A Summary of Ξ^o Physics at KTEV

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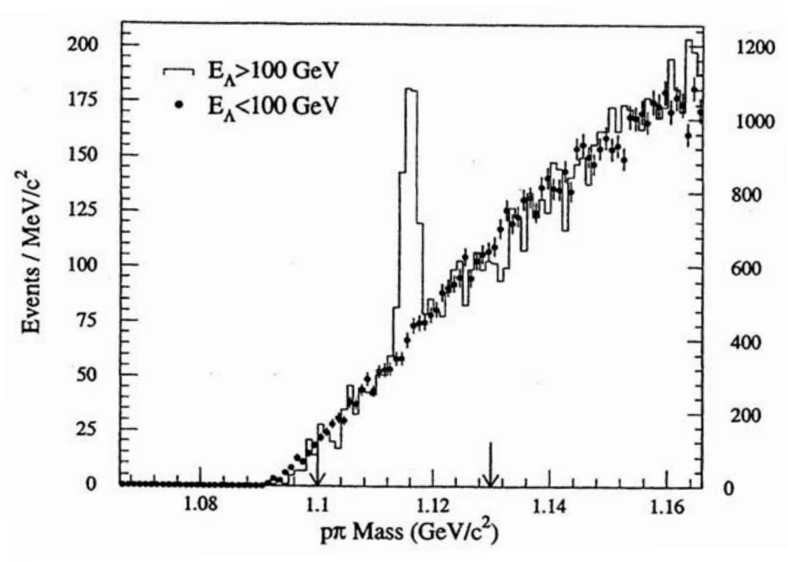
Genesis of an idea

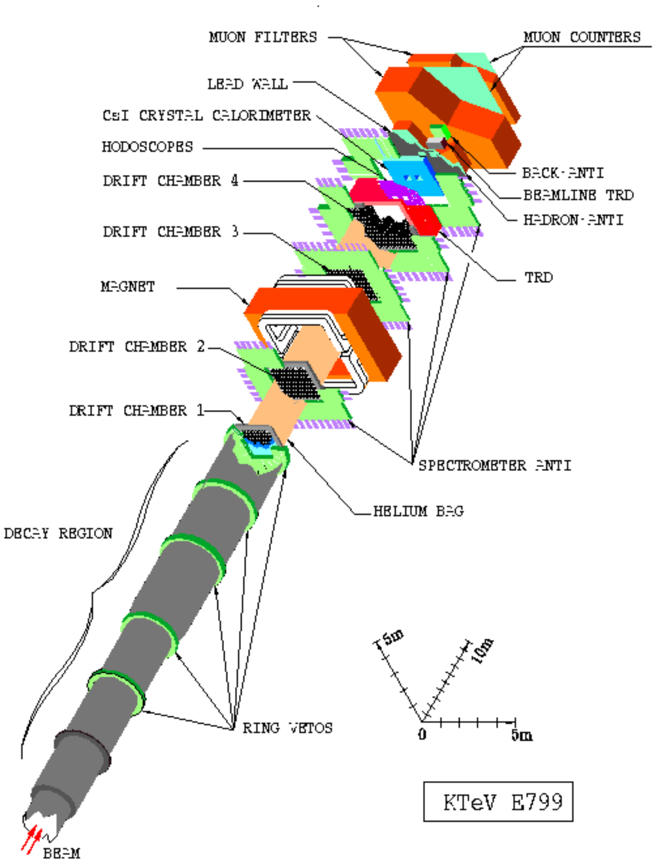
- It was noticed in the Fermilab neutral kaon experiment E731(1983-1987) that a significant Λ flux was evident as a background to kaon decays.



- In the E799 experiment (1990-1992), we upgraded the apparatus and decided to trigger on the Λ decays to determine polarization at 800 GeV production.

The KTeV experiment at Fermilab

- Designed in 1992, finished construction in 1996 and took data in 1997-1999.
- Ultimate goal of the experiment was to measure the CP violation parameter ε'/ε of the neutral kaon system, to a precision of 1×10^{-4}
- The beam was approximately 20 MHz of neutrons/kaons/hyperons in a 150:50:1 ratio
- The experiment was a long vacuum decay channel, followed by a precision drift chamber spectrometer and a high quality CsI electromagnetic calorimeter.



The KTeV Collaboration

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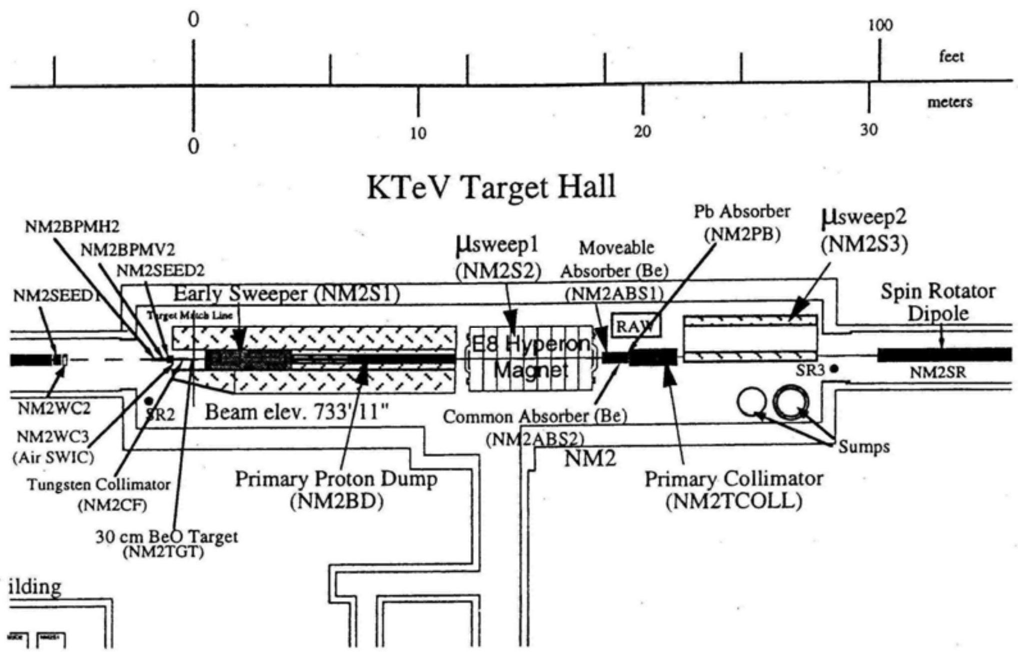
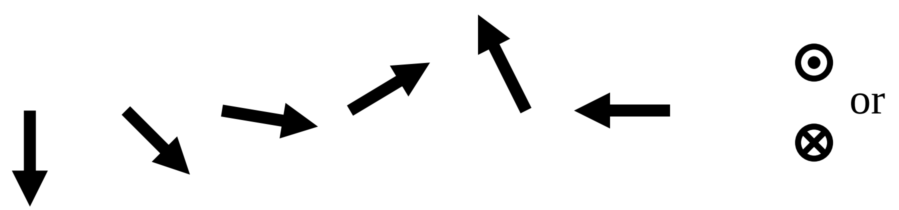
The KTeV Beamline



vertical targeting angle = 4.8 mrad

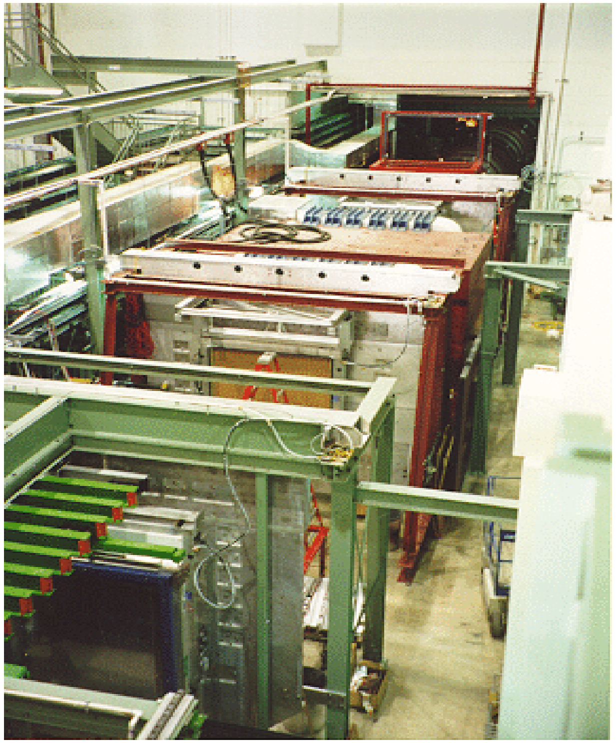
- KTeV beamline was designed with consideration for hyperon polarization:

Ξ^o Spin Vector:

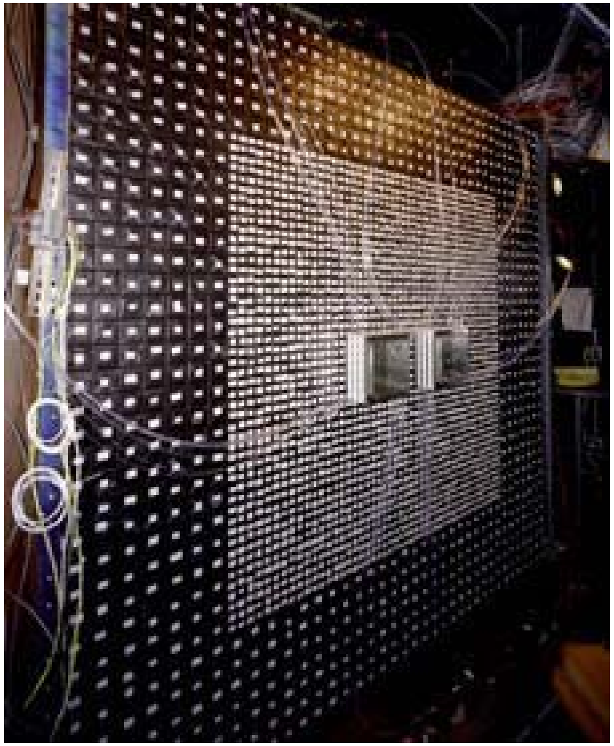


- Half of the KTeV data was taken with each of the two vertical polarization states

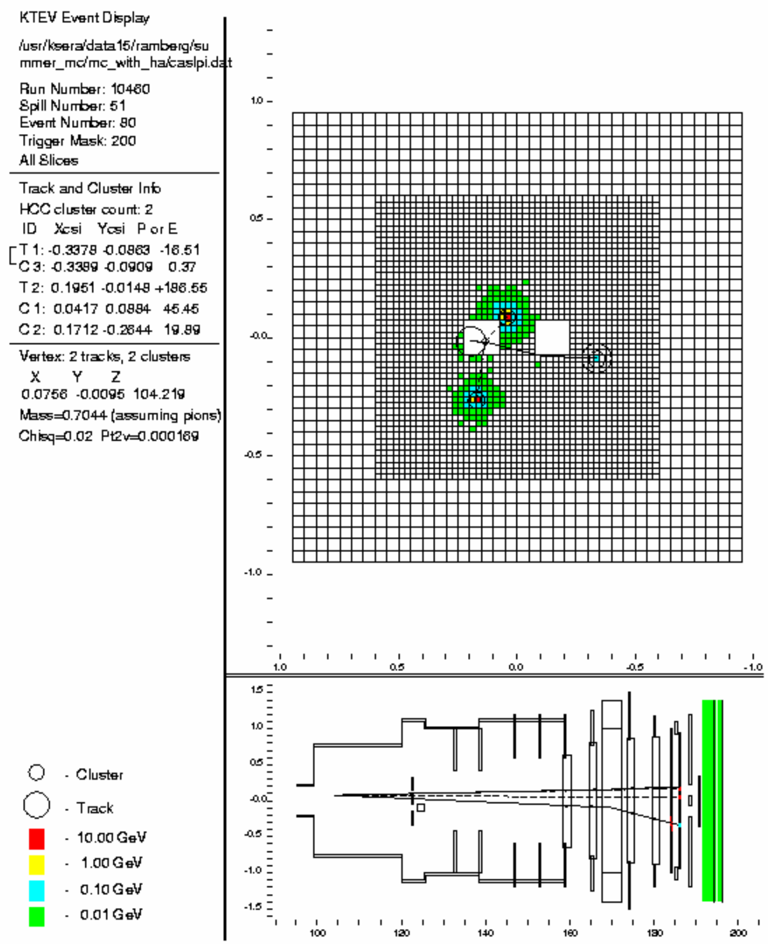
A view of the KTeV experiment, looking upstream, with the TRD system in the foreground and the large analysis magnet in center.



3100 crystals of pure CsI formed the electromagnetic calorimeter. Approximately 1 mm spatial resolution and better than 1% energy resolution.



$\Xi^o \longrightarrow \Lambda\pi^o \longrightarrow (p\pi^-)(\gamma\gamma)$ event in KTeV



Minimum bias 'Stiff Track Trigger" demanded:

- High momentum track down one of the beam holes
- Two clusters and at least 16 GeV in the calorimeter
- Momentum ratio between high momentum track and low momentum track of >2.5

Ξ^o beta decay trigger demanded:

- Stiff Track Trigger
- No energy in hadron calorimeter behind CsI

In the 1999 run there were about:

- 3×10^8 Ξ^o decays in the KTEV decay volume
- 1.7×10^6 $\Xi^o \longrightarrow \Lambda\pi^o$ decays in the minimum bias trigger (which was prescaled)
- 1300 Ξ^o beta decays
- 9 Ξ^o muon semi-leptonic decays

(Since the spectrometer is 100 meters from the target, only high energy hyperons survive.)

Hyperon studies planned for KTeV

- $\mathbf{\Lambda^0 \to p\pi^-}$, $\mathbf{\overline{\Lambda^0} \to \overline{p}\pi^+}$
  $\to$ Polarization studies (With polarized Λ^0 beam)
- $\mathbf{\Lambda^0 \to pe^-\overline{\nu_e}}$, $\mathbf{\overline{\Lambda^0} \to \overline{p}e^+\nu_e}$
  $\to$ Form factors (With polarized Λ^0 beam)
- $\mathbf{\Xi^0 \to \Lambda^0\pi^0}$, $\mathbf{\overline{\Xi^0} \to \overline{\Lambda^0}\pi^0}$
  $\to$ Precise mass measurement, Polarization studies (With polarized Ξ^0 beam)
- $\mathbf{\Xi^0 \to \Sigma^+e^-\overline{\nu_e}}$, $\mathbf{\overline{\Xi^0} \to \overline{\Sigma}^-e^+\nu_e}$
  $\to$ Branching ratio, Form factors (up to g_2)
- $\mathbf{\Xi^0 \to \Sigma^+\mu^-\overline{\nu_\mu}}$, $\mathbf{\overline{\Xi^0} \to \overline{\Sigma}^-\mu^+\nu_\mu}$
  $\to$ Branching ratio, Form factors (up to g_3)
- $\mathbf{\Xi^0 \to p\pi^-}$, $\mathbf{\overline{\Xi^0} \to \overline{p}\pi^+}$
  $\to$ Branching ratio, SM test
- $\mathbf{\Xi^0 \to \Sigma^0\gamma}$, $\mathbf{\overline{\Xi^0} \to \overline{\Sigma^0}\gamma}$
  $\to$ Branching ratio and Asymetrie studies
- $\mathbf{\Xi^0 \to \Lambda^0\gamma}$ $\mathbf{\overline{\Xi^0} \to \overline{\Lambda^0}\gamma}$
  $\to$ Branching ratio and Asymetrie studies

First hyperon result from KTeV: Search for H^0 (uuddss) Dibaryon

- Jaffe (1977) proposed a metastable bound dibaryon state H^0 with quark structure (uuddss).
- For masses between the Λn and $\Lambda\Lambda$, the H^0 would decay weakly with a lifetime expected to be between 10^{-7} and 10^{-10} sec. The decay would be:

  $H^0 \longrightarrow \Lambda p \pi^- \longrightarrow p\pi^- p\pi^-$

- KTeV, with its 800 GeV production, and 60 meter decay length, was an ideal place to search for this particle.
- We searched for a 4 particle final state, and normalized the acceptance with the mode

  $\Xi^o \longrightarrow \Lambda\pi^o \longrightarrow p\pi^- e^+e^-\gamma$

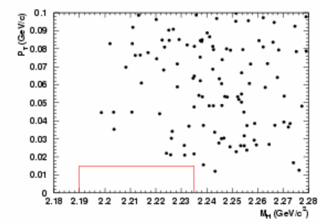


FIG. 2. The transverse momentum of the H^0 versus M_H for events passing all the selection criteria except the cuts on $P_T(H^0)$ and M_H. The box shows the signal region. The background events outside the signal region are from simultaneous decays of two particles in the fiducial volume, the predominant contribution coming from the decays $K_L \to \pi^\pm l^\mp \nu$.

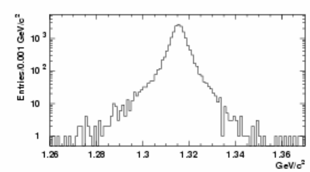


FIG. 3. The invariant mass of the $\Lambda\pi^0_D$ sample used to normalize the signal mode ($M_\Xi = 1.315$ GeV/c^2). There are a total of 17 160 events in the mass peak.

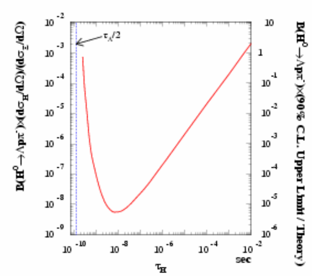


FIG. 4. The 90% C.L. upper limit on the ratio of the product of the H^0 branching ratio and the production cross-section to the Ξ^0 production cross-section as a function of the H^0 lifetime. M_H is assumed to be 2.21 GeV/c^2. The sensitivity scale on the right ordinate axis assumes the production model of reference [9].

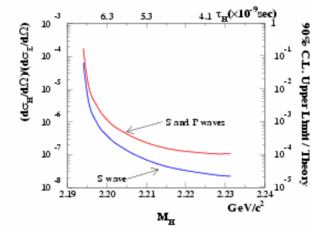


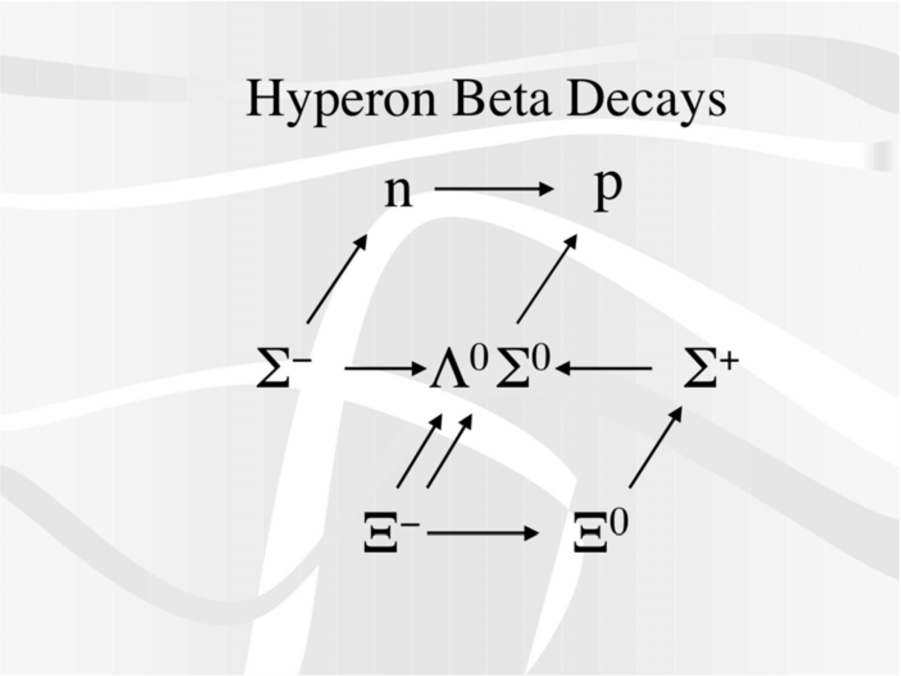
FIG. 5. The 90% C.L. upper limit on the ratio of the H^0 production cross-section to the Ξ^0 production cross-section as a function of M_H. The top abscissa axis shows the H^0 lifetime associated with M_H assuming the H^0's wave function is a pure S wave state, as predicted in reference [5]. If the H^0 contains both S and P wave contributions, reference [5] estimates the lifetime could be as low as half the lifetime of the pure S wave state, worsening our sensitivity to the H^0. The curve for the S and P wave state is derived using half the lifetime of the pure S wave.

A.Alavi-Harati et al., PRL 84, 2593 (2000).

- **In 1997, the Ξ^o beta decay had not been observed and was the last of the hyperon beta decays to be studied.**

- **This beta decay is an SU(3) symmetry reflection of the neutron beta decay (i.e. a quark transition of uss → uus instead of udd → uud. The g1 and f1 form factors in the decay are identical to neutron beta decay.**

- **Thus this beta decay is quite important to disentangle the SU(3) symmetry breaking effects**



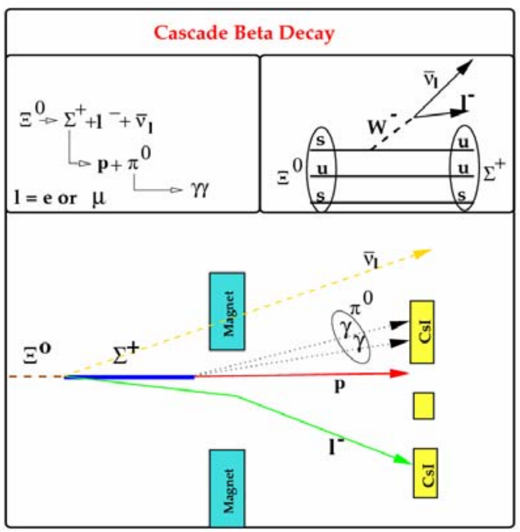
$$< B_{final} \mid J^{\alpha} \mid A_{initial} > =$$
$$u(B) \left[f_1(q^2)\,\gamma^{\alpha} + f_2(q^2)/M_A\,\sigma^{\alpha\nu}\gamma_{\nu} + f_3(q^2)/M_A\,q^{\alpha} + \{g_1(q^2)\gamma^{\alpha} + g_2(q^2)/M_A\,\sigma^{\alpha\nu}\gamma_{\nu} + g_3(q^2)/M_A\,q^{\alpha}\}\,\gamma_5 \right] u(A)$$

$g_1/f_1 = 1.267$ for neutron beta decay (V-A interaction)
g_3 and f_3 essentially vanish for electron mass
No evidence for g2 ‘weak electricity’

Discovery of Ξ^o Beta Decay at KTeV:

$\Xi^o \longrightarrow \Sigma^+ e^- \bar{\nu}$

- Momentum vector of Σ^+ is determined by reconstructing the z position of the π^o decay and adding in the proton momentum.
- The Ξ^o is reconstructed by finding the distance of closest approach of the electron.



Monte Carlo simulation of the beam and detector.

During reconstruction and analysis, we sought to minimize event losses and to treat beta and $\Lambda^0\pi^0$ candidates as similarly as possible. All events were required to have at least two neutral ECAL clusters (π^0 candidate) above 3 GeV and separated by more than 15 cm, and a low momentum negative track (2.5–50 GeV/c for e^- and 2.5–75 GeV/c for π^-) pointing outside of the beam hole regions of the ECAL. The proton was identified by a high momentum (110–400 GeV/c) positive track pointing to one of the beam holes of the ECAL. To reject K^0 backgrounds, the ratio of the positive track momentum over the negative track momentum was required to be greater than 3.5. Identical track quality and fiducial requirements were imposed on all events.

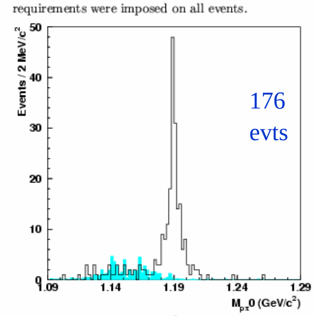


FIG. 2. Reconstructed $p\pi^0$ invariant mass distribution for the Ξ^0 beta decay candidates. Superimposed in gray is the simulated background from $\Xi^0 \to \Lambda^0\pi^0$ decays with $\Lambda^0 \to p$ + anything.

Candidate $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ reconstruction proceeded from downstream to upstream. The secondary Σ^+ decay vertex was located, with a longitudinal resolution of 0.4 m, at the point along the proton track where the two highest energy neutral ECAL clusters matched the π^0 mass. The primary Ξ^0 vertex was then defined at the point of closest approach of the extrapolated Σ^+ path and the negative track. To remove $\Xi^0 \to \Lambda^0\pi^0$ background candidates, a $\Xi^0 \to \Lambda^0\pi^0$ hypothesis, described below, was used to reject candidates with a reconstructed $\Lambda^0\pi^0$ mass below 1.33 GeV/c^2.

All vertices were required to fall within the decay region fiducial volume (95-150 m), and primary Ξ^0 vertices were required to lie within a neutral beam. We eliminated primary Λ^0 or K^0 two-body decays by rejecting events with charged vertex transverse momentum squared less than 0.001 (GeV/c)^2. To enforce correct vertex geometry and to reduce further the primary Λ^0 or K^0 decay backgrounds, each secondary vertex was required to be 1–20 m downstream of the primary vertex. Further requirements were imposed on reconstructed Ξ^0 momentum (160–500 GeV/c) and decay distance (< 10 lifetimes).

Only those events in the beta decay trigger sample which contain an e^-, identified by the deposition of more than 90% of its energy in the ECAL, were retained. We also required a suitable $\Sigma^+ e^-$ invariant mass (1.20–1.32 GeV/c^2) and a missing transverse momentum which was (within a 25 MeV/c uncertainty) less than the reconstructed neutrino momentum in the Ξ^0 rest frame.

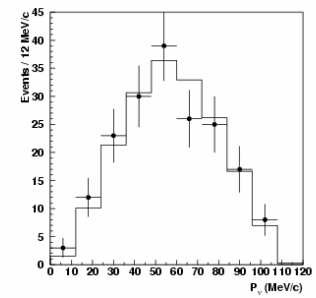


FIG. 3. Neutrino momentum spectrum in the Ξ^0 rest frame. Points are data with statistical uncertainties, and the histogram is our Monte Carlo simulation normalized to the same number of events. The acceptance has little effect on this distribution.

The $p\pi^0$ invariant mass distribution for the 235 remaining candidates is shown in Fig. 2. A clear Σ^+ mass peak is apparent, containing 183 events within ± 15 MeV/c^2 (± 3 standard deviations) of the Σ^+ mass [7]. The gray region of Fig. 2 is the distribution for the primary predicted backg… meas… distri… the m… from… estim… 15 Me… 1.170… $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ events. The reconstructed Σ^+ and Ξ^0 decay distance distributions matched those predicted from known lifetime values. Distributions such as the proton and electron momentum spectra in the laboratory frame and the neutrino momentum spectrum in the Ξ^0 rest frame (Fig. 3) for simulated $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ decays all agreed with the data.

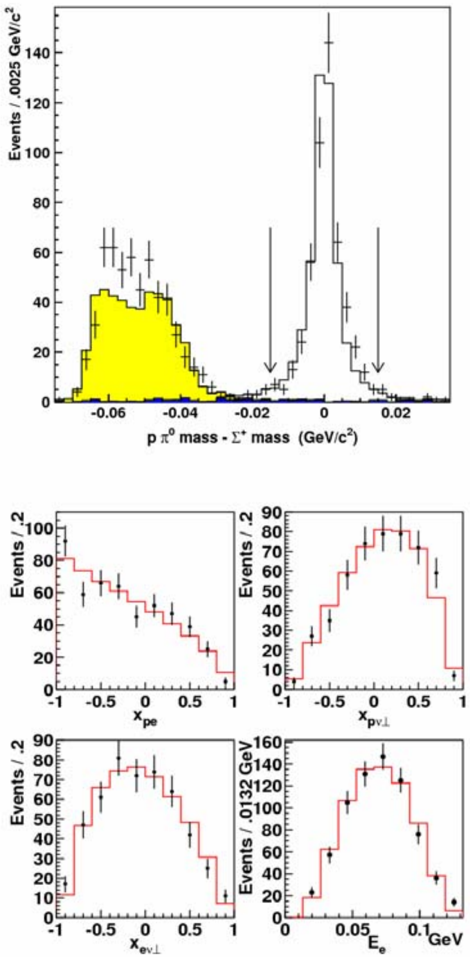
A.Affolder et al.,
PRL 82, 3751 (1999)

B.R.(Ξ^o β decay) = (2.71 +/- 0.22 +/- 0.31) x 10^{-4}	Prediction = (2.61 +/- 0.11) x 10-4

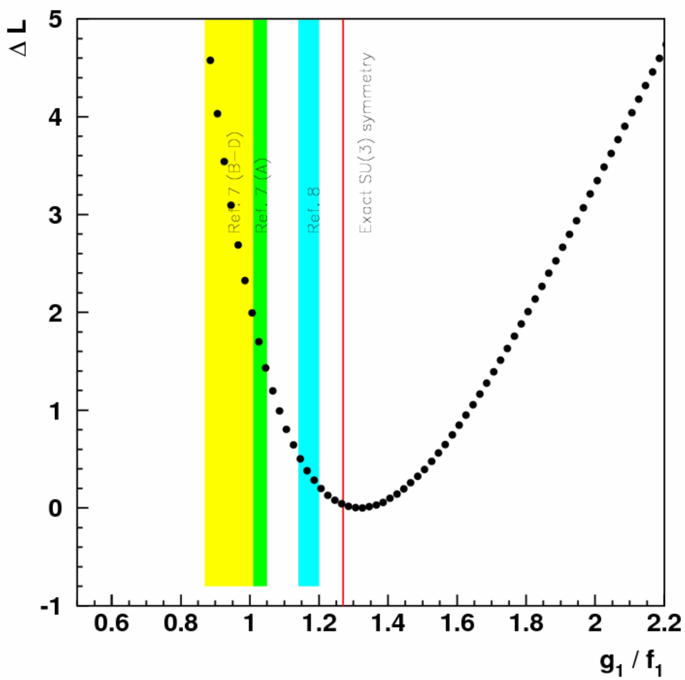
(early 1997 data)

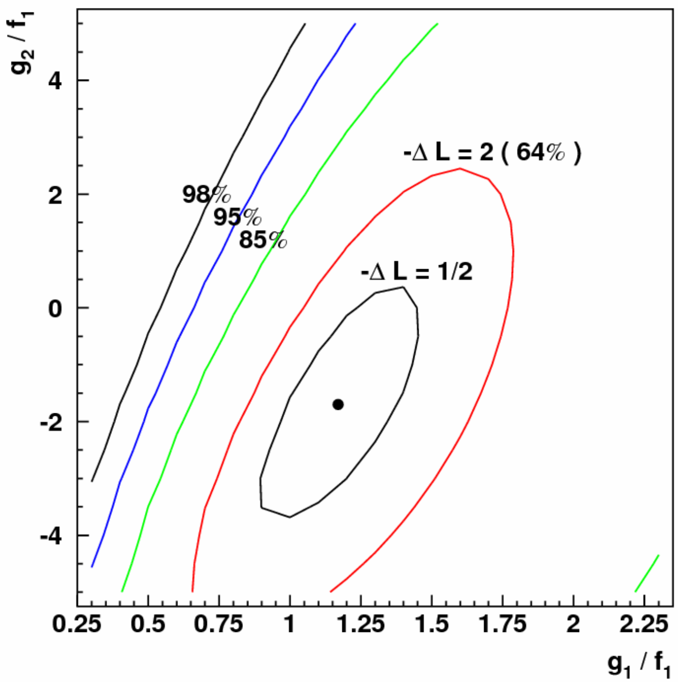
Measurement of Ξ^o beta decay form factors

Phys.Rev.Lett. 87 (2001) 132001



- Data collected during a 4 week period in 1997, with improved triggering.
- 494 signal events with estimated 7 events background.
- Due to frequent swapping of spin rotator dipole currents, the data sample is unpolarized.
- All kinematic variables were formed and compared to Monte Carlo distributions. (the SU(3) symmetric value for g1,f1,f2 is shown here).
- Monte Carlo variables were reweighted with respect to g1/f1, g2 and f2/f1 and the log likelihood function was formed.





If you make the assumption that g2=0, then the best fit for g1/f1 is almost identical to that predicted by SU(3) flavor symmetry.

Letting both g2 and g1 float shows that there is no significant evidence for a non-zero g2 or a SU(3) symmetry breaking effect.

g1/f1 = 1.32 +/- 0.21 +/- 0.17

Fixing g2=0, and using this value of g1/f1, we obtain f2/f1 = 2.0 +/- 1.2 +/- 0.5

(As a verification of the data, we calculated $\alpha_\Xi\alpha_\Lambda$ = -0.286 +/- 0.008 +/- 0.015, as compared to the previously measured value of -0.264 +/- 0.013)

Discovery of Ξ^o Semi-leptonic Muon Decay: $\Xi^o \rightarrow \Sigma^+ \mu^- \bar{\nu}$

- During 1999 we concentrated on looking for the muon semi-leptonic decay of the Ξ^o.
- We had shown evidence for this mode from the 1997 data, but there were only 5 events, with 1 background.
- The 1999 run about doubled our statistics. There were 1139 beta decays seen.

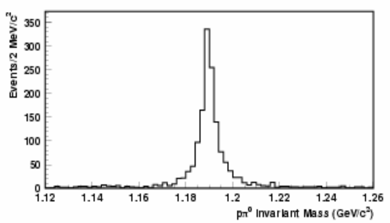


FIG. 3: Reconstructed $p\pi^0$ invariant mass distribution for 1999 data events passing the $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ selection criteria.

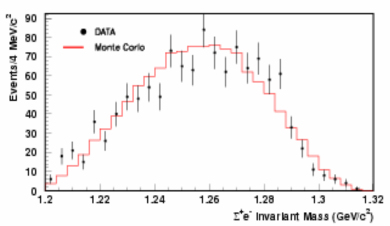
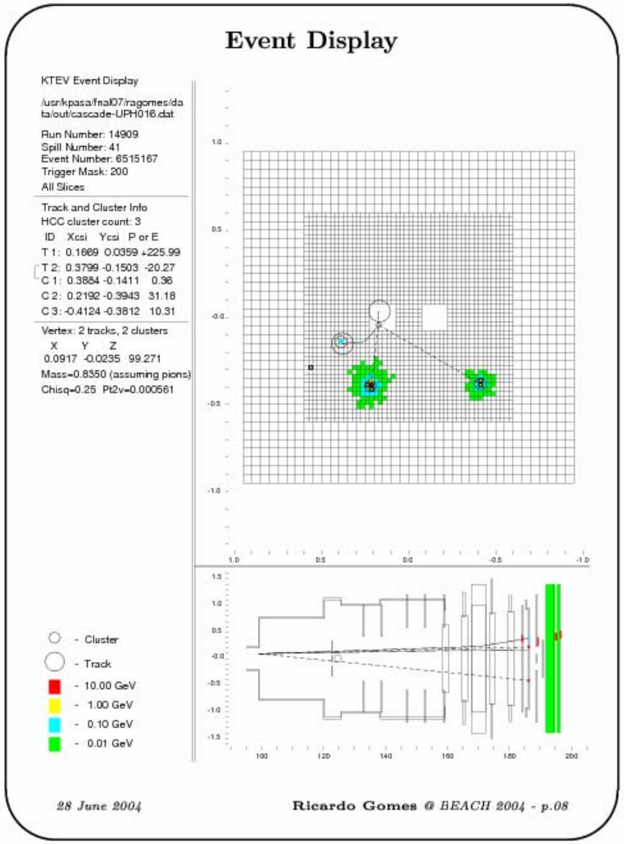
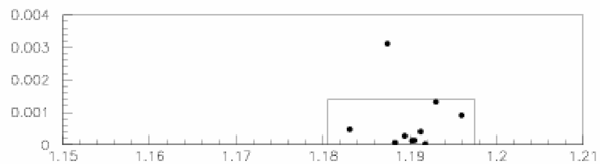


FIG. 4: Data-MC comparison of $\Sigma^+ e^-$ invariant mass distribution for events passing the Ξ^0 beta decay selection criteria. Data are shown in dots; MC in histogram.

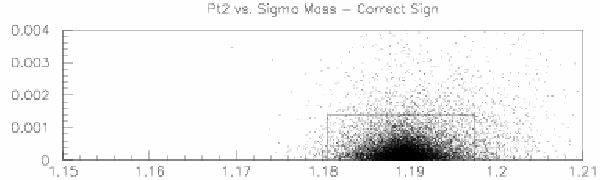


Searching for Correct and Wrong Sign of $\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu$ Events on DATA

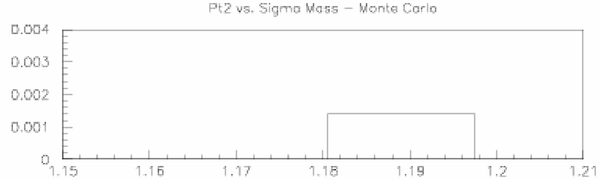
(Final Result)



Pt2 vs. Sigma Mass – Correct Sign



Pt2 vs. Sigma Mass – Monte Carlo



Pt2 vs. Sigma Mass – Wrong Sign

Branching Ratio Analysis

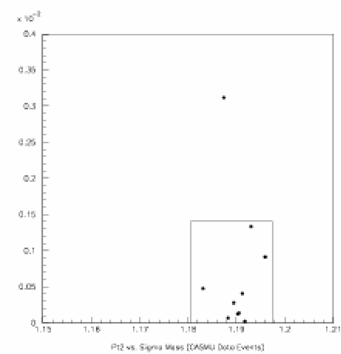
$$BR_{\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu} =$$

$$\frac{N_{Signal}}{A_{Signal}} \times \frac{A_{Norm}}{N_{Norm}} \times \frac{BR_{\Xi^0 \to \Lambda \pi^0} \times BR_{\Lambda \to p\pi}}{BR_{\Sigma^+ \to p\pi^0}} \times ps$$

$$\frac{9}{0.01356} \times \frac{0.06281}{1\,702\,965} \times \frac{0.9952 \times 0.639}{0.5157} \times \frac{1}{7}$$

$$\mathbf{BR_{\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu} = (4.3 \pm 1.4) \times 10^{-6}}$$

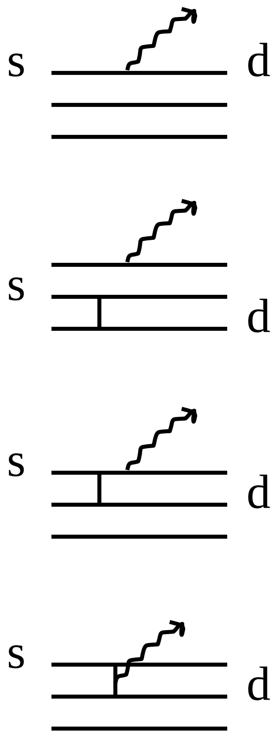
Theoretical Prediction: 2.3×10^{-6}



E.Abouzaid et al.,
PRL 95, 081801 (2005).

Weak Radiative Hyperon Decays (WRHD)

- Hara (1964) showed that asymmetry of photon emission in WRHD should be zero, assuming CP invariance and U spin symmetry.
- Vasanti (1976) predicted that asymmetries would be positive definite.
- When KTeV began, only one of the WRHD ($\Sigma^+ \to p\gamma$) had been accurately measured, and it had $\alpha = -0.76 \pm 0.08$.
- Other models for WRHD had asymmetries ranging from -1.0 to 1.0 !!
- During our analysis, it was discovered that the two previously published low statistics measurements of $\Xi^o \to \Sigma^o\gamma$ and $\Xi^o \to \Lambda\gamma$ had both made errors by neglecting the spin flip due to photon emission and by ignoring the depolarization in the electromagnetic decay of the Σ^o.



Pole term

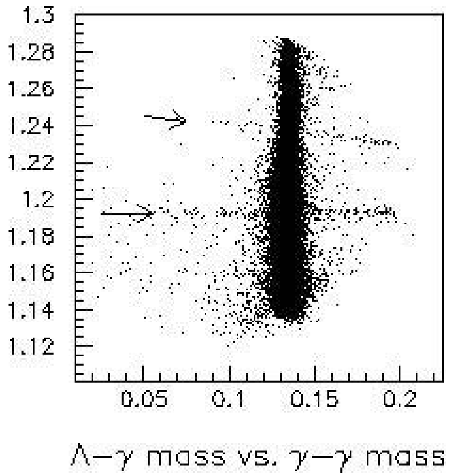
Internal W exchange

Penguin term

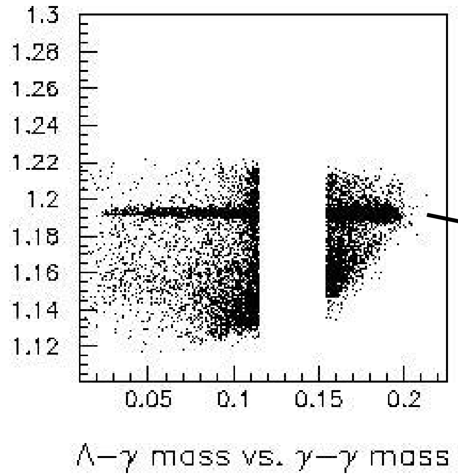
Feynman diagrams for WRHD

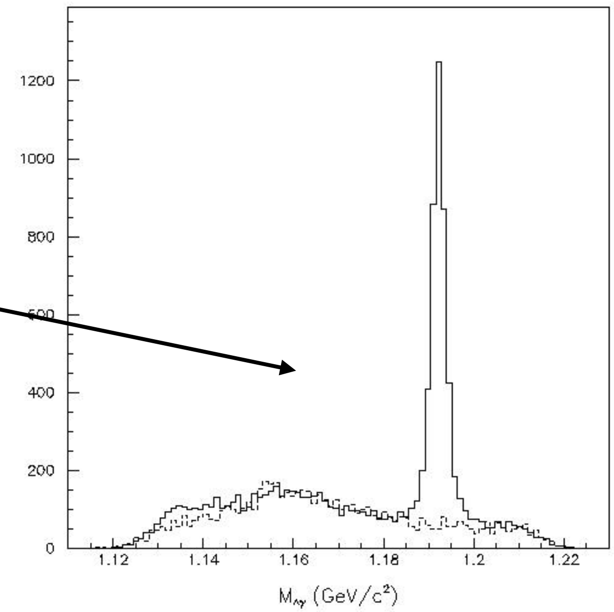
Reconstructing $\Xi^o \rightarrow \Sigma^o\gamma \rightarrow \Lambda\gamma\gamma$ decays

Partial data sample



Full data set



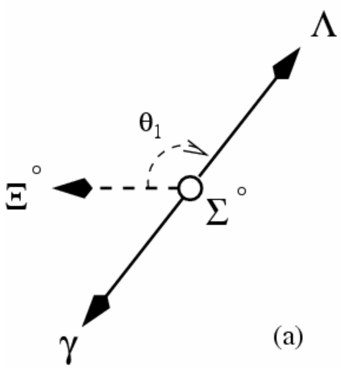


Reconstructing this decay was fun!
It is the only 3 stage WRHD.
A final data sample of 4045 events.

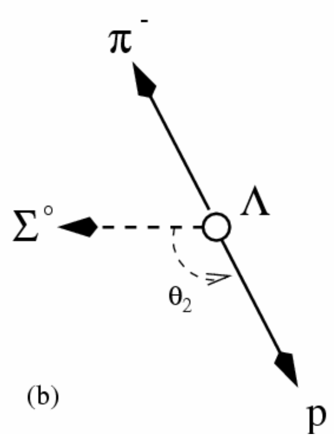
A.Alavi-Harati et al.,
PRL 86, 3239-3243 (2001)

B.R.($\Xi^o \rightarrow \Sigma^o\gamma$) = (3.34 +/– 0.05 +/– 0.09) x 10^{-3}

Determining the asymmetry in $\Xi^o \to \Sigma^o\gamma$

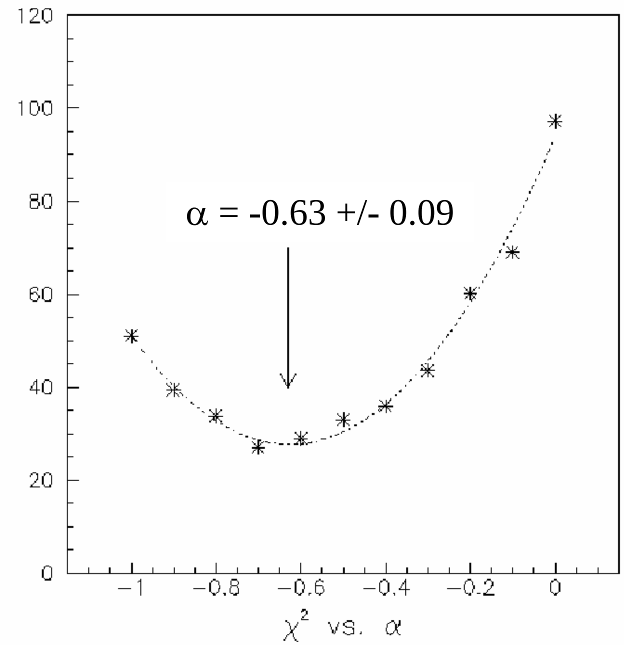


Magnitude of polarization of Σ^o is equal to α and its direction is opposite to the decay direction. This is unlike hadronic hyperon decays because of the spin of the photon.



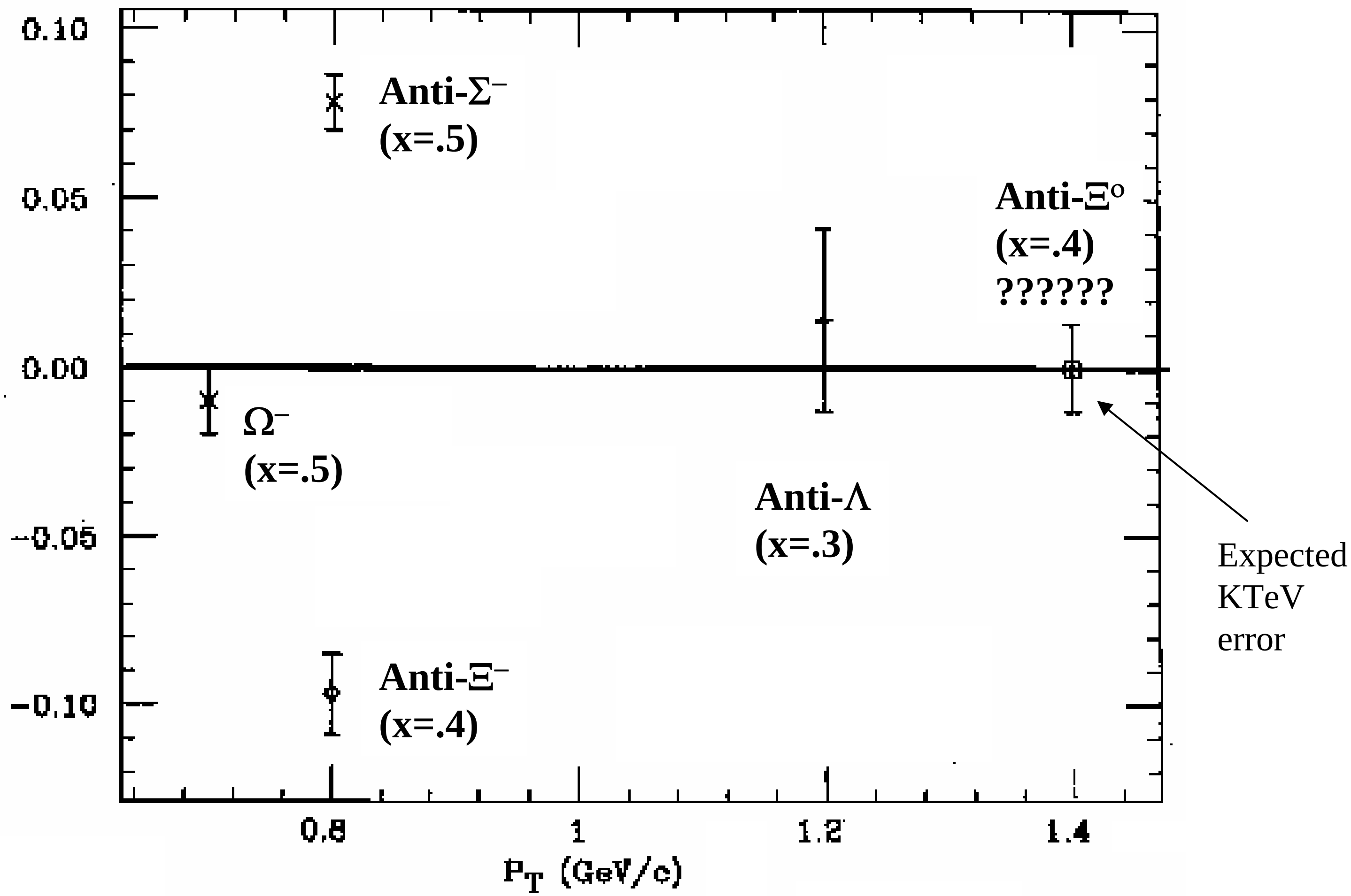
Polarization of Λ is reduced by 1/3 on average due to the nature of the electromagnetic decay of the Σ.

Polarization of the final state proton is along its decay direction, since the spin of the π is zero.



Determine asymmetry parameter by comparing the 2 dimensional angular distribution to a series of Monte Carlo data with varying α

Anti-hyperon polarization at 800 GeV

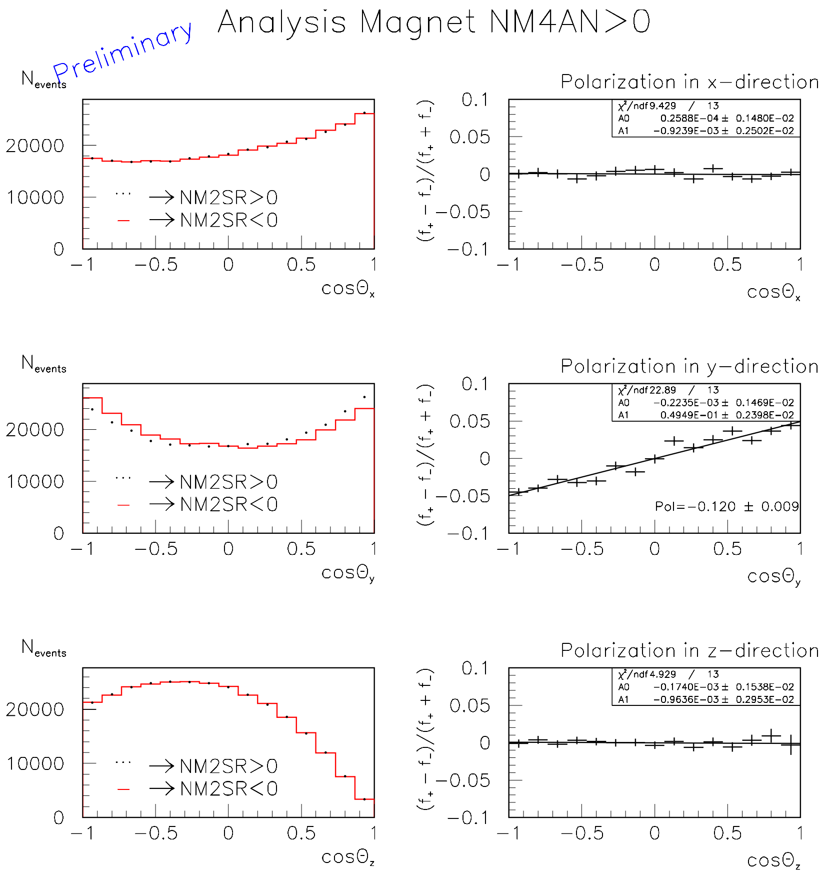


A series of experiments at Fermilab in the 1980's had showed an astonishing result: some anti-hyperons are produced polarized with respect to the beam direction! Because all of their quarks arise from the sea, how is this direction remembered? This is still unexplained.

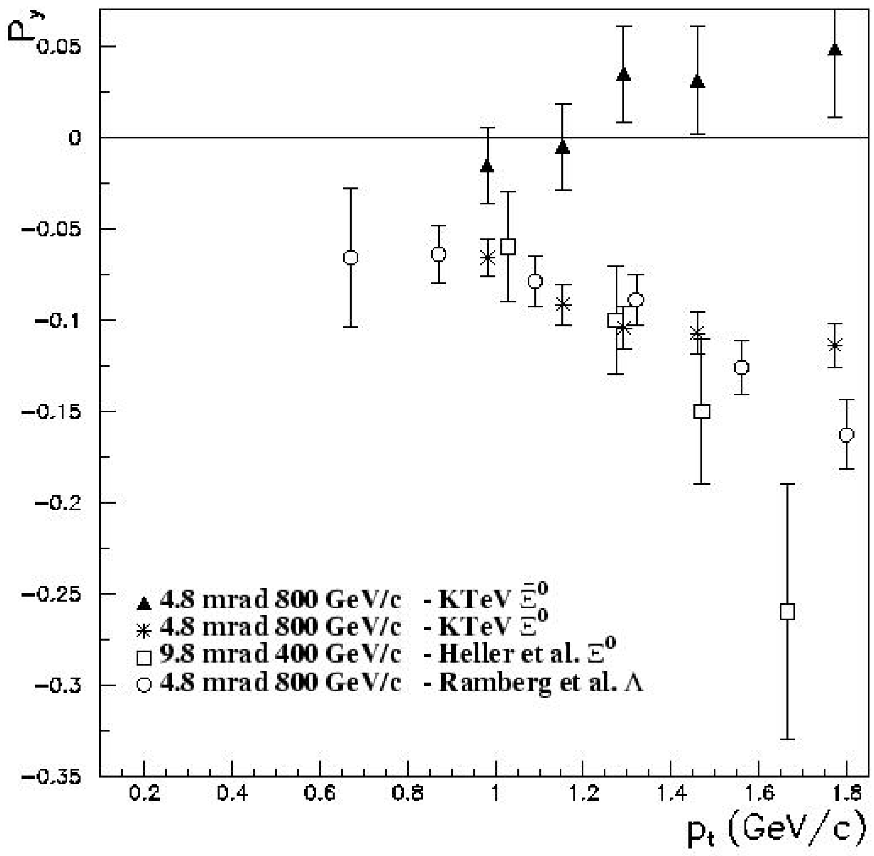
Ξ^o Polarization at 800 GeV

- Use β decay trigger, and reconstruct $\Xi^o \rightarrow \Lambda\pi^o$
- Reconstruct c.o.m. angles for the Λ direction in the lab coordinate frame: $\theta_x, \theta_y, \theta_z$
- Take ratio of two polarization settings:

$$\frac{[N_+(\cos\theta_i) - N_-(\cos\theta_i)]}{[N_+(\cos\theta_i) + N_-(\cos\theta_i)]} = 1 + \alpha_\Xi P_i(\cos\theta_i)$$



KTeV Ξ^0 and $\overline{\Xi}^0$ polarization results

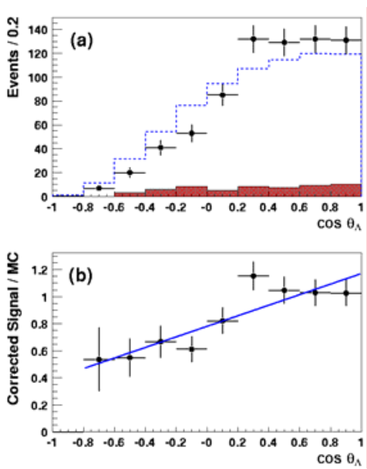


Results show that there is no energy dependence in Ξ^o polarization and that $\overline{\Xi}^o$ are produced unpolarized.

NA48 – Our esteemed competition

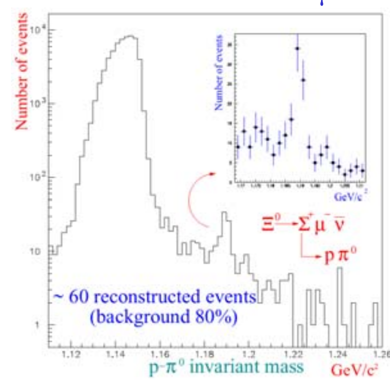
Already published results on hyperon physics from NA48:

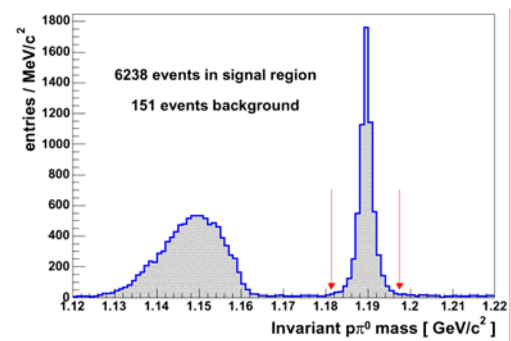
- Measurement of the $\Xi^0 \to \Lambda\gamma$ decay asymmetry and branching fraction. (Phys.Lett.B584:251-259,2004)
- Precision measurement of the Ξ^0 mass and the branching ratios of the decays $\Xi^0 \to \Lambda\gamma$ and $\Xi^0 \to \Sigma^0\gamma$ (Eur.Phys.J.C12:69-76,2000)



asymmetry:
$\alpha(\Xi 0\to\Lambda\gamma)$ = -0.78 ± 0.18stat ± 0.06sys
branching ratio:
$BR(\Xi 0\to\Lambda\gamma)$ = (1.16 ± 0.05stat ± 0.06sys) ×10-3

$\Xi^0 \to \Sigma^+\mu^-\nu_\mu$





preliminary NA48 result for the beta decay branching ratio:

$Br(\Xi^0 \to \Sigma^+ e^- \nu_e) = (2.51 \pm 0.03_{stat} \pm 0.11_{sys}) \times 10^{-4}$

Summary

- The kaon program at Fermilab (E731, E799 and KTeV) reenergized the study of high energy Ξ^o production and decay physics.
- The KTeV beamline was designed from the start with the idea of being able to rotate the polarization vector into two opposite states. This gave an overall unpolarized sample, or two oppositely polarized samples.
- Both the beta decay and muon semi-leptonic decays of the Ξ^o were discovered in the KTeV data.
- In studying the $\Xi^o \rightarrow \Sigma^o \gamma$ decay, an error was discovered in both previous Ξ^o weak radiative decay papers. The correct analysis of this decay gives a highly negative assymetry.
- The polarization of hadroproduced Ξ^o hyperons follows the Λ pattern, and the anti-Ξ^o is produced unpolarized.