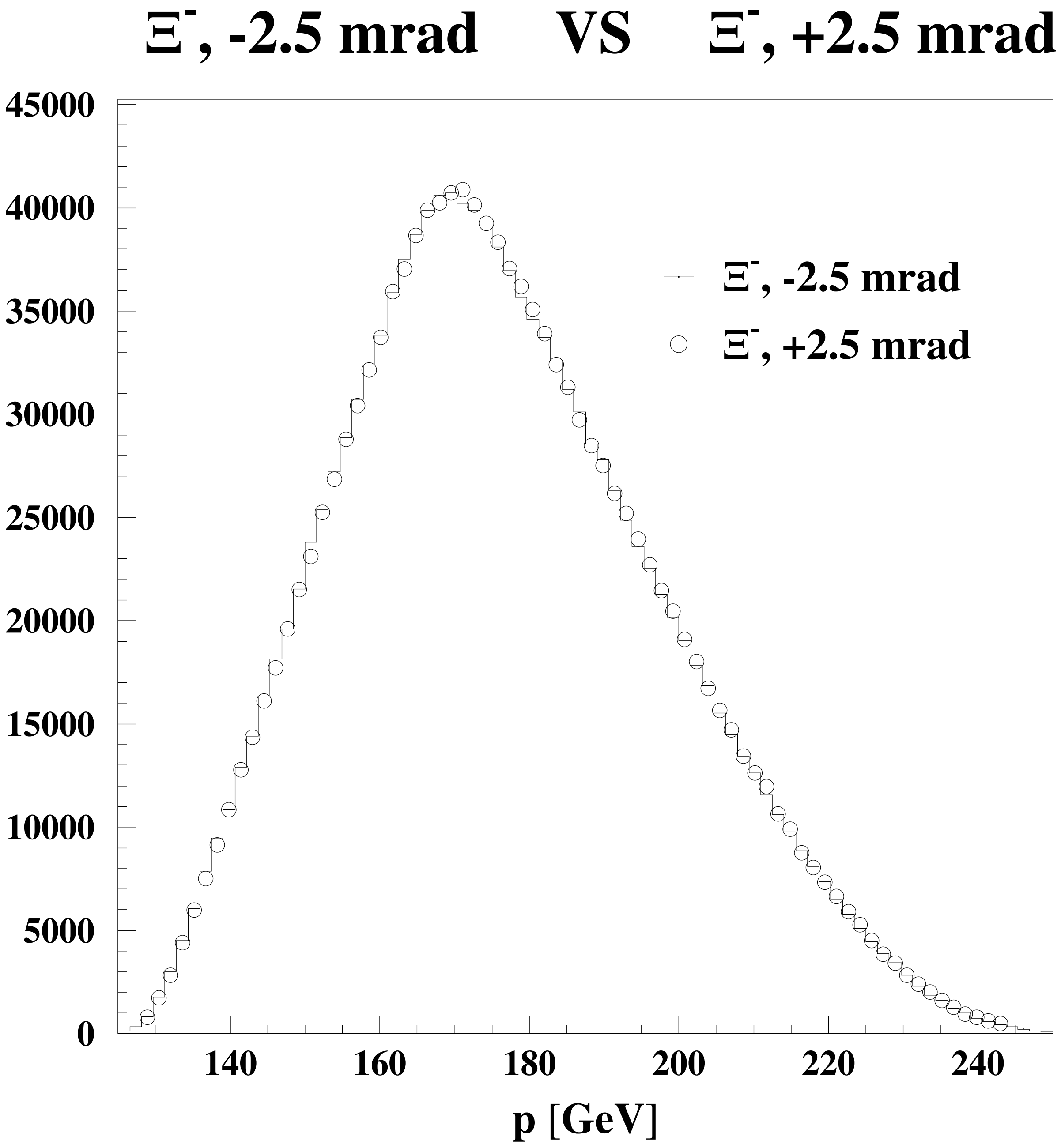
- Acceptance differences
  - targeting differences
  - magnetic field differences
  - chamber efficiency differences
  - temporal changes
  - different backgrounds for Λ, Ξ^- versus $\overline{\Lambda}$, $\overline{\Xi}^+$
- Nonzero Ξ^-, $\overline{\Xi}^+$ polarizations
- Different interaction cross sections between π^- and π^+ and between p and $\overline{p}$

ANALYSIS METHOD MINIMIZES POTENTIAL BIASES

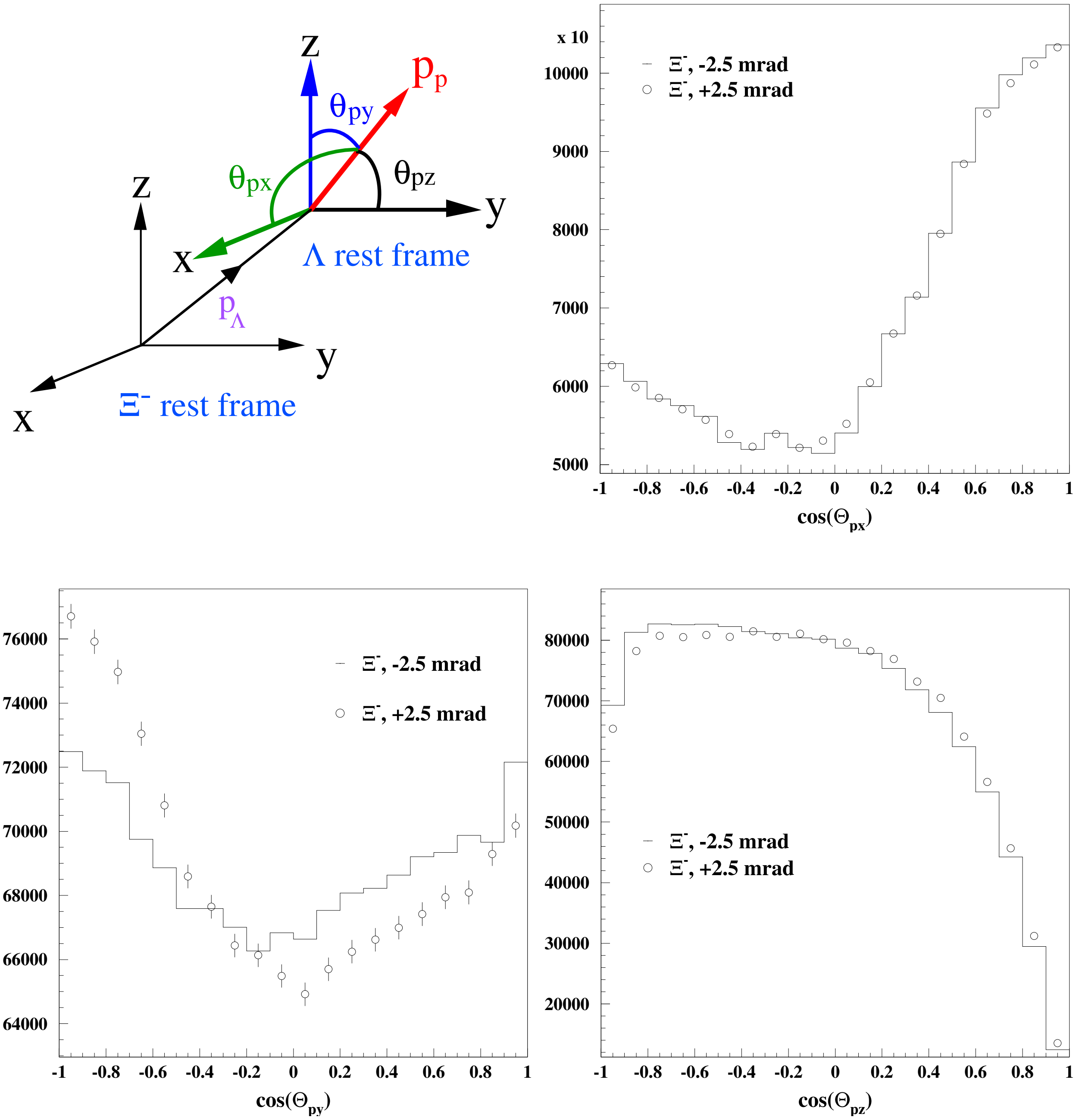
- **The z-axis of the analysis frame, defined as the direction of the Λ momentum in Ξ rest frame, changes from event to event.**

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

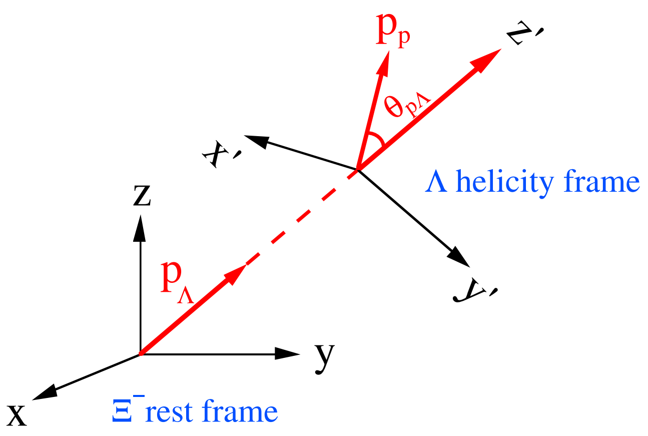

ID 1000000
Entries 87837
Mean -11.85
RMS 3.829
x8p4
ID 1000000
Entries 8563
Mean -.1023
RMS .5732
cospl

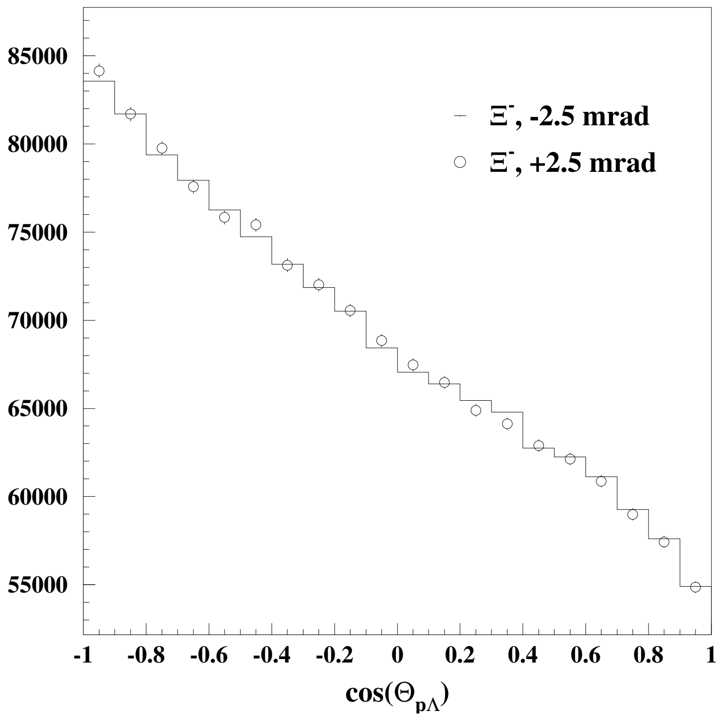


Ξ^-, -2.5 mrad VS Ξ^-, +2.5 mrad
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
140
160
180
200
220
240
p [GeV]
Ξ^-, -2.5 mrad
Ξ^-, +2.5 mrad

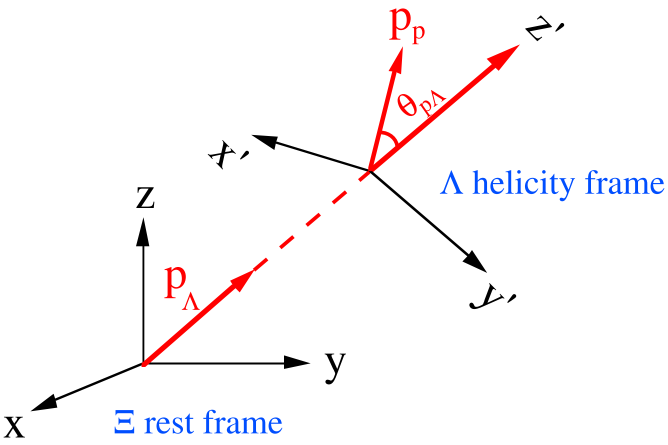

z
p_p
θ_{py}
θ_{px}
θ_{pz}
z
y
x
Λ rest frame
p_Λ
y
x
Ξ^- rest frame
x 10
Ξ^-, -2.5 mrad
Ξ^-, +2.5 mrad
$\cos(\Theta_{px})$
Ξ^-, -2.5 mrad
Ξ^-, +2.5 mrad
$\cos(\Theta_{py})$
Ξ^-, -2.5 mrad
Ξ^-, +2.5 mrad
$\cos(\Theta_{pz})$

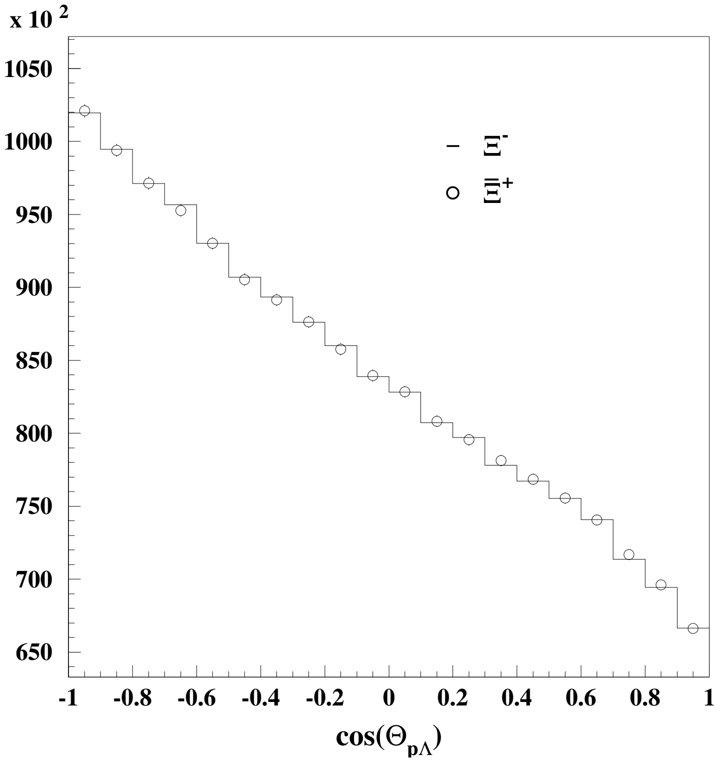
Ξ^- (-2.5 mrad) vs Ξ^- (+2.5 mrad)





Ξ^- (0 mrad) vs $\overline{\Xi}^+$ (0 mrad)





OTHER PHYSICS TOPICS

- **Production**
  - $*$ **Production cross sections, A-dependence and particle ratios of π, K, hyperons and their anti-particles**
  - $*$ **Production polarization of hyperons and anti-hyperons at low x$_F$ and low p$_T$**
  - $*$ **Search for parity violation**

- **Decays**
  - $*$ **Precision measurements of decay parameters, α (and β) of $\Xi \to \Lambda\pi$, and $\Omega \to \Lambda K$ decays**
  - $*$ **Search for ΔS=2 decays**
    - $\diamond$ $\Xi^- \to p\pi^-\pi^-$
    - $\diamond$ $\Omega^- \to \Lambda\pi^-$
  - $*$ **Search for ΔS=3 decay**
    - $\diamond$ $\Omega^- \to p\pi^-\pi^-$

* Search for forbidden or rare decays
  - $K^- \to \pi^- \mu^+ \mu^-$
  - $K^- \to \pi^+ \mu^- \mu^-$
  - $\Sigma^- \to p\mu^- \mu^-$
  - $\Sigma^+ \to p\mu^+ \mu^-$
  - $\Xi^- \to p\mu^- \mu^-$

- **Discrete Symmetries**
  * **Search for CP violation**
    - **the asymmetry Δg in the slope parameter of Dalitz plot between**

$$K^+ \to \pi^+\pi^+\pi^- \quad \text{and} \quad K^- \to \pi^-\pi^+\pi^-$$

    - **Asymmetry A_Ω for $\Omega^- \to \Lambda K^-$ decay**
    - **Asymmetry B_Ξ for $\Xi^- \to \Lambda\pi^-$ decay**
  * **Search for T violation**
    - **edm of Ξ hyperon**
  * **CPT test**
    - **Difference in masses in Ξ, Ω, Λ, and K systems**
    - **Difference in lifetimes in Ξ, Ω and Λ system**
    - **Difference in Ξ^- and $\overline{\Xi}^+$ magnetic moments**

1999 RUN

- **Data taking in Spring 1999**

- **The goal:**
  at least 4 times more data

$$\delta A_{\Lambda\Xi} \lesssim 1 \times 10^{-4}$$

- **Improvements:**

  - **further optimize the performance of PWC**
  - **reduce dead-time of readout system**
  - **increase throughput of DAQ to $\sim$40 Mb/s**

CONCLUSIONS

- **Hyper$\mathcal{CP}$ had a successful 1997 run and has collected the largest sample of Ξ^- and $\overline{\Xi}^+$.**

- **The projected sensitivity in CP asymmetry in $\Xi,\ \Lambda$ decays is**

$$2 \times 10^{-4},$$

  two orders of magnitude better that the present limit and where some theories predict an effect.

- **E871 has been approved to run in the 1999 fixed target program at Fermilab and expects to reach**

$$1 \times 10^{-4} \text{ or better}$$

  sensitivity in $A_{\Lambda\Xi}$