HyperCP search for direct CP Violation

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Representing Hyper$\mathcal{CP}$ (FNAL E871) Collaboration

LNF Spring School
and
EURODAPHNE Collaboration Meeting

Frascati, Italy
April 12 to 17, 1999

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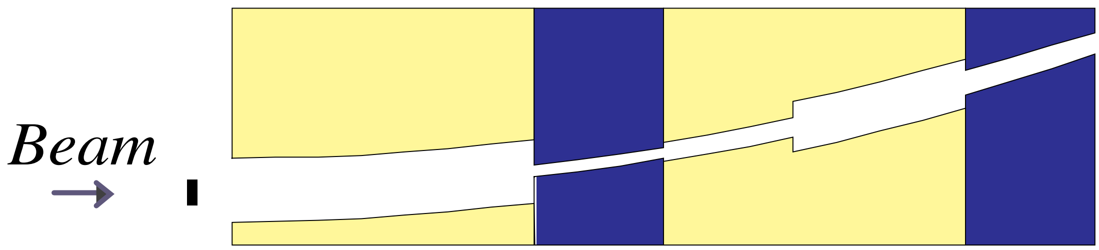
Talk summary

- Description of the apparatus
- Direct CP violation in hyperon decay
- Preliminary data will be presented to illustrate systematics
- Direct CP violation in $K \to 3\pi$
- Other physics topics
- Conclusion

Production of Hyperons



p (800 GeV/c) + Cu $\rightarrow$ Hyperon + X

Central orbit momentum = 157 GeV/c at 1.67 T

Bend angle = 19.5 mrad

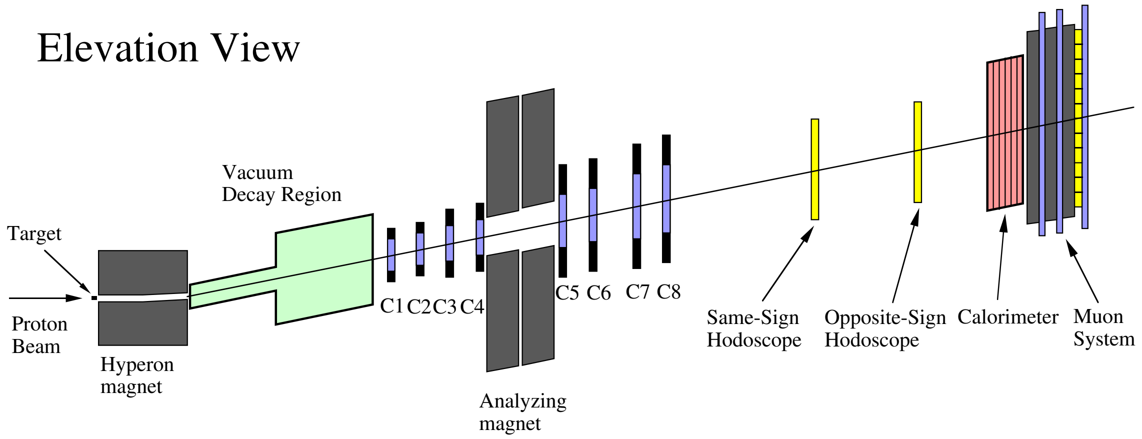
Ω , Ξ , Σ , produced at 0^0 are unpolarized

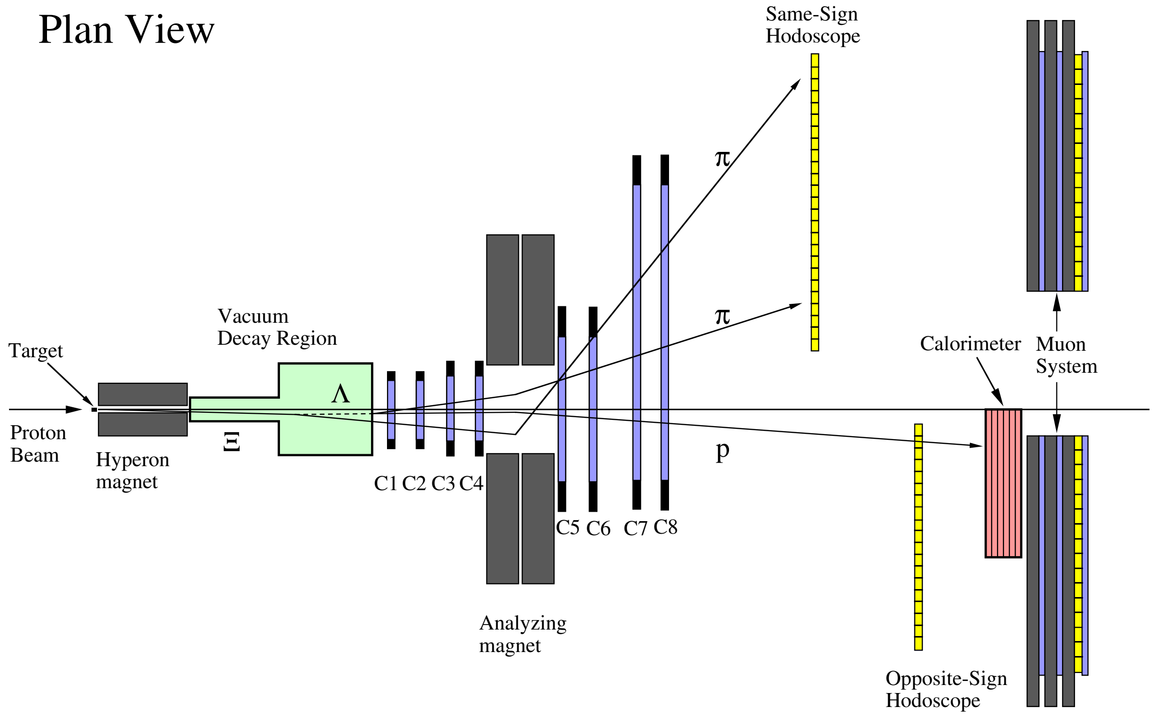
Beam incidence can be varied in the horizontal plane from - 2.5 mrad to 2.5 mrad to produce a small vertical polarization *P*

$$P \propto p_t$$

With 6 cm Cu and negative selection
or
2.2 cm Cu and positive selection

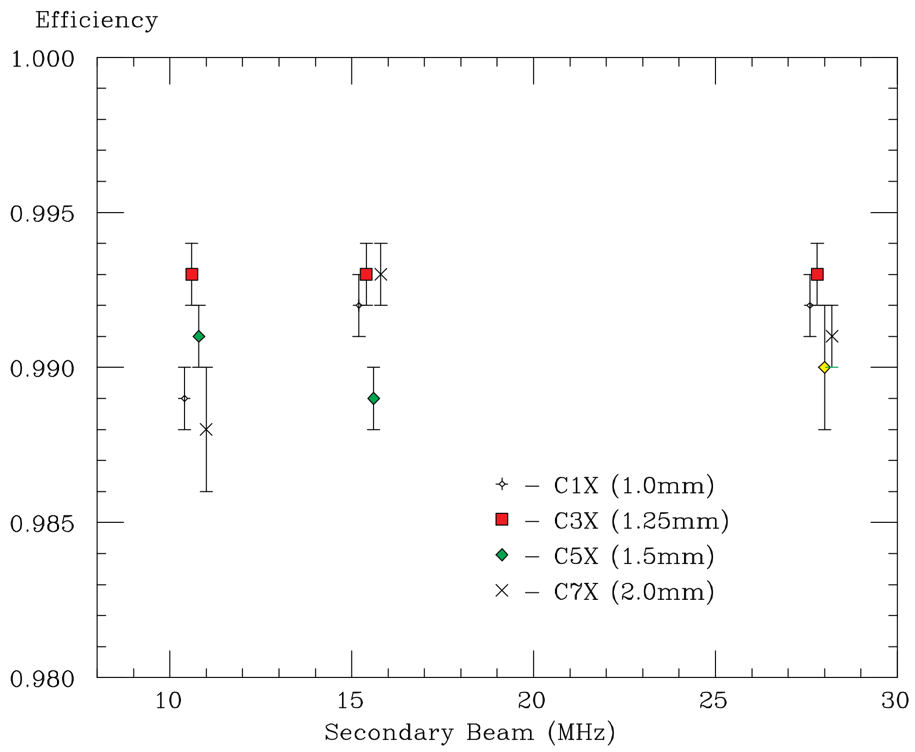
1.5 10^{11} p/spill on target gives about 14 MHz at exit
(p , π , κ and hyperons)





- 8 fast narrow-pitch wire chambers (32 planes)
- High-rate DAQ (13 MB/s or 63K events/s to tape)
- Simple trigger (2 particles of opposite signs and calorimeter energy for Ξ and K)

Performance of the spectrometer



- Average efficiency 0.992 independent of rate
- No evidence of aging
- Fast, all the signal within 2 buckets (2 x 18.9 ns) in front chambers and 5 buckets in rear chambers
-

14 MHz channeled beam	negative	positive
Trigger rate	30 KHz	25 KHz
$\Xi \rightarrow \Lambda\pi$ yield	1600 Hz	150 Hz
$K \rightarrow \pi\pi\pi$ yield	100 Hz	120 Hz

NONLEPTONIC HYPERON DECAYS

- **In the $\Delta S = 1$ decay of spin-$\frac{1}{2}$ strange baryon, angular momentum conservation allows only two final states for the spin-$\frac{1}{2}$ baryon and pion**

Parity violating S-wave
Parity conserving P-wave

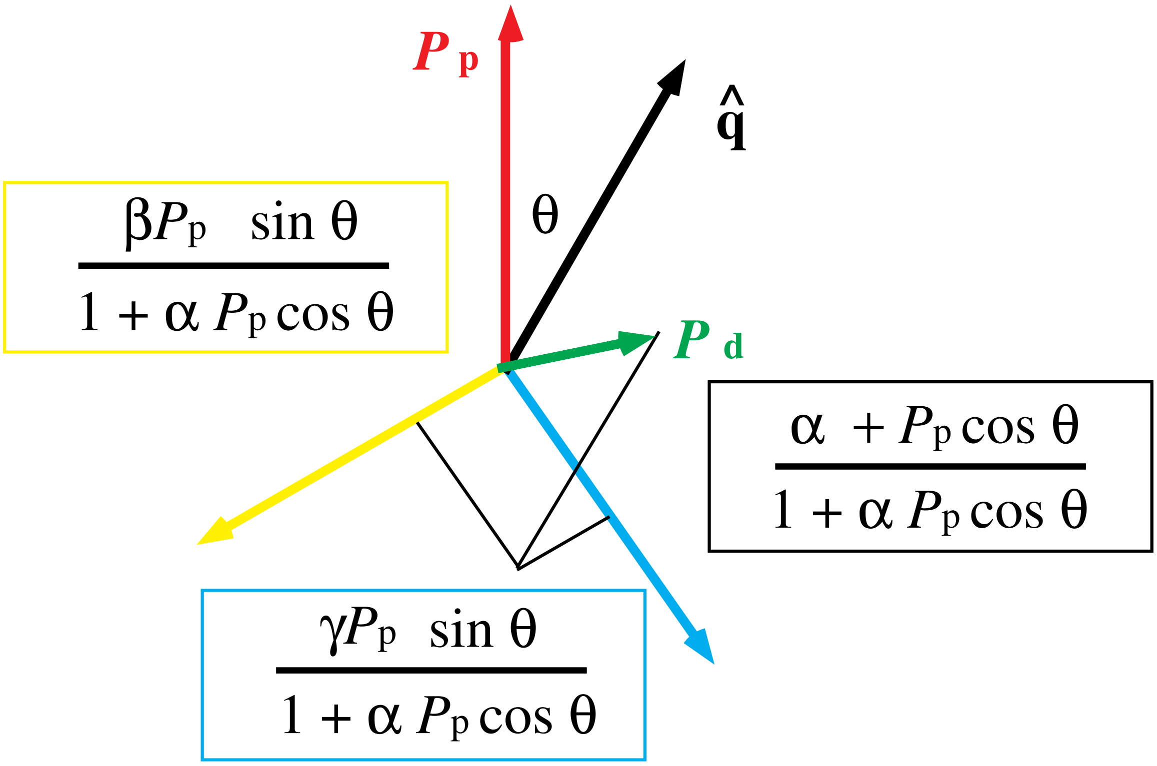
- **Decay parameters**

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

$$\alpha^2 + \beta^2 + \gamma^2 = 1$$

- **The angular distribution of the final state baryon in the rest frame of the parent baryon with polarization $\mathcal{P}$ depend on α**

$$\frac{dn}{d\Omega} = \frac{1}{4\pi}(1 + \alpha\vec{\mathcal{P}} \cdot \hat{q}) = \frac{1}{4\pi}(1 + \alpha\mathcal{P}\cos\theta)$$



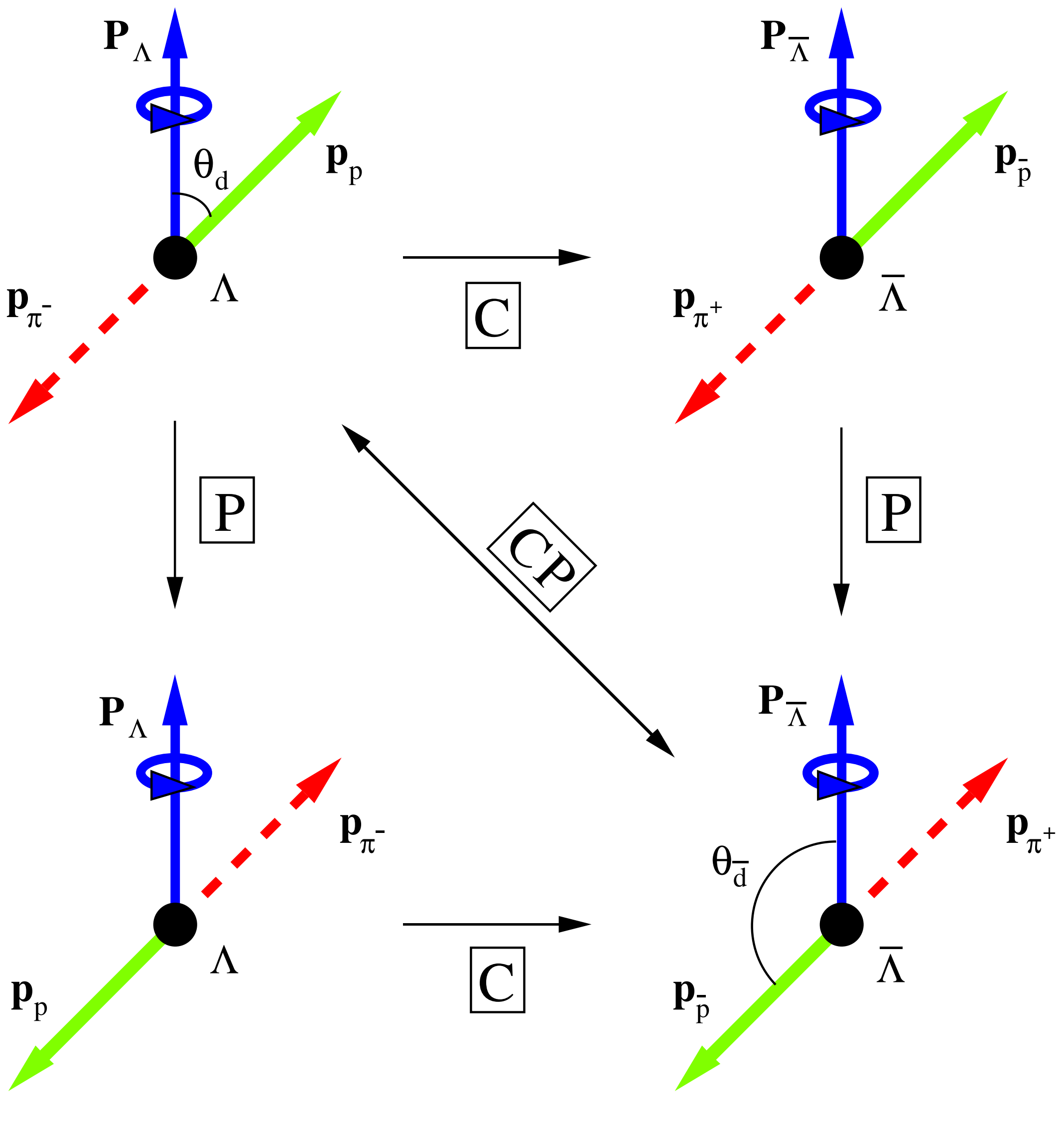
$$\vec{\mathcal{P}}_d = \frac{(\alpha + \vec{\mathcal{P}}_p \cdot \hat{q})\hat{q} + \beta \vec{\mathcal{P}}_p \times \hat{q} + \gamma \hat{q} \times (\vec{\mathcal{P}}_p \times \hat{q})}{(1 + \alpha \vec{\mathcal{P}}_p \cdot \hat{q})}$$

- **Thus β gives the component of polarization perpendicular to the plane formed by $\vec{\mathcal{P}}_p$ and $\hat{q}$**

- **For an unpolarized parent baryon α is the magnitude of the longitudinal polarization of the decay baryon**

$$\vec{\mathcal{P}}_d = \alpha \hat{q}$$

CP IN HYPERON DECAYS



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

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

- **If CP is conserved**

$$\bar{\Gamma} = \Gamma \qquad \bar{\alpha} = -\alpha \qquad \bar{\beta} = -\beta$$

- **Some CP violation observables**

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \quad A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}} \quad B = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}$$

- **Search for direct CP violation in Λ decays**
  Need to produce Λ, $\bar{\Lambda}$ with known polarizations

Experiment	Decay Mode	$\mathbf{A}_{\Lambda}$
R608 at ISR	$pp \to \Lambda X, \bar{p}p \to \bar{\Lambda}X$	**-0.02 $\pm$ 0.14**
DM2 at Orsay	$e^+e^- \to J/\Psi \to \Lambda\bar{\Lambda}$	**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 Ξ's to obtain Λ's with longitudinal polarization α_Ξ from Ξ decays**

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

identified via decays

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

- **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**	$(-10,-0.5) \times 10^{-5}$	$(10, 1) \times 10^{-3}$
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**

STATUS OF DATA ANALYSIS

- Data collected between April and September of 1997 should yield

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

- 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 20,000 MIPS. About 80% of the entire data set has already been processed

SYSTEMATICS

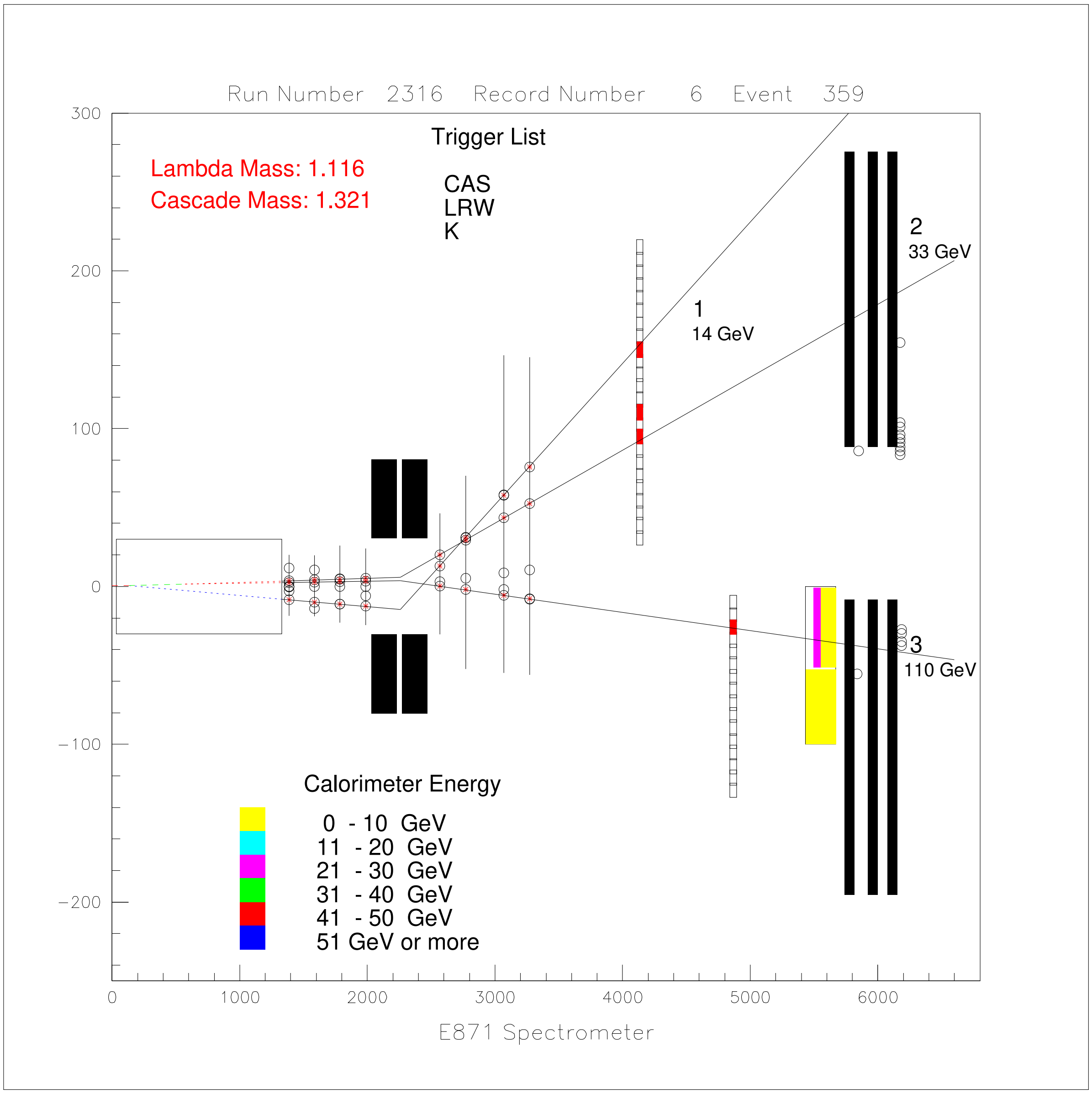
- Acceptance differences
  - position and angle of beam on target
  - production cross sections
  - magnetic field
  - chamber efficiency
  - trigger efficiency
  - temporal changes

- different backgrounds for Λ, Ξ^- versus $\overline{\Lambda}$, $\overline{\Xi}^+$

- Nonzero Ξ^-, $\overline{\Xi}^+$ polarizations

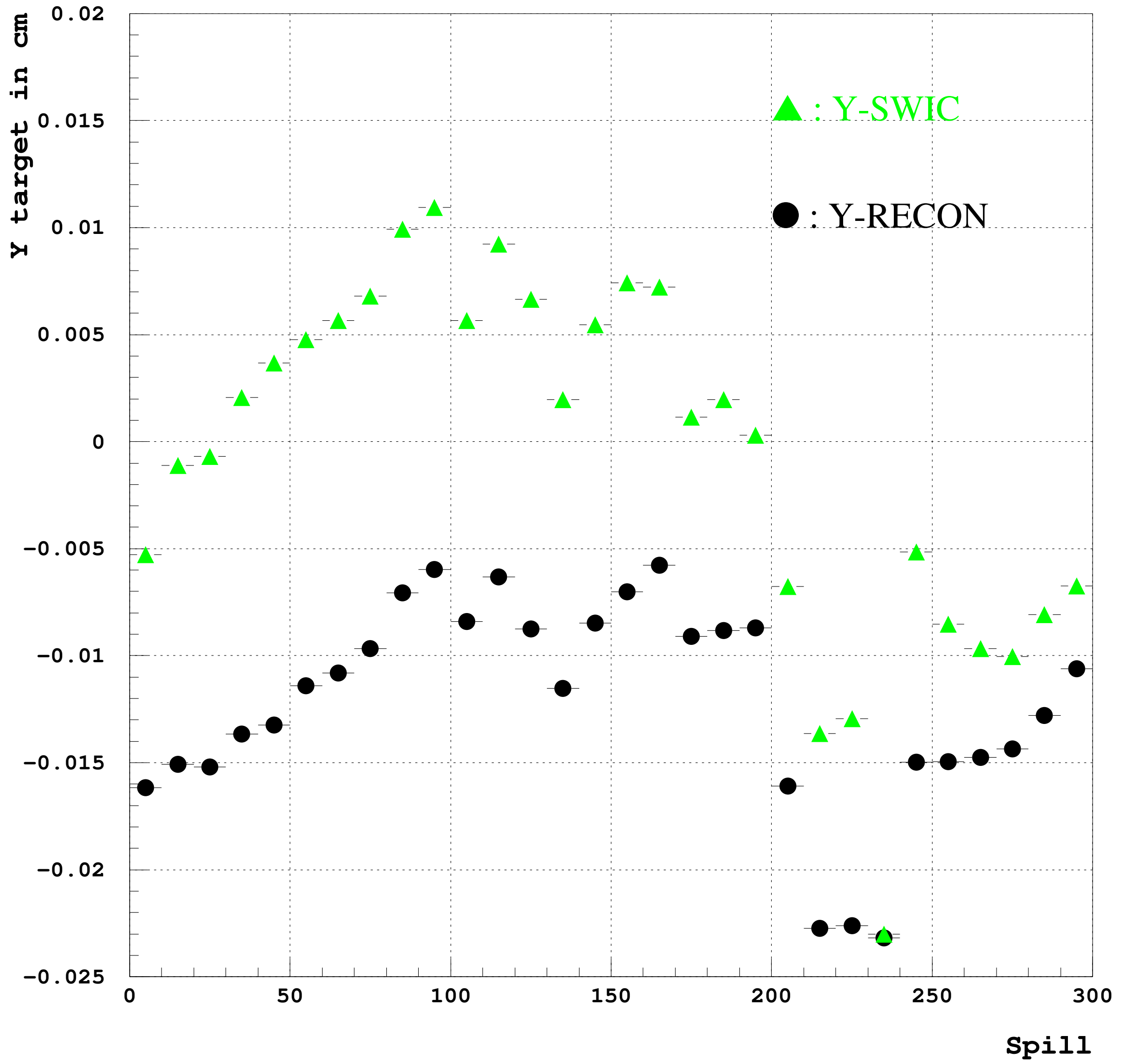
- Different interaction cross sections between π^- and π^+ and between p and $\overline{p}$

- data are VERY PRELIMINARY and are shown only to illustrate some aspects of the analysis


Run Number 2316 Record Number 6 Event 359
Lambda Mass: 1.116
Cascade Mass: 1.321
Trigger List
CAS
LRW
K
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

Position of beam

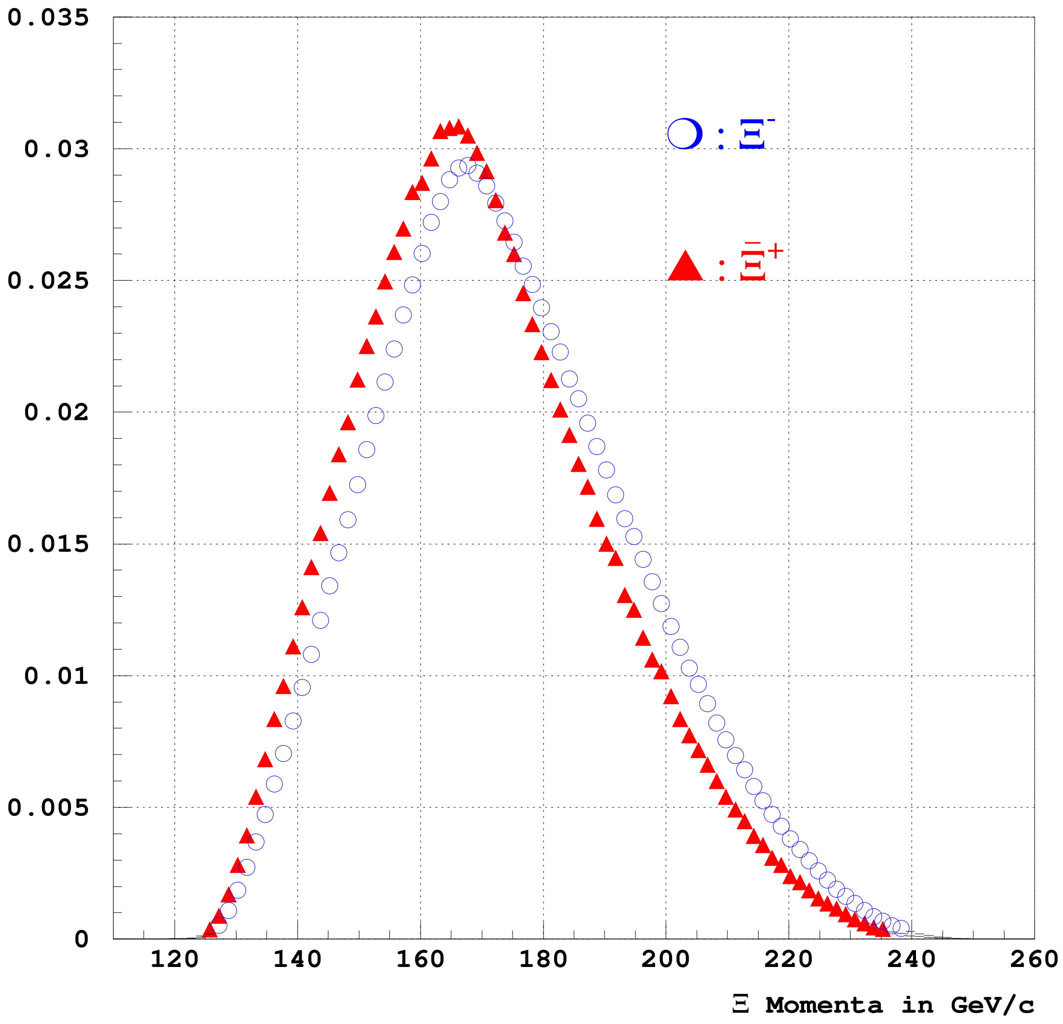
- Change in beam position can lead to acceptance differences



- Y position of the beam as function of spill number. Measured by primary beam chambers and from the reconstruction of Ξ events

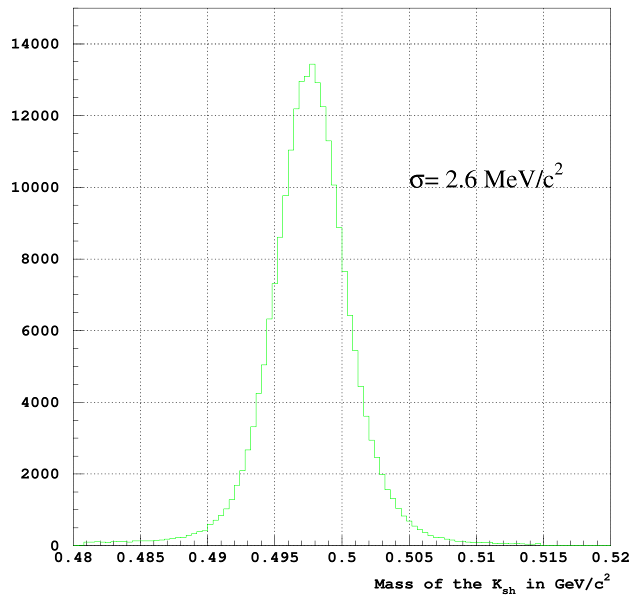
Production cross sections

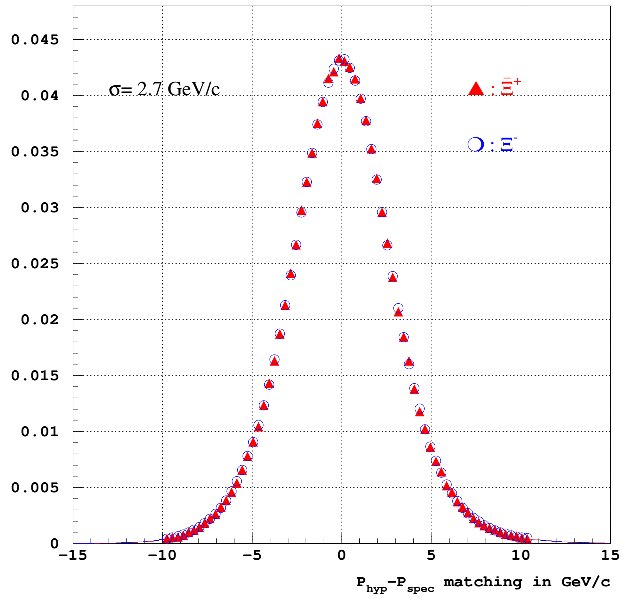
- **Differences in production dynamic can induce acceptance differences**



- **Momentum spectra for Ξ^- and $\overline{\Xi}^+$ normalized to the same number of events**

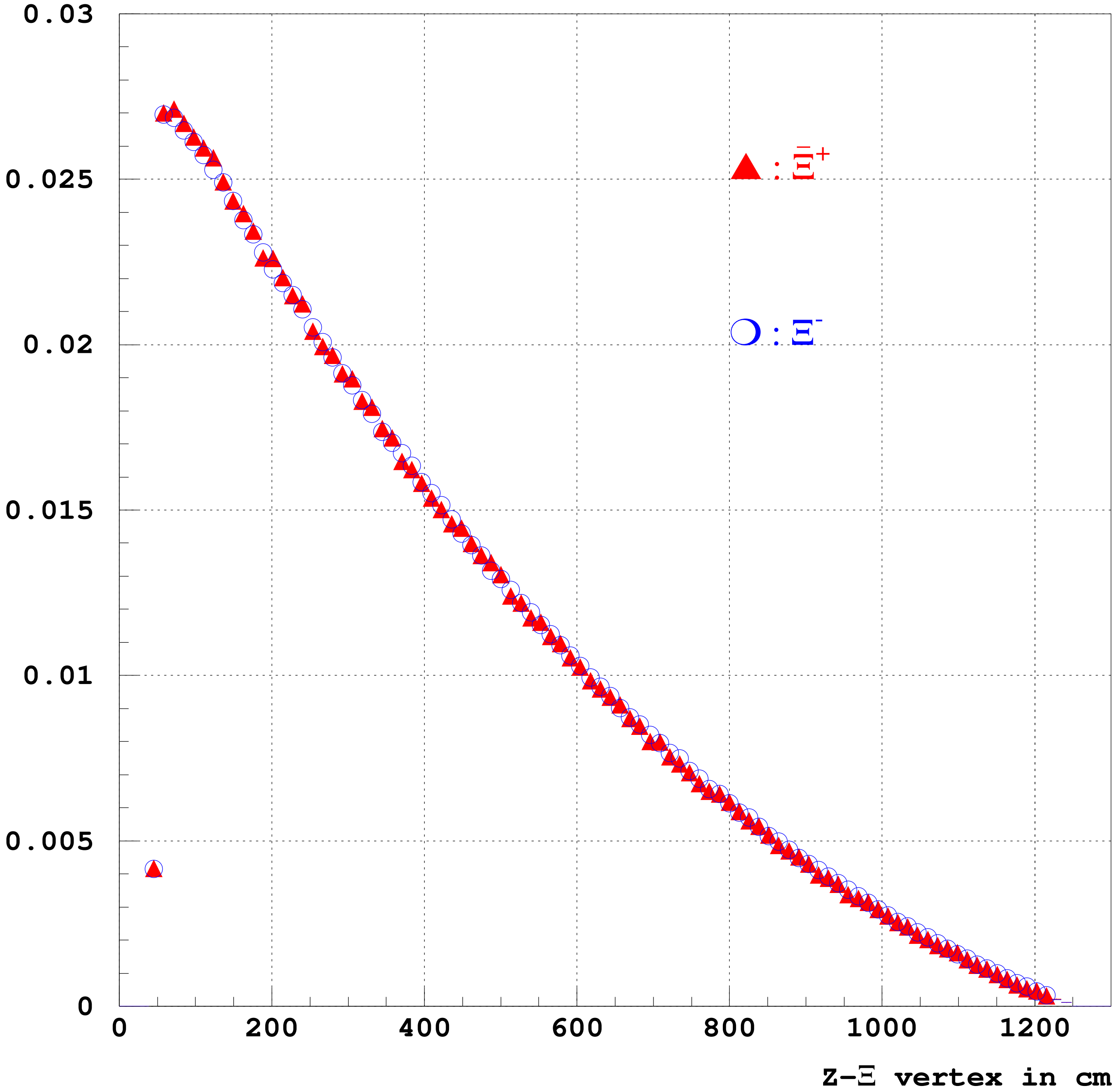
Magnetic fields control





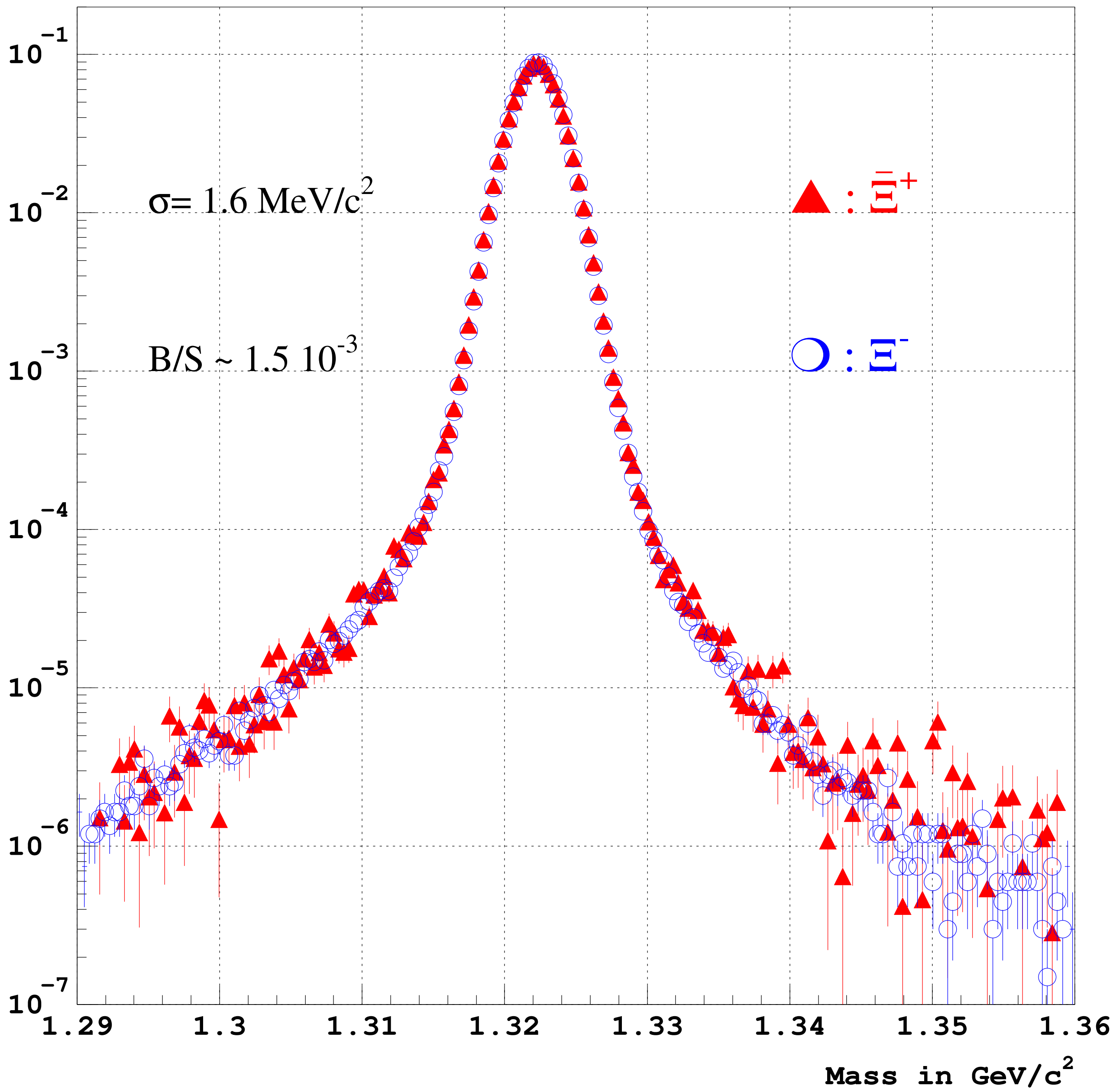
- **The spectrometer calibration can be done with K_s produced in the collimator. (Top)**
- **For a pointlike target the momentum of a particle is determined by its position and direction at the collimator exit, this can be used to calibrate the hyperon magnet. (Bottom)**

Ξ decay vertices distribution



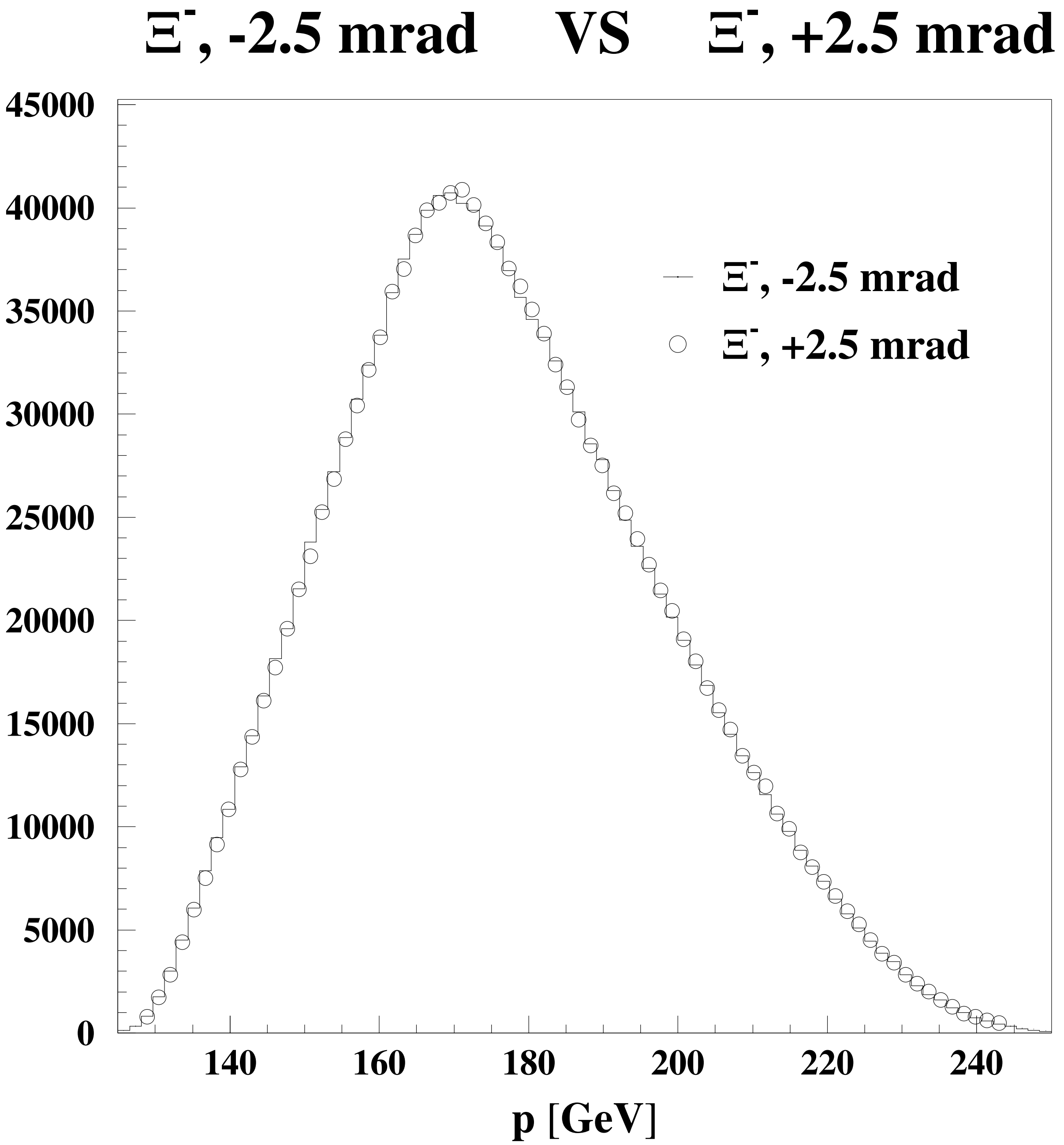
- Data for Ξ^- and $\overline{\Xi}^+$ have been normalized to the same number of events
- Very similar dispite different momentum distributions

Mass spectra for Ξ^- and $\overline{\Xi}^+$

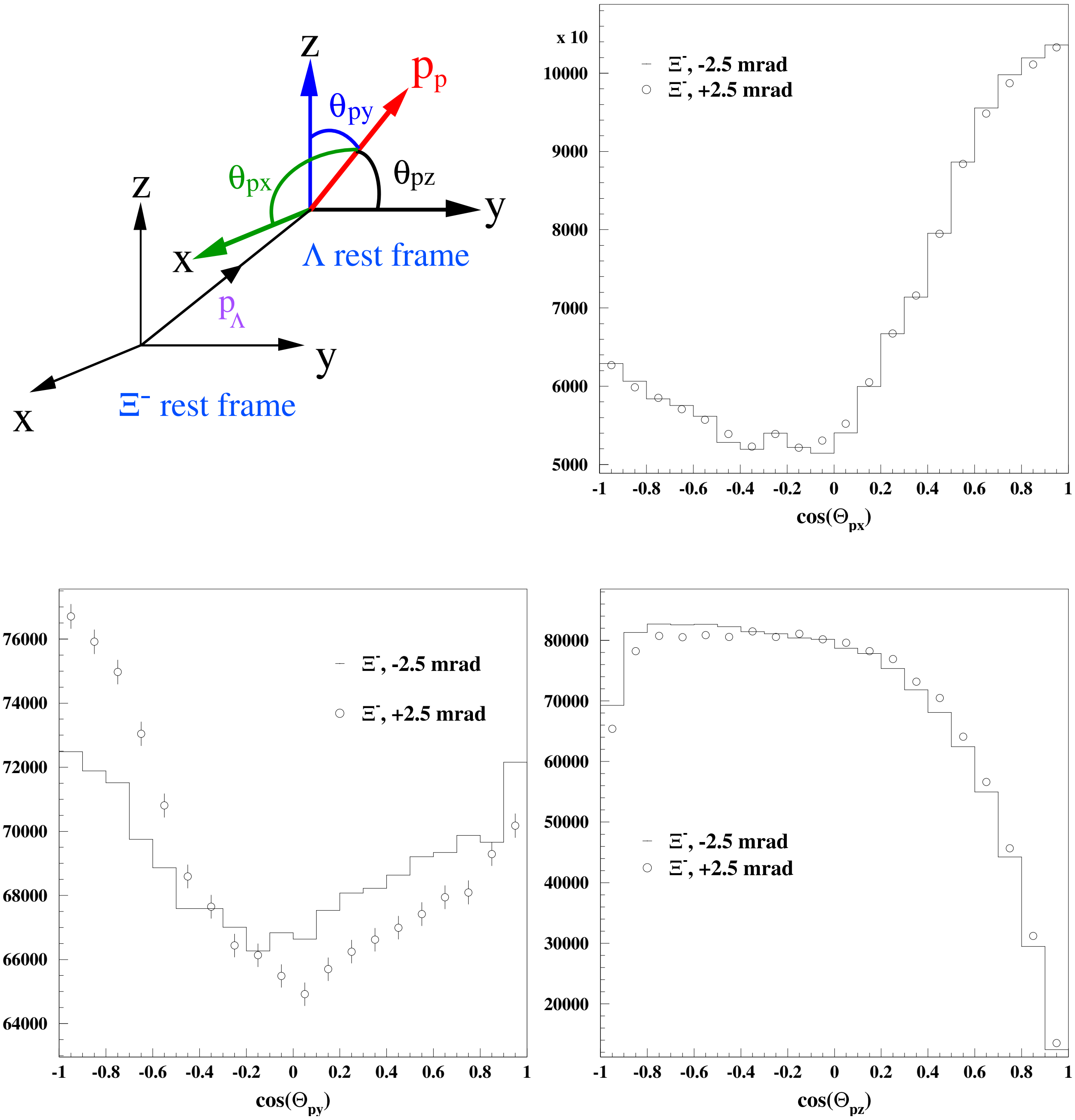


- Background under the mass peak is about 1×10^{-3} and tails are very similar for both charges

Decay of Ξ with small vertical polarization

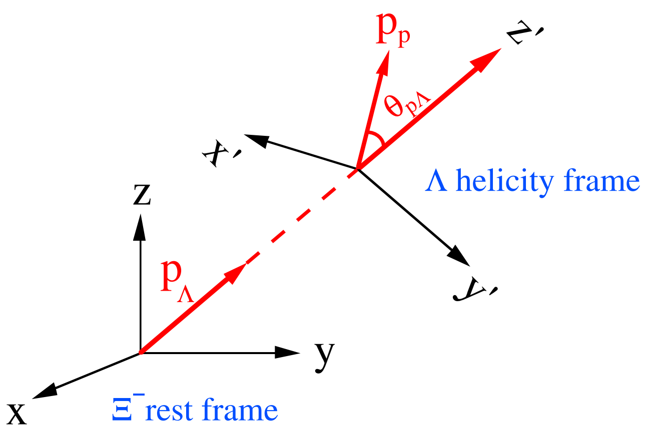


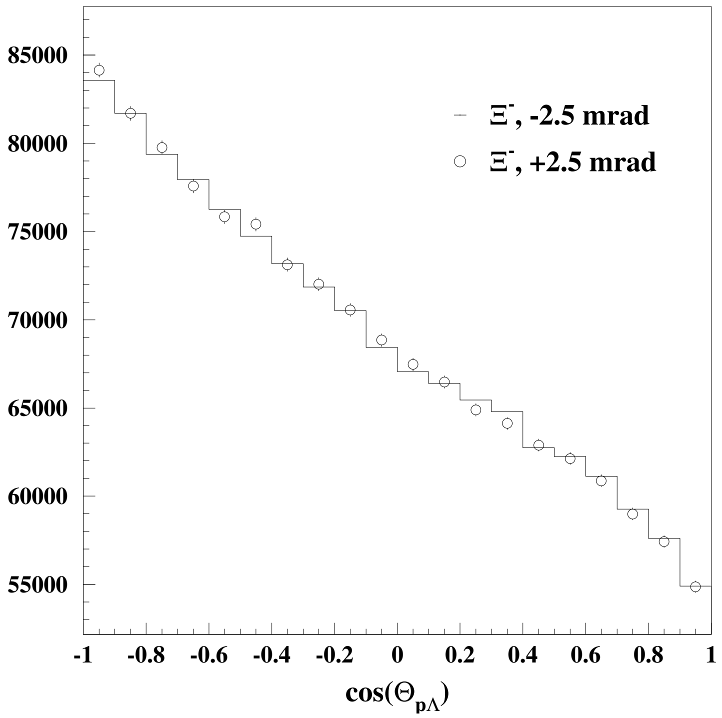
- Production at ± 2.5 mrad in the horizontal plane. Vertical polarization but in opposite direction for the two sets.



- **The effect of the small polarization is clearly seen in the $cos(\theta_{py})$ distribution in the Λ rest frame**

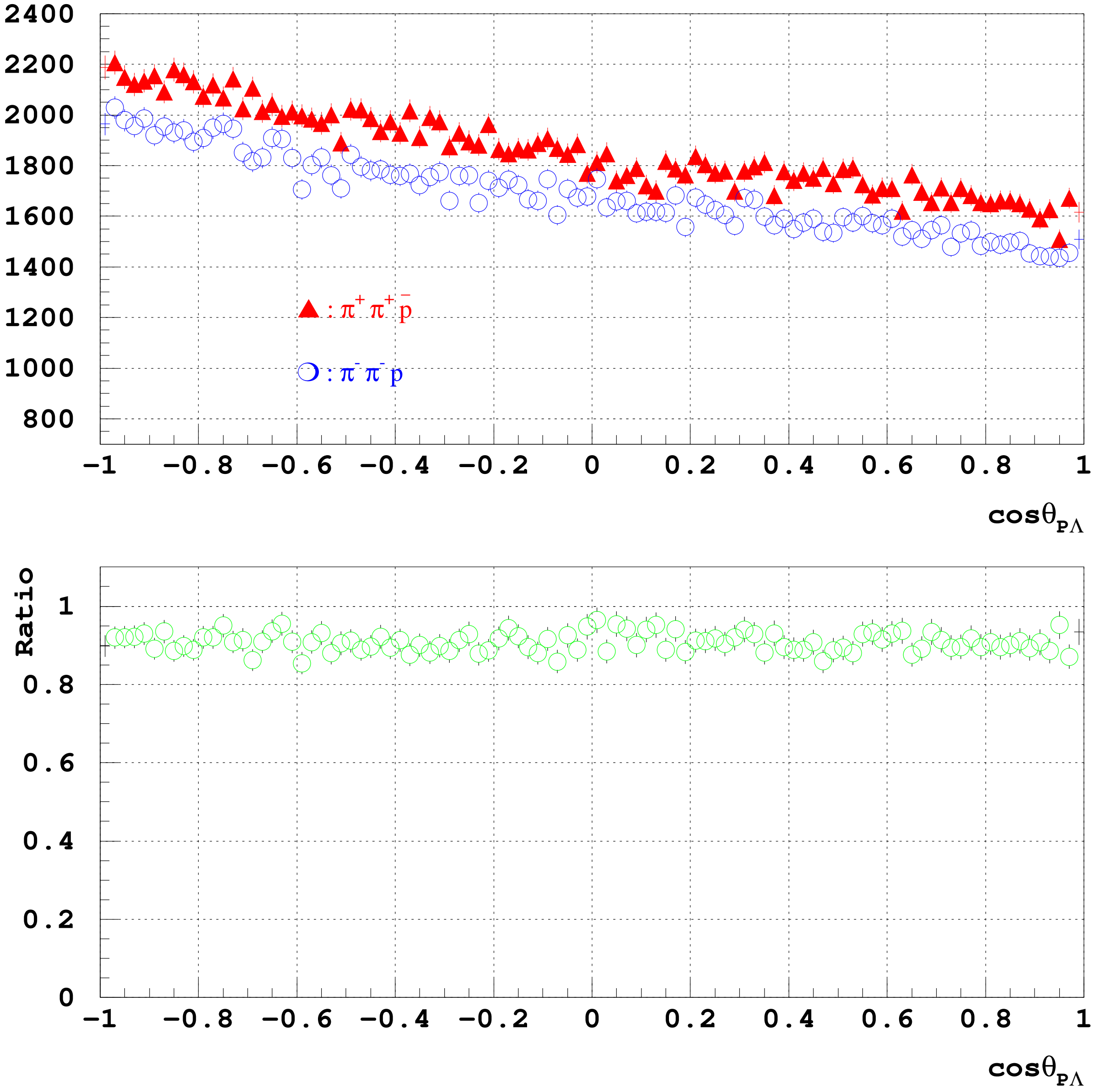
Ξ^- (-2.5 mrad) vs Ξ^- (+2.5 mrad)





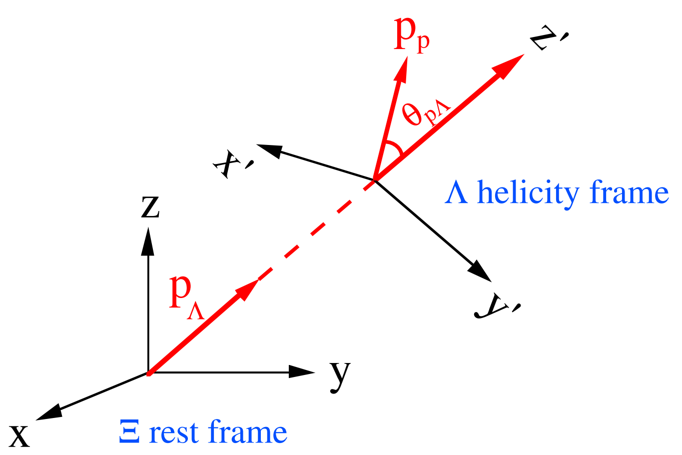
- **In the Λ helicity frame the effect of the small polarization on the $cos(\theta_{p\Lambda})$ distribution disappears**
- **Monte-Carlo studies show that a 1% polarization only modifies the slope of the $cos(\theta_{p\Lambda})$ at the 2×10^{-4} level**

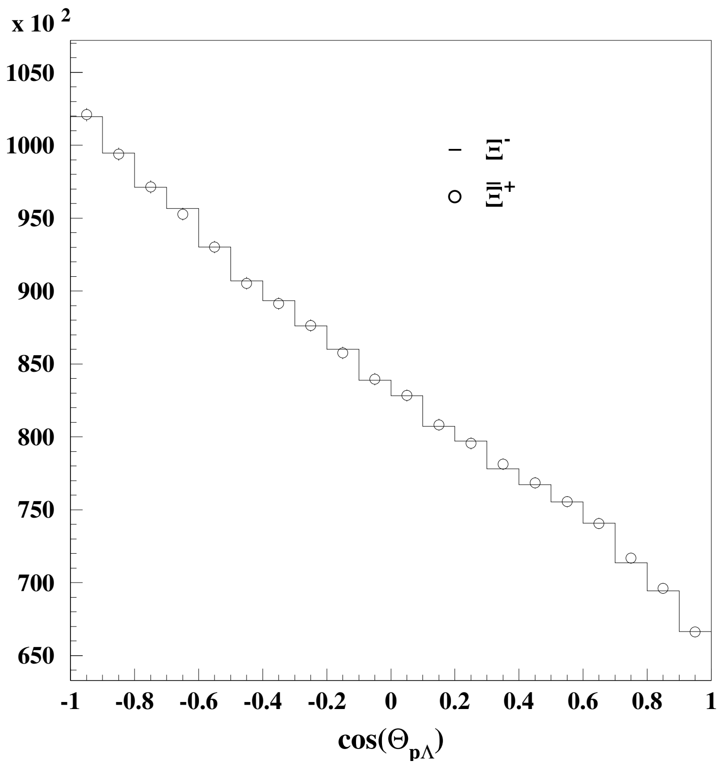
Interactions



- **For a given sample of Ξ events, using actual cross-sections, the number of lost events (interaction of one of the decay particles) for both charges as function of $cos\theta_{p\Lambda}$**
- **The ratio shows very low $cos\theta_{p\Lambda}$ dependency**

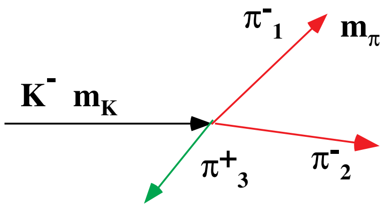
Ξ^- (0 mrad) vs $\overline{\Xi}^+$ (0 mrad)





- **This is the uncorrected plot which will be used for CP violation in hyperon decay**
- **A lot more work is needed before any number can be quoted about CP violation**

Direct CP violation in $K \to 3\pi$



- **Dalitz kinematical variables**

$$X = \frac{s_2 - s_1}{m_\pi^2} \qquad Y = \frac{s_3 - s_0}{m_\pi^2}$$

with

$$s_i = (\mathbf{p}_K - \mathbf{p}_i)^2 \qquad s_0 = \frac{1}{3}(m_K^2 + 3m_\pi^2)$$

- **Distribution in phase space**

$$|A(K \to 3\pi)|^2 \propto 1 + gY + hY^2 + kX^2$$

PDG: $g = -0.2154 \pm 0.0035, h = 0.012 \pm 0.008, k = -0.0101 \pm 0.0034$

- **Any differences between K^+ and K^- would indicate direct CP violation**

e.g. Slope asymmetry

$$\delta g = \frac{g - \bar{g}}{g + \bar{g}}$$

- **Theoretical Predictions**

	$\lvert\delta g\rvert$
H.-Y. Cheng (1991)	$< 1 \times 10^{-5}$
D'Ambrosio *et al.* (1991)	$\leq 1 \times 10^{-5}$
Isidori *et al.* (1992)	$\sim 1 \times 10^{-6}$
E.P. Shabalin (1993)	$\leq (5 \pm 2) \times 10^{-5} \lvert sin\delta\rvert$
A.A. Bel'kov *et al.* (1993)	$\sim 0.5 \times \lvert\epsilon'/\epsilon\rvert$
D'Ambrosio *et al.* (1998)	$\sim 2 \times 10^{-6}$
E.P. Shabalin (1998)	$\sim 2 \times 10^{-4}$

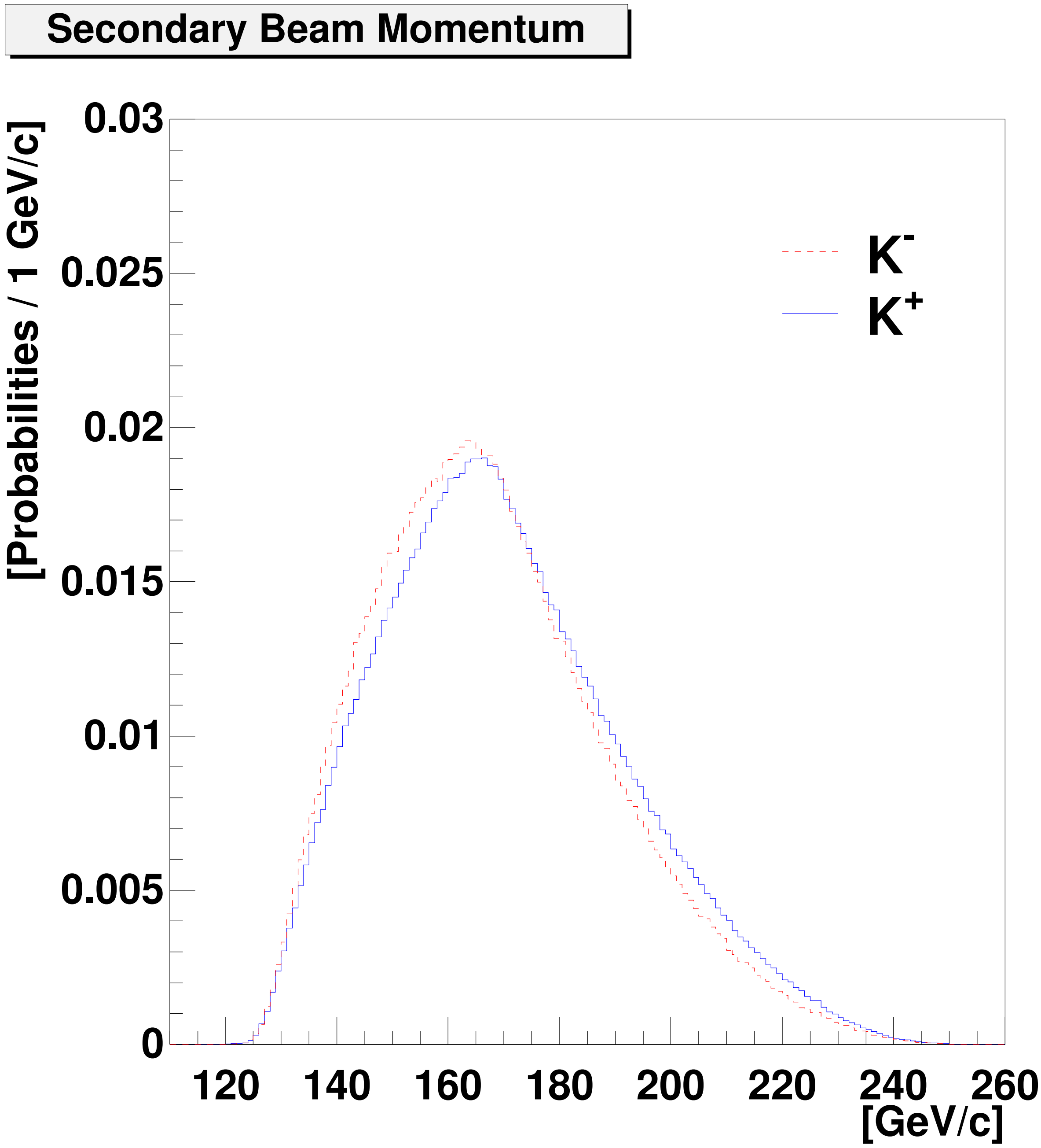
- **Previous experiment**

1970: Dedicated search at BNL AGS.
Collected 1.6 **million** $K \rightarrow 3\pi$ **decays for each charge.**
$\delta g = (-0.70 \pm 0.53) \times 10^{-2}$

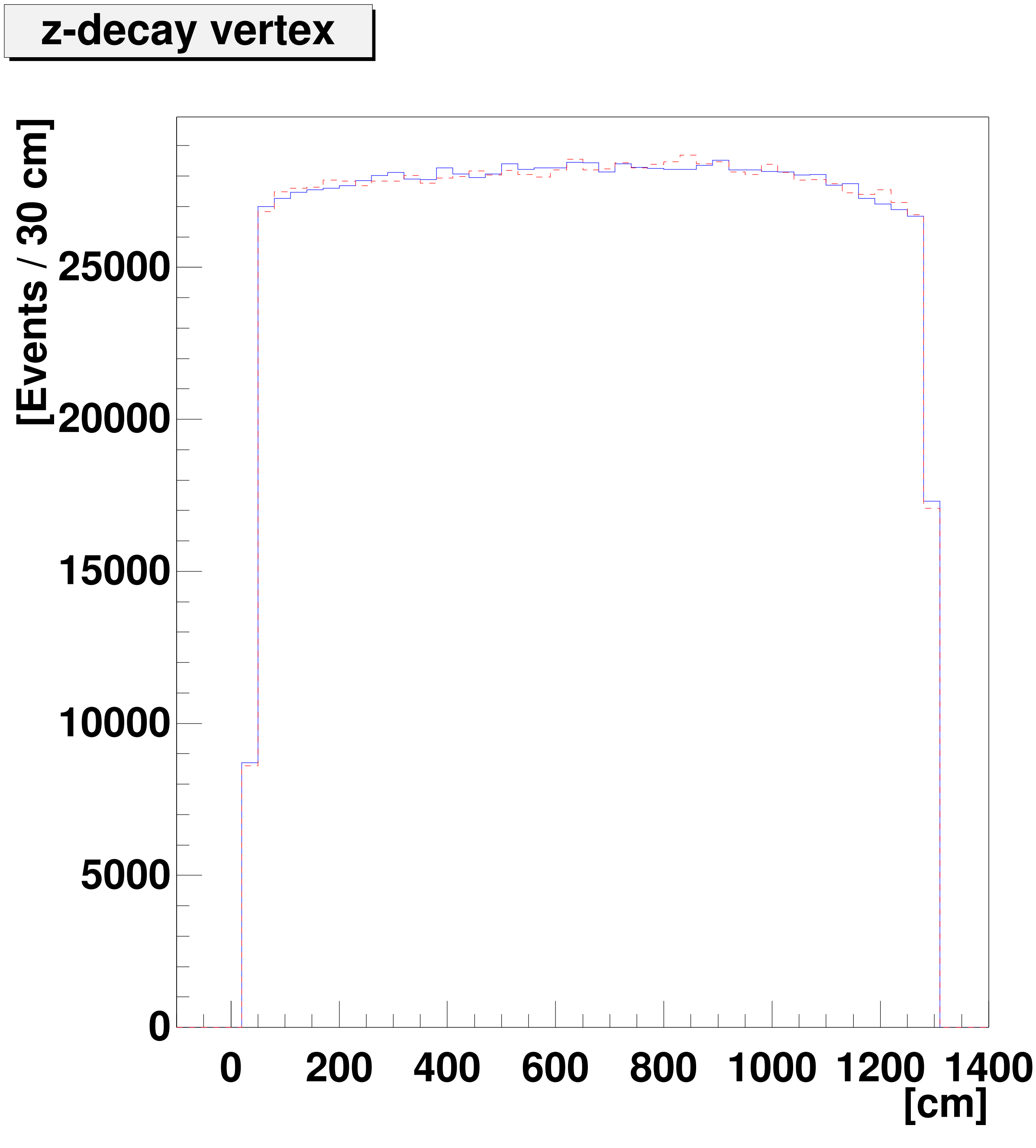
- **FNAL E871 (HyperCP)**

Data collected between April 1997 and september 1997
109 $K^+ \rightarrow 3\pi$ **and 48** $K^- \rightarrow 3\pi$ **million events expected**
Sensitivity in δg **of about** 6.8×10^{-4}

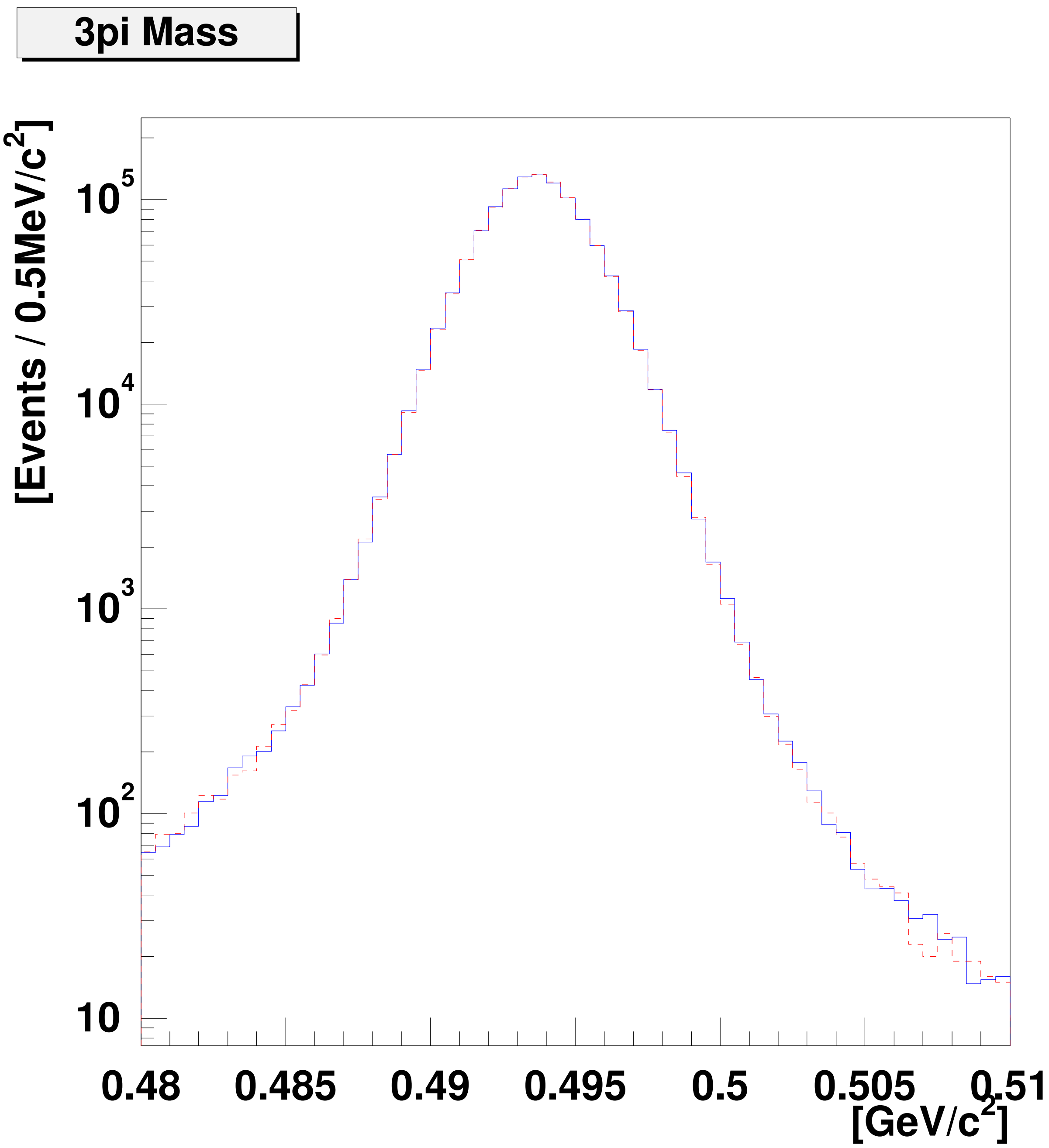
- **Plots shown are VERY PRELIMINARY**



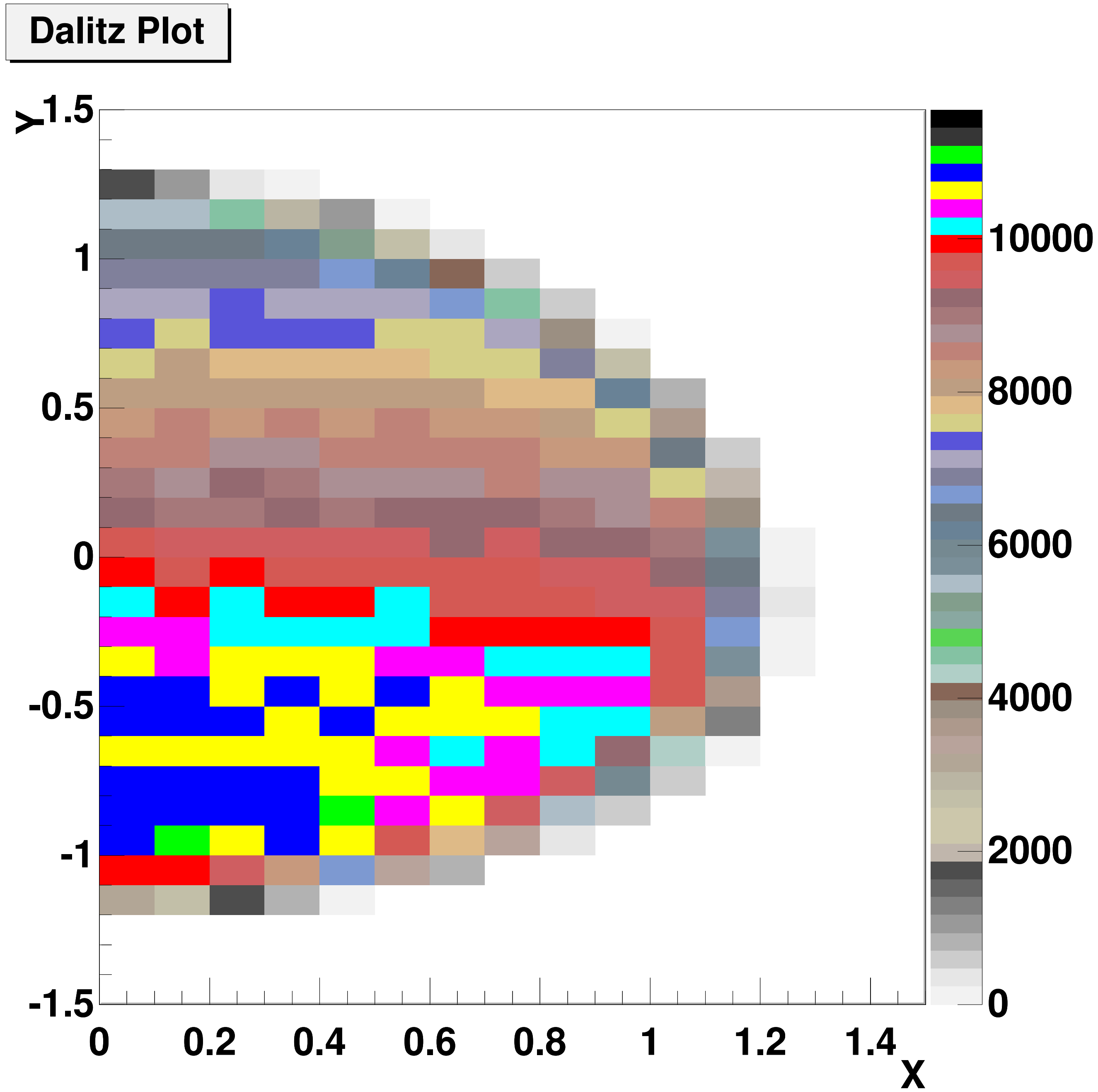
- Due to different production physics of particle and anti-particle, the momentum spectra for K^+ and K^- are different which can introduce an acceptance difference between K^+ and K^-.
- K^+ data set is scaled down using $1GeV/c$ momentum bin to make its momentum spectra the same as K^-.

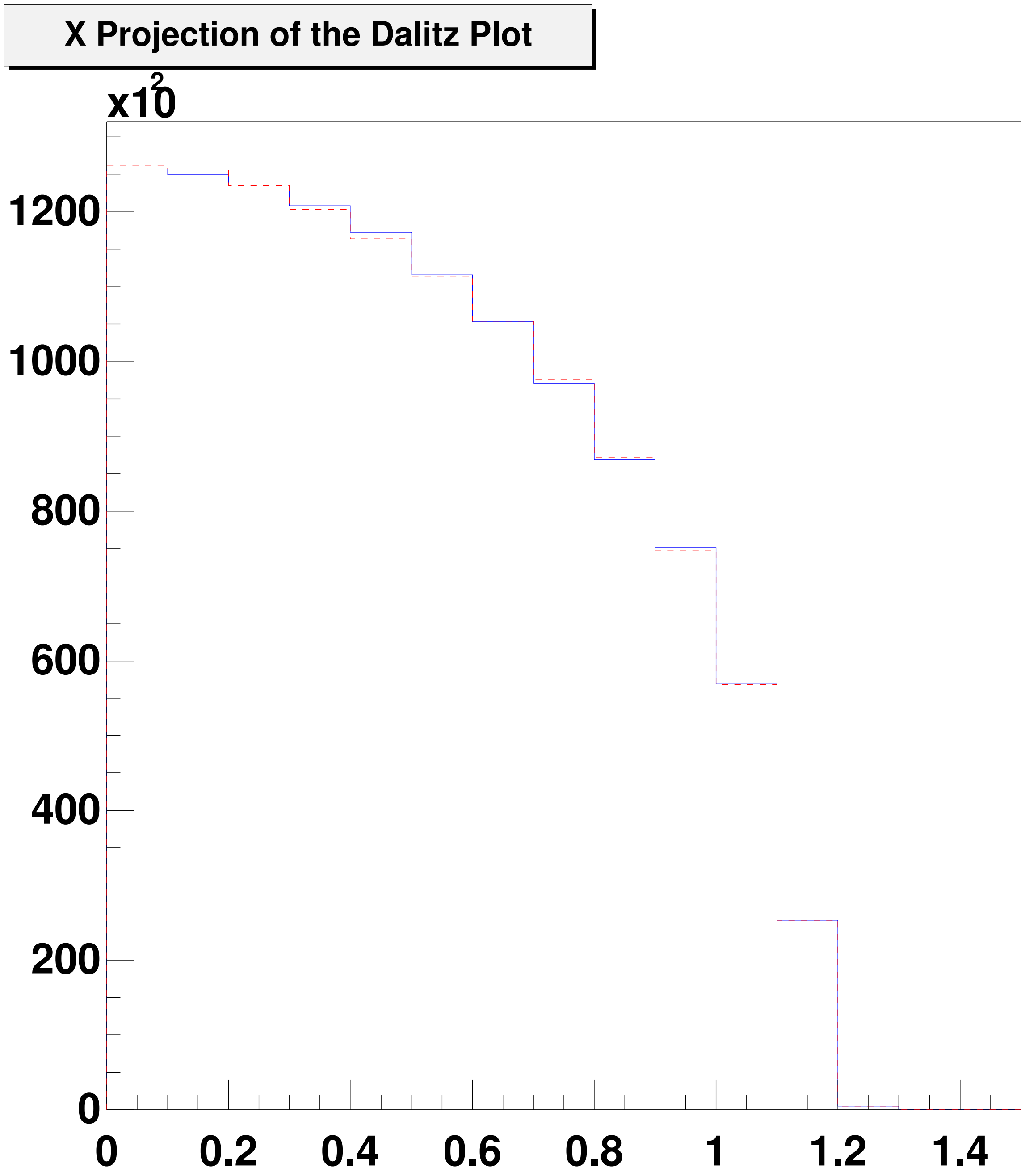


z-decay vertex
[Events / 30 cm]
25000
20000
15000
10000
5000
0
0
200
400
600
800
1000
1200
1400
[cm]



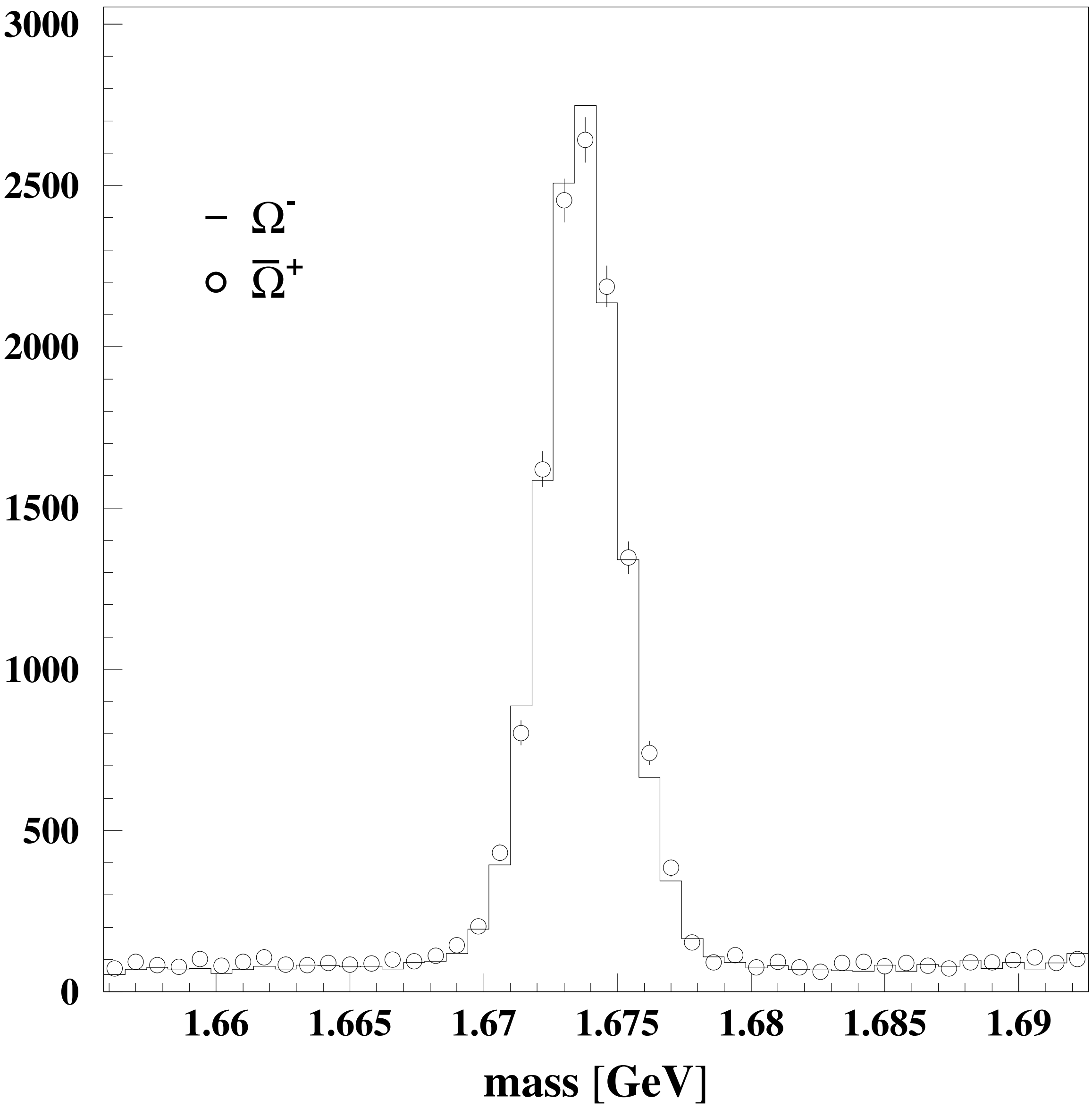
- **Good mass resolution ($\sigma_{mass} \sim 1.9MeV/c^2$).**
- **Good signal to background ratio ($B/S < 10^{-3}$).**
- **Possible differences (e.g, magnetic field, background) between positive and negative have not been corrected which might contribute to the observed mass asymmetry of about 1%.**


Dalitz Plot
Y
1.5
1
0.5
0
-0.5
-1
-1.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
X
10000
8000
6000
4000
2000
0



- The asymmetry in the X projection of the Dalitz plot is expected to be zero.
- Any observed asymmetry would indicate an acceptance difference between the positive and negative data.

Asymmetry A_Ω for $\Omega^- \rightarrow \Lambda K^-$ decay



- **Invariant mass for ΛK**
- **Expect to reconstruct $\approx 10^7 \Omega$**

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**
    - ◇ $\Xi^- \to p\pi^-\pi^-$
    - ◇ $\Omega^- \to \Lambda\pi^-$
  - ∗ **Search for ΔS=3 decay**
    - ◇ $\Omega^- \to p\pi^-\pi^-$
  - ∗ **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**
    - **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 world 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.

- It will also improve by one order of magnitude in the asymmetry in the slope of the Dalitz plot for the $K \rightarrow 3\pi$ decay with a projected sensitivity of

$$6.8 \times 10^{-4}$$

- E871 will start running again within a month and expects to reach

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

  sensitivity in $A_{\Lambda\Xi}$