First Measurement of Form Factors for Beta Decay of the Neutral Cascade Hyperon Using Final State Polarization

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For the KTeV Collaboration

ICHEP 2000

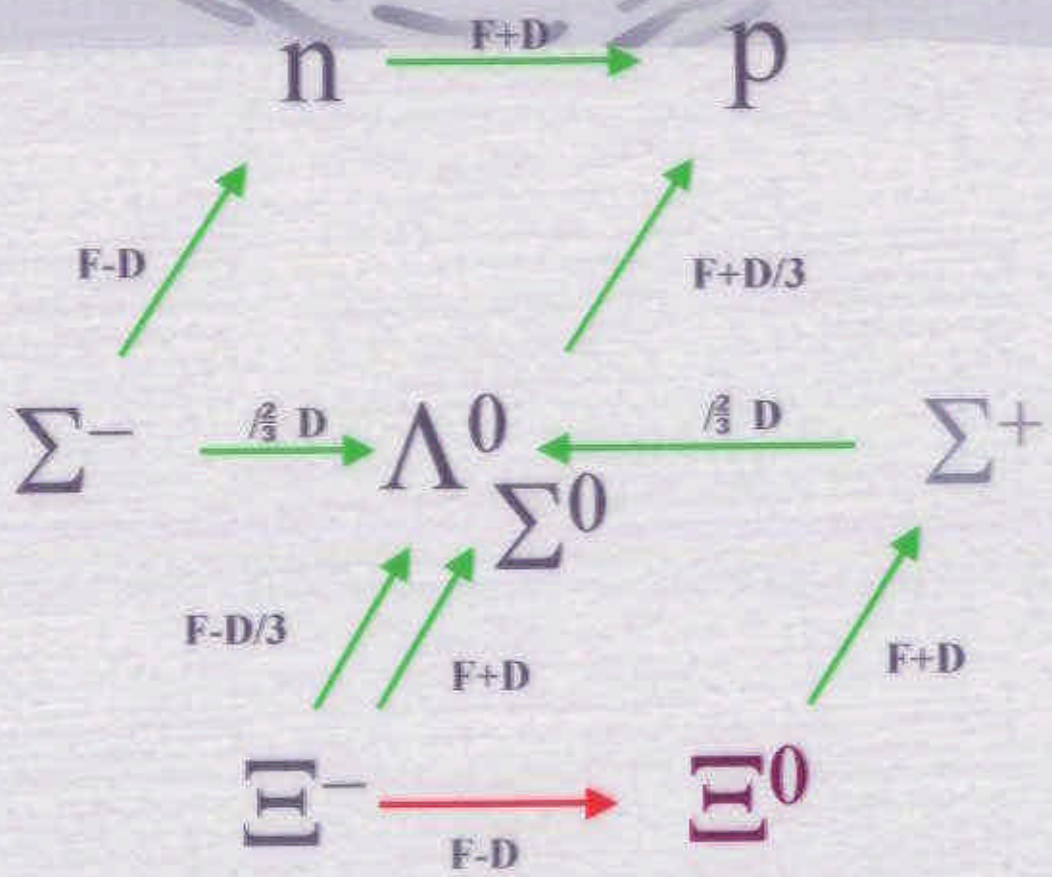
PA-01d Hadron Spectroscopy (Light and Heavy Quarks, Glueballs, Exotics)

Sat, Jul 29, 2000, 16:00 - 17:30 at Room AB

Outline:

- Introduction to Hyperon semi-leptonic Decay
- Description of the KTeV experiment
- Neutral Cascade Beta Decay (Asymmetry and Form Factor measurement)
- Muon Decay (Branching Ratio)
- Radiative decay (Branching ratio and asymmetry)

Beta Decays in the Hyperon Octet



Semi-leptonic hyperon decay

Amplitude for decay of spin 1/2 baryon ($B \to b\, e \bar{\nu}$)

$$M = G_F V_{CKM} (\sqrt{2}/2)\, \bar{u}_b (O^V_\alpha + O^A_\alpha) u_B \times \bar{u}_e \gamma^\alpha (1+\gamma_5) u_\nu + H.C.$$

where

$$O^V_\alpha = f_1 \gamma_\alpha + f_2 \sigma_{\alpha\beta} q^\beta / M_B + f_3 q^\alpha / M_B$$

$$O^A_\alpha = (g_1 \gamma_\alpha + g_2 \sigma_{\alpha\beta} q^\beta / M_B + g_3 q^\alpha / M_B) \gamma_5$$

$$q = (p_e + p_\nu) = (p_B - p_b)$$

where G_F is the Fermi constant and V_{CKM} the CKM matrix elt.

Reduction to 2-components (The Primakoff Method)

ADVANTAGES:

Simplicity

Transparency

Accuracy **(up to and including $(q/M)^2$)**

$$M = \langle be | H_{effective} | B\nu \rangle$$

$$H_{effective} = (1 - \sigma_l \cdot e)[G_V + G_A \sigma_l \cdot \sigma_b + G_{Pe} \sigma_b \cdot e + G_{P\nu} \sigma_b \cdot \nu](1 - \sigma_l \cdot \nu)$$

PRD 60, 117505 (1999)

Form Factor Properties

	f_1	f_2	f_3	g_1	g_2	g_3
CVC	✓	✓	✗	N.A.	N.A.	N.A.
G parity +SU(3)	✓	✓	✗	✓	✗	✓
me/mb ≈ 0	✓	✓	✗	✓	✓	✗

Measuring Form Factors

	f_1	f_2/f_1	g_1/f_1	g_2/f_1
Branching Ratio	✓			
Polarization			✓	✓
$e \bullet \nu$ correlation	✓		✓	✓
electron spectrum		✓		

Special features of Ξ^0 "the last hyperon decay"

1. Σ^+ in final state excludes 2-body background (by kinematics)
2. Σ^+ is 98% self analyzing, form all correlations with p from $\Sigma^+ \rightarrow p+\pi^0$
3. SU(3) analogue of neutron decay, predicted by Nicola Cabibbo in 1963.

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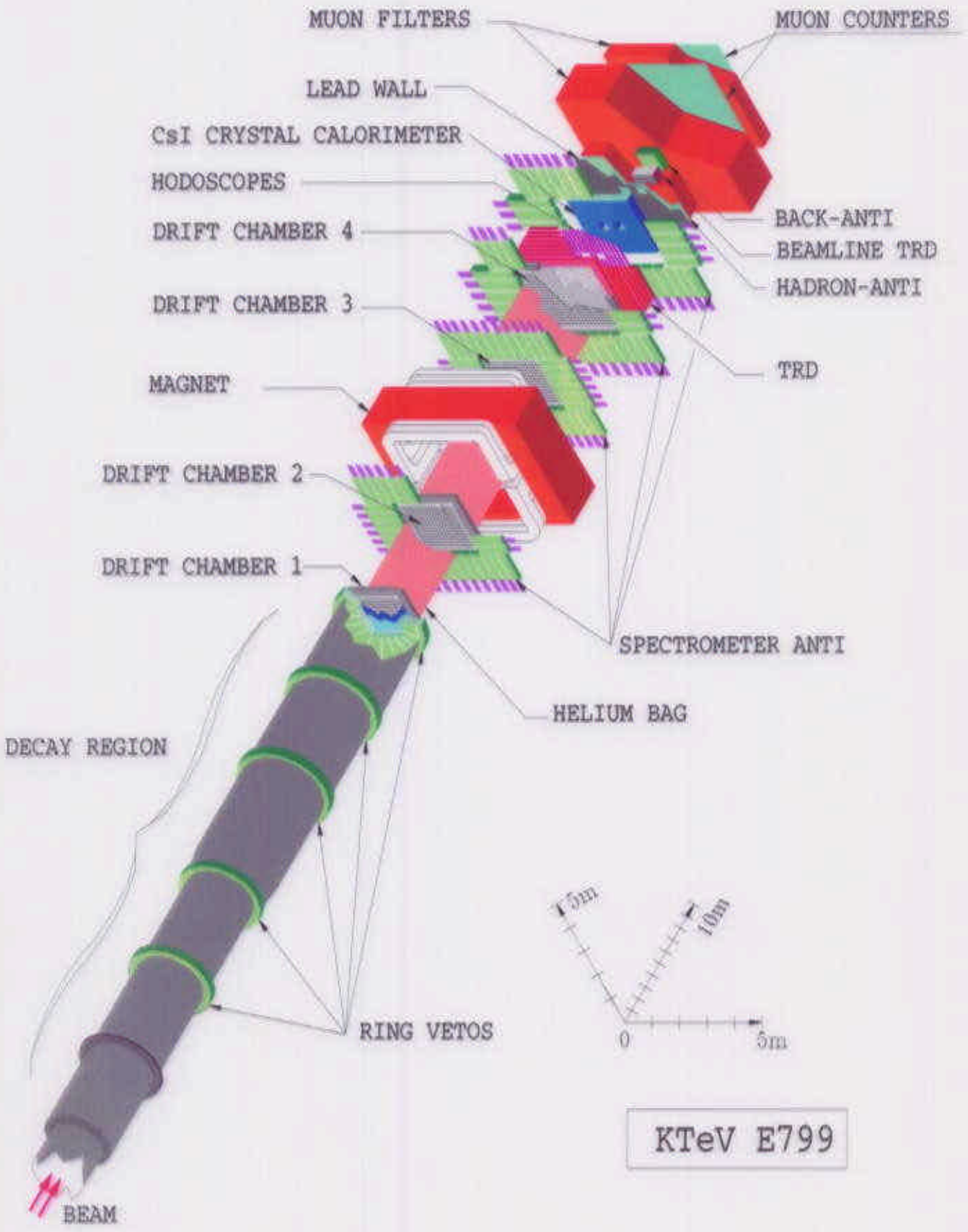
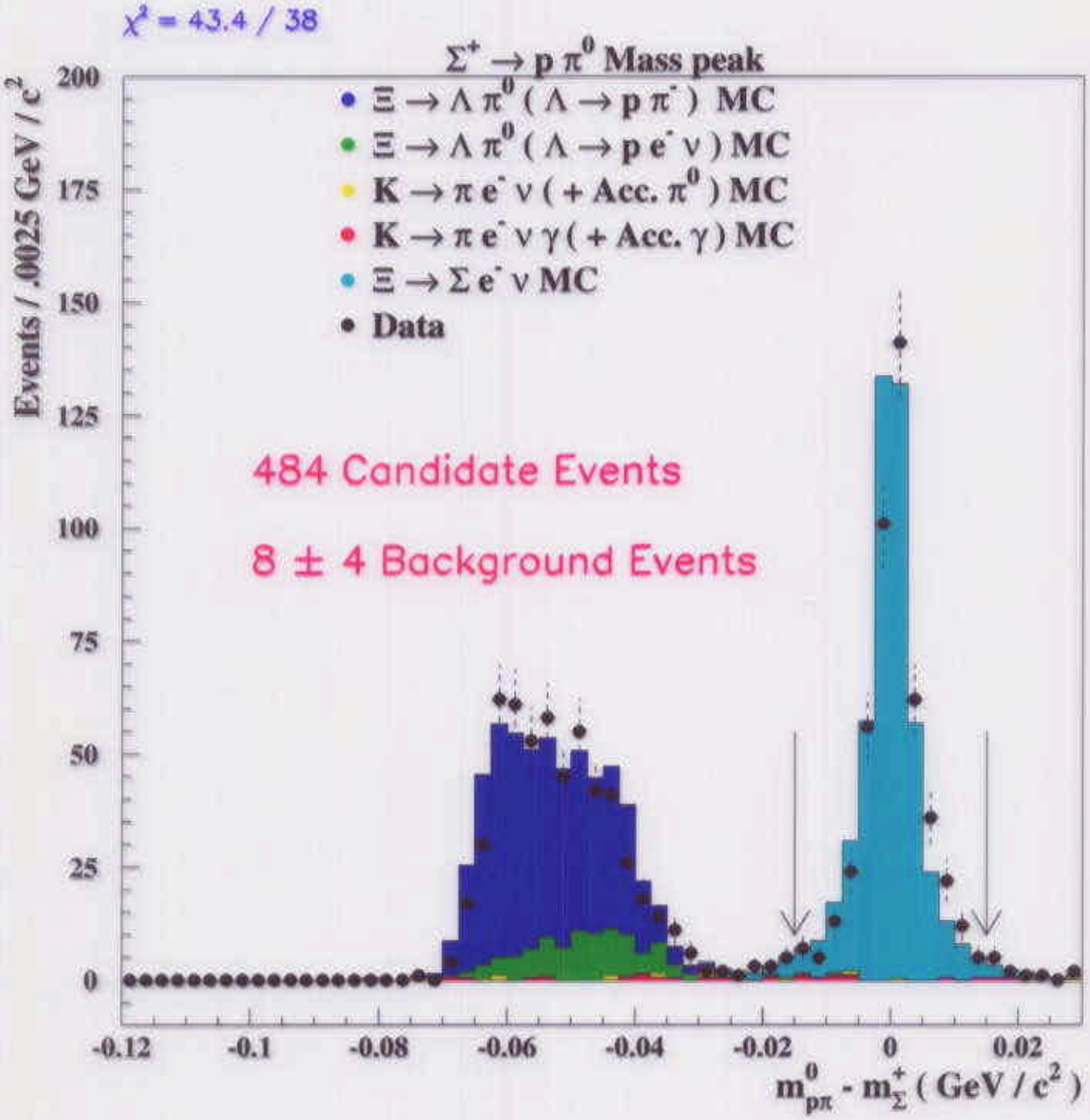
- **12 Institutions (1 Japan and 11 USA)**


MUON FILTERS
MUON COUNTERS
LEAD WALL
CsI CRYSTAL CALORIMETER
HODOSCOPES
DRIFT CHAMBER 4
BACK-ANTI
BEAMLINE TRD
HADRON-ANTI
DRIFT CHAMBER 3
TRD
MAGNET
DRIFT CHAMBER 2
DRIFT CHAMBER 1
SPECTROMETER ANTI
HELIUM BAG
DECAY REGION
RING VETOS
0
5m
10m
BEAM
KTeV E799


χ^2 = 43.4 / 38
$\Sigma^+ \to p\,\pi^0$ Mass peak
$\Xi \to \Lambda\,\pi^0\,(\Lambda \to p\,\pi^-)$ MC
$\Xi \to \Lambda\,\pi^0\,(\Lambda \to p\,e^-\,\nu)$ MC
$K \to \pi\,e^-\,\nu\,(+\,Acc.\,\pi^0)$ MC
$K \to \pi\,e^-\,\nu\,\gamma\,(+\,Acc.\,\gamma)$ MC
$\Xi \to \Sigma\,e^-\,\nu$ MC
Data
484 Candidate Events
8 ± 4 Background Events
Events / .0025 GeV / c^2
200
175
150
125
100
75
50
25
0
-0.12
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
$m^0_{p\pi} - m^+_\Sigma$ (GeV / c^2)

Branching ratio

$\Gamma=(2.71+/-0.22_{statistical}+/-0.31_{systematic})x10^{-4}$

(Phys Rev D 82, pgs. 3751-3754 (1999))

$\Gamma=(2.54+/-0.11_{statistical}+/-0.16_{systematic})x10^{-4}$

(1997 data)

Expectation from neutron decay rate$x\tan^2(\theta_{Cabibbo})$:

$\Gamma=(2.61+/-0.11_{l})x10^{-4}$

Expectations for Form Factors

f_1 (weak vector charge) protected by the Ademollo-Gatto theorem to $(q/M)^2$

f_2 (weak magnetism) related to magnetic moments, e.g, in neutron decay the anomolous magnetic moment is:

$(1/2)(1+\tau_3)\mu_p + (1/2)(1-\tau_3)\mu_n$ so the isovector part is $(1/2)(\mu_p - \mu_n)\,\tau_3$ and for β decay $(1/2)(\mu_p - \mu_n)\,\tau^+$
Therefore f_2 (weak magnetism) $= (1/2)(\mu_p - \mu_n)$

Final State Polarization in

$\Xi^0 \to \Lambda\,\pi^0$ with $\Lambda \to p\,\pi^-$

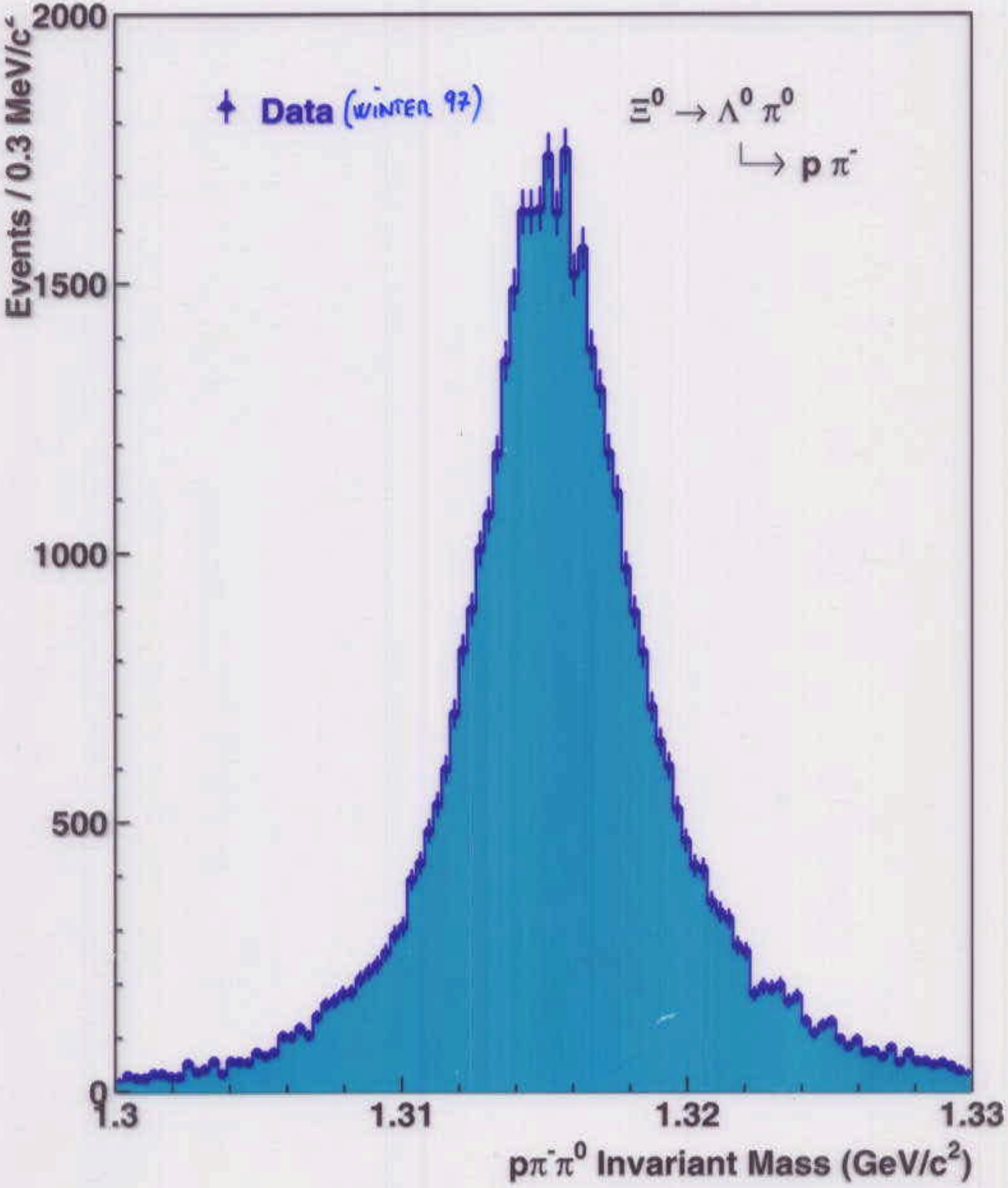
The polarization of the Λ is equal to

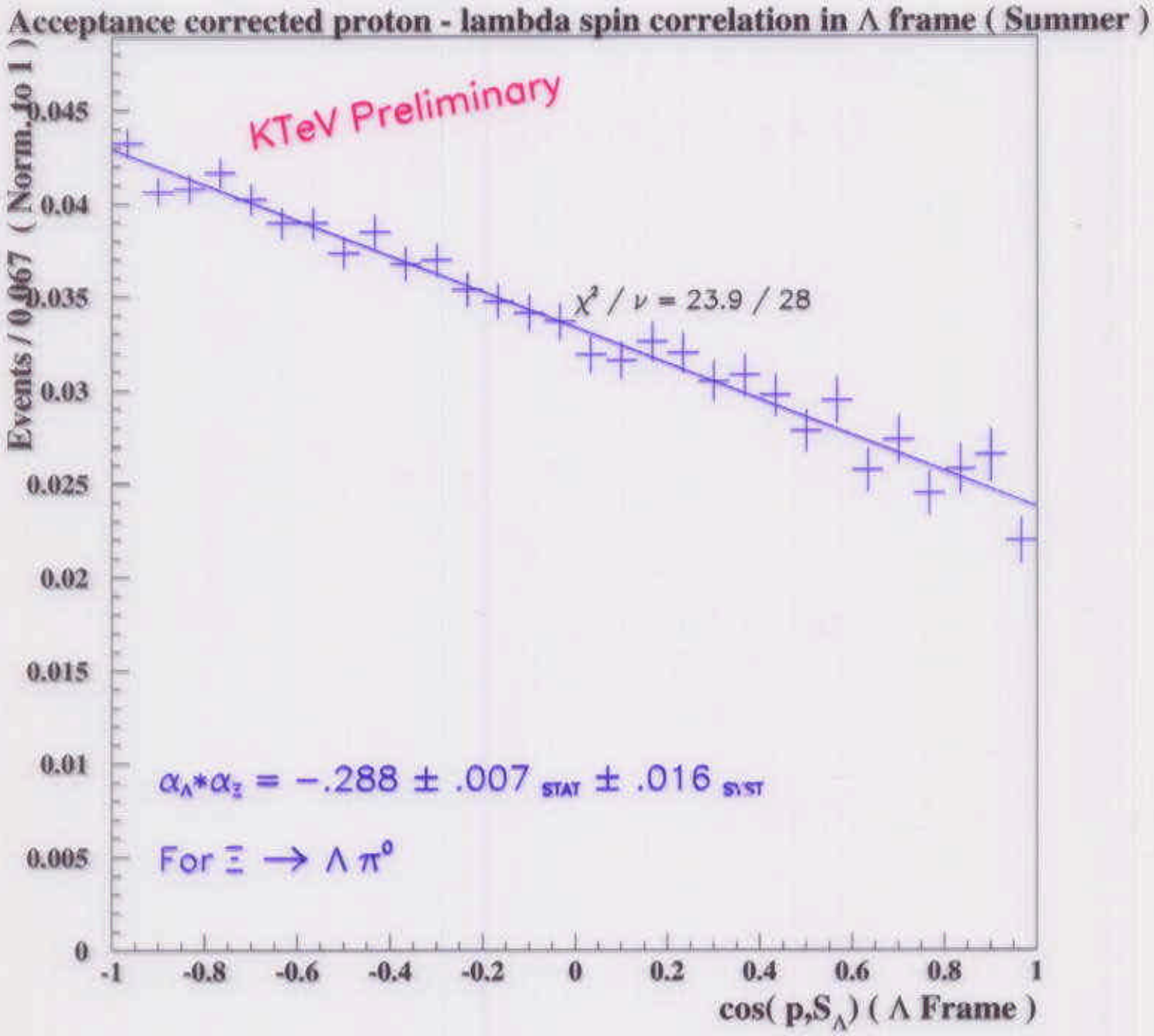
$$\vec{P}_\Lambda = \alpha_\Xi \hat{\Lambda}$$

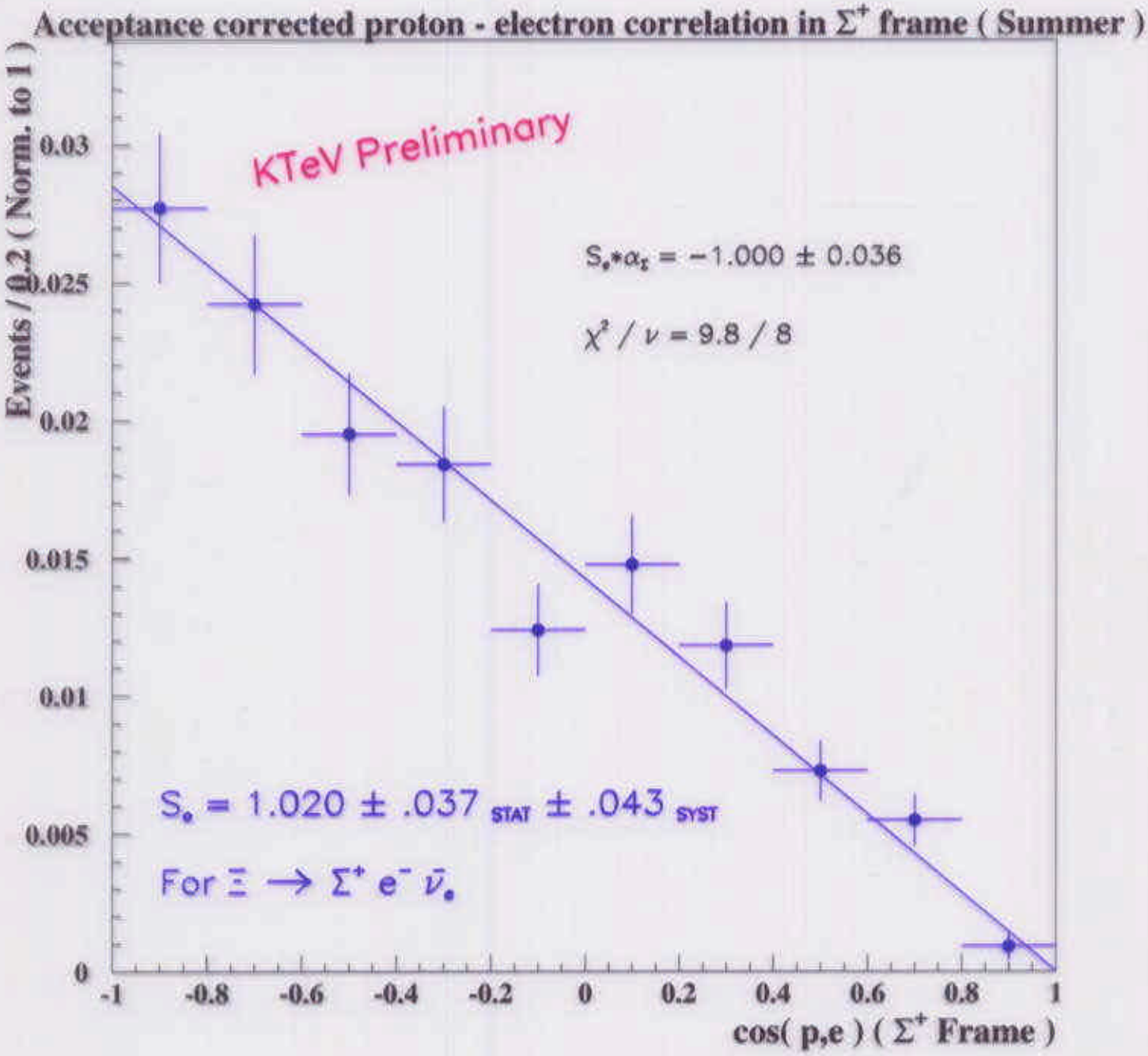
The distribution of the cosine of the angle between the proton and the polarization direction of the Λ is equal to

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega_p} = \frac{1}{4\pi}(1 + \alpha_{\Xi^0}\alpha_\Lambda \hat{p}\cdot\hat{P}_\Lambda),$$

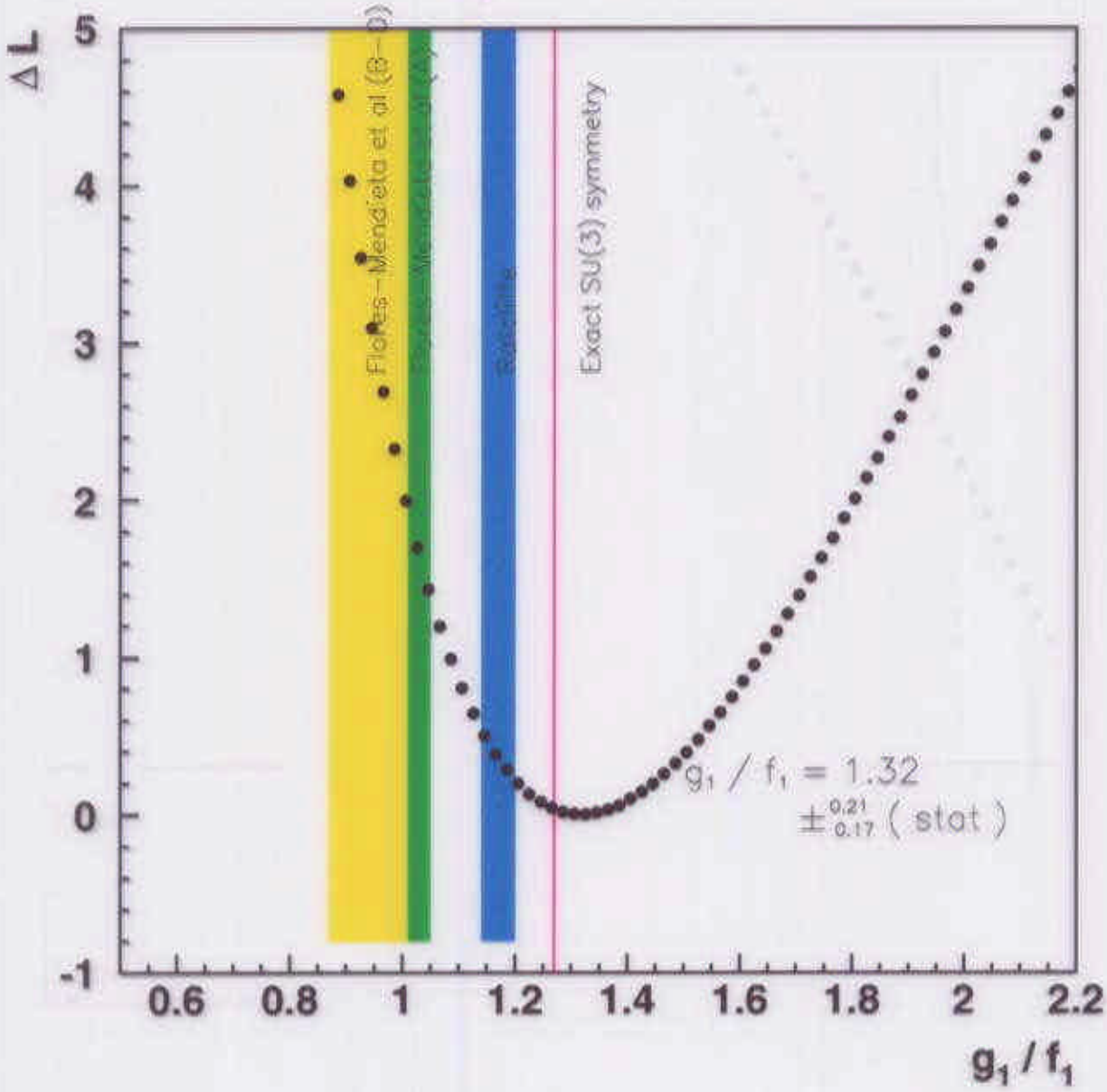
$$\alpha_{\Xi^0}\alpha_\Lambda = -0.264 \pm .013(PDG\,Value)$$

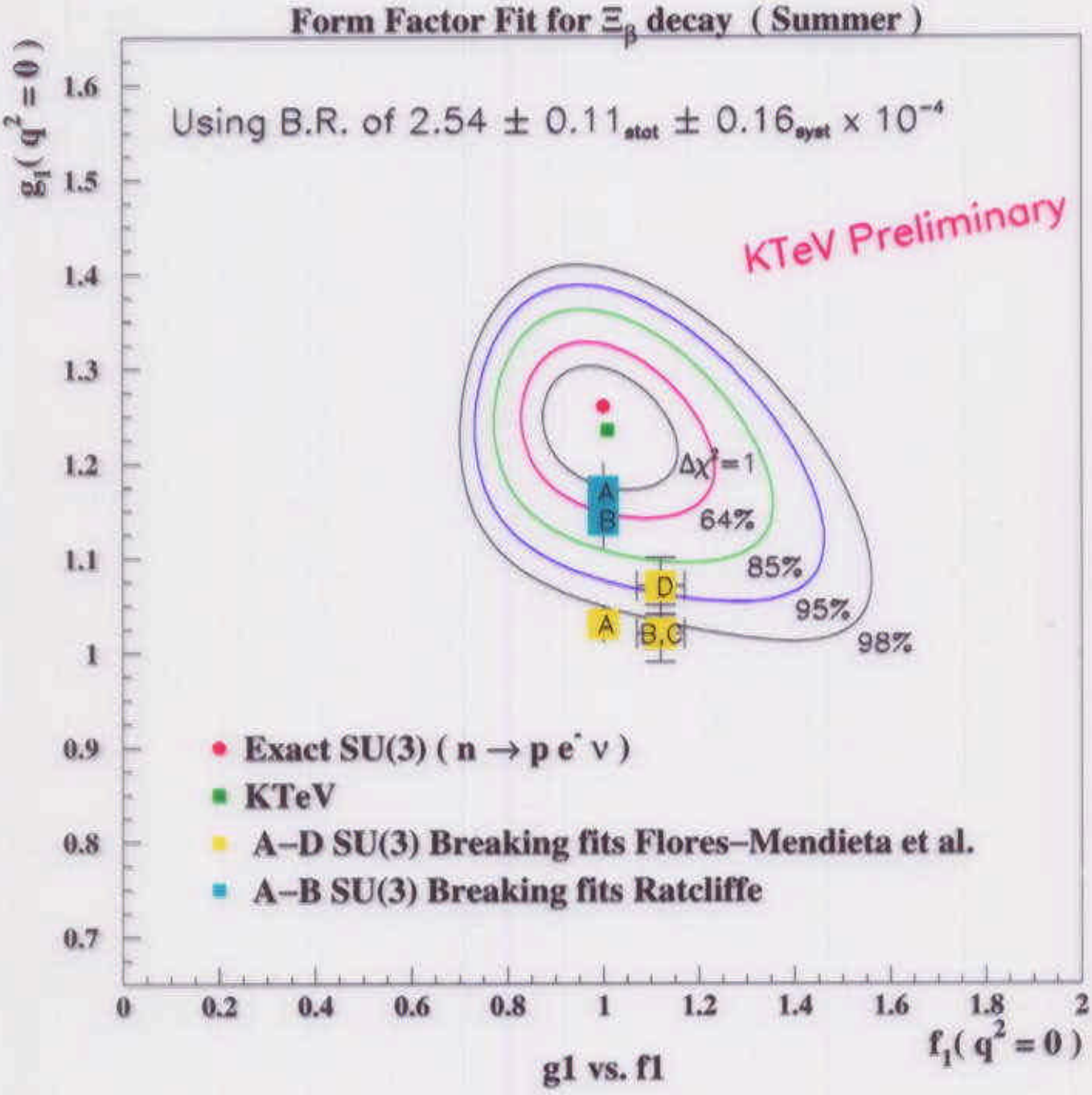

Data (WINTER 97)
$\Xi^0 \to \Lambda^0 \pi^0$
$\hookrightarrow p\,\pi^-$
Events / 0.3 MeV/c²
2000
1500
1000
500
0
1.3
1.31
1.32
1.33
$p\pi^-\pi^0$ Invariant Mass (GeV/c²)


Acceptance corrected proton - lambda spin correlation in Λ frame (Summer)
KTeV Preliminary
$\chi^2 / \nu = 23.9 / 28$
$\alpha_\Lambda * \alpha_\Xi = -.288 \pm .007_{STAT} \pm .016_{SYST}$
For $\Xi \rightarrow \Lambda \pi^0$
Events / 0.067 (Norm. to 1)
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos(p,S_Λ) (Λ Frame)


Acceptance corrected proton - electron correlation in Σ+ frame (Summer)
KTeV Preliminary
S•*αΣ = −1.000 ± 0.036
χ² / ν = 9.8 / 8
S• = 1.020 ± .037 STAT ± .043 SYST
For Ξ → Σ+ e− ν̄•
Events / 0.2 (Norm. to 1)
0.03
0.025
0.02
0.015
0.01
0.005
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos(p,e) (Σ+ Frame)

g_1/f_1


ΔL
5
4
3
2
1
0
-1
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
g1 / f1
Exact SU(3) symmetry
g1 / f1 = 1.32
±0.21 0.17 (stat)



PRD 58-094028 (1998)
PRD 59-014038 (1999)

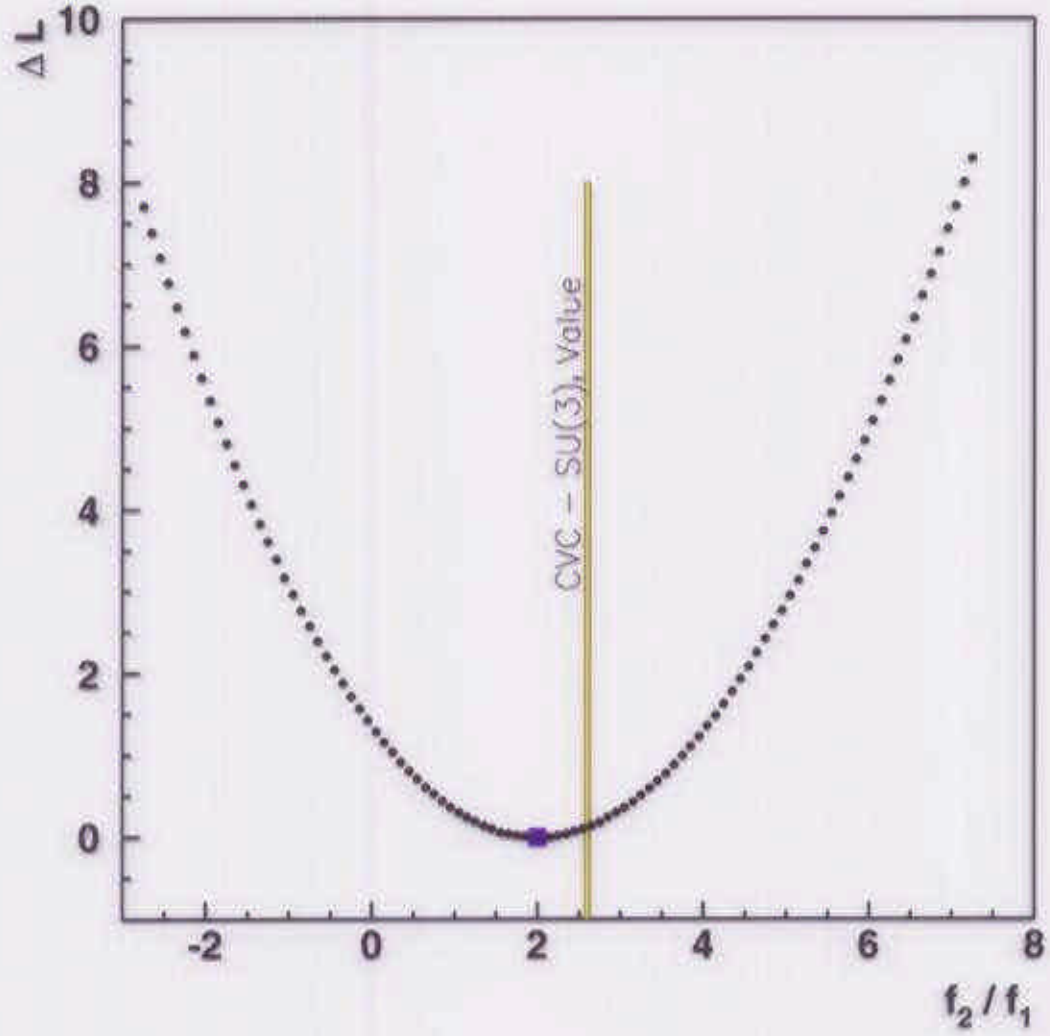


Figure 63. Extraction of f_2/f_1 using maximum likelihood of energy spectrum of electron in Σ^+ frame ($E_e^{[\Sigma]}$).

The g_2 "conspiracy"

1. The rate is $|f_1|^2 + 3\,|g_1|^2 - 4\Delta M/M^2 g_1 g_2$
2. The energy spectrum is $|f_1|^2 - |g_1|^2 + 4\Delta M/M^2 g_1 g_2$
3. Therefore, the unpolarized data depend to first order on g_2 with a significant coefficient but only to second order on f_2

Unpolarized experiments must (a) set $g_2 = 0$ or (b) quote result as a linear combination of g_1 and g_2. e.g., result from E-715 (Σ^- beta decay) PRD 38, 2056 (1988)

"from energy spectrum only",

$|g_1/f_1| - 0.237 g_2/f_1 = 0.327 +/- 0.007 +/- 0.019$

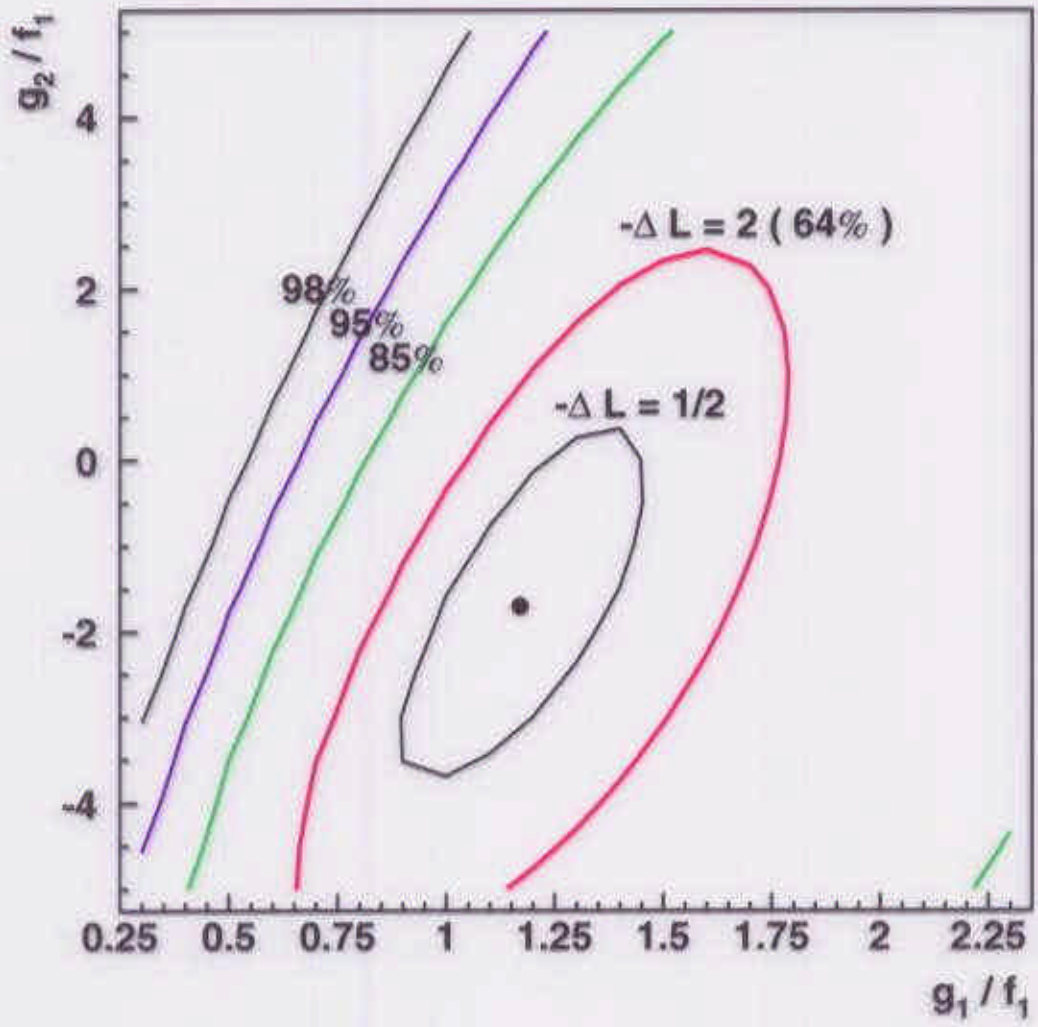
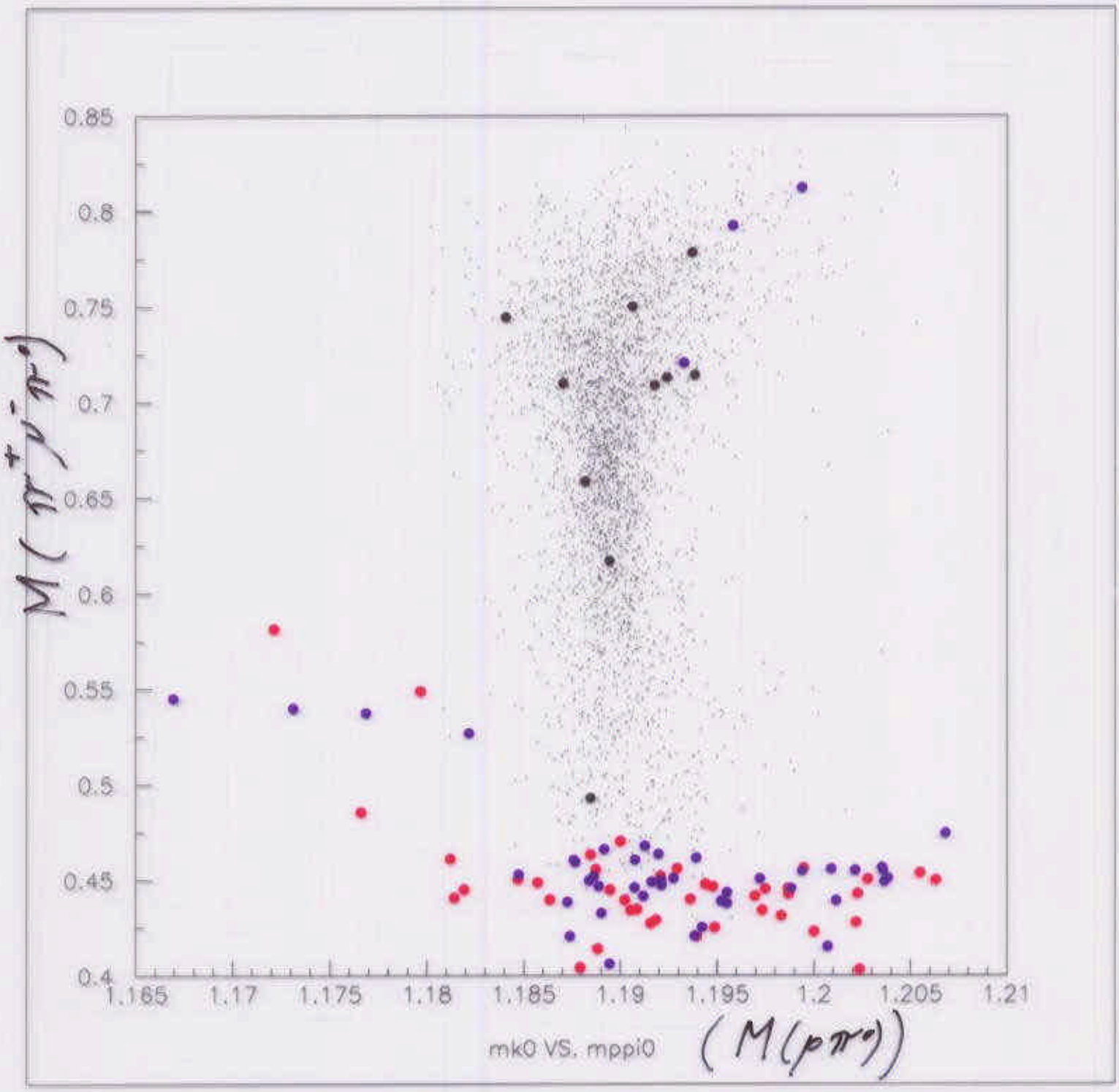


Figure 62. Confidence interval plot for g_1/f_1-g_2/f_1.

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



Branching ratio calculation

- Five candidate events with an estimated Monte-Carlo background of zero events in the 90% cut box:

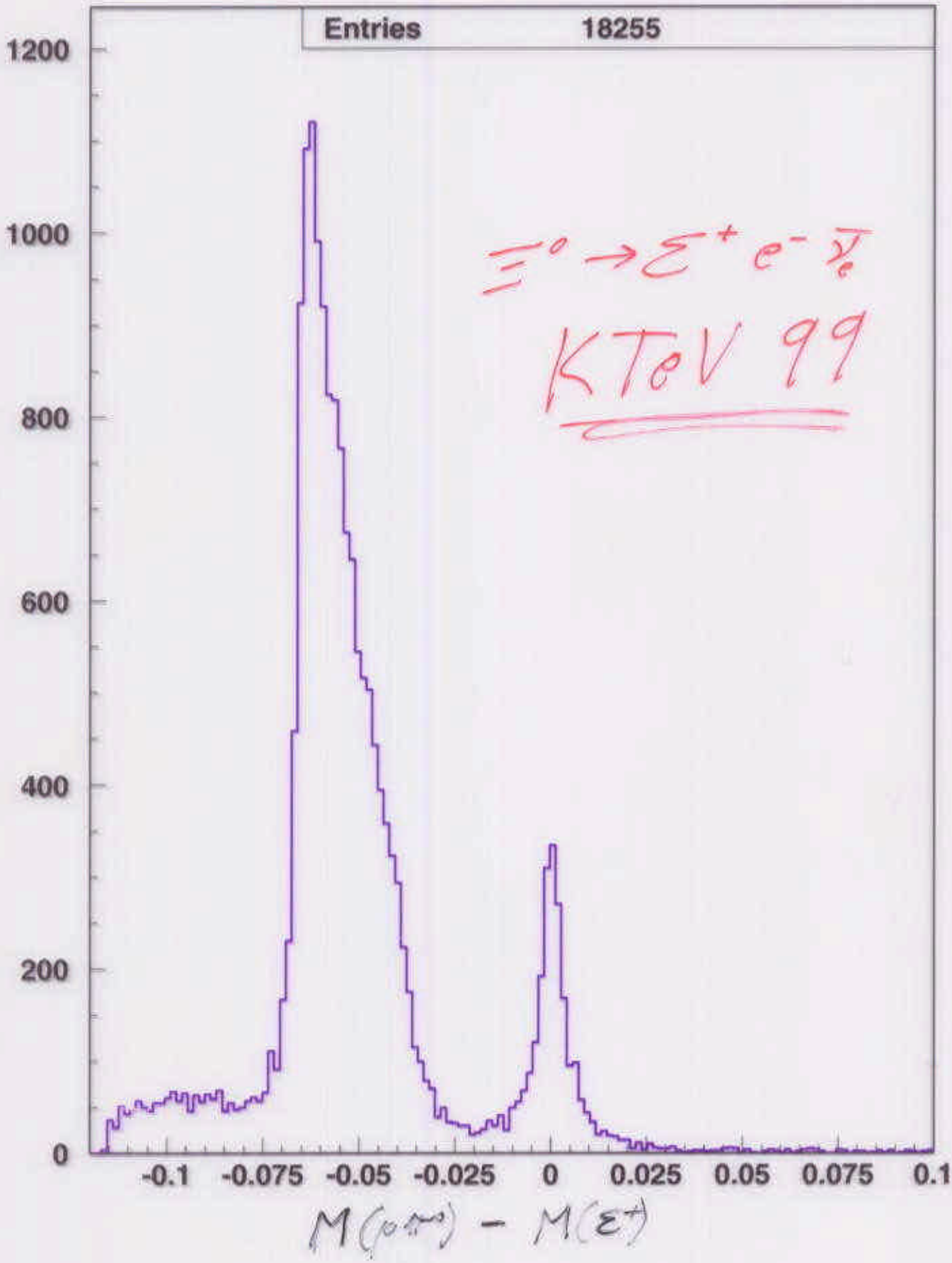
$$\Gamma(\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}) = (N_{muon} / N_{beta})(A_{beta} / A_{muon})\,\Gamma_{beta}$$

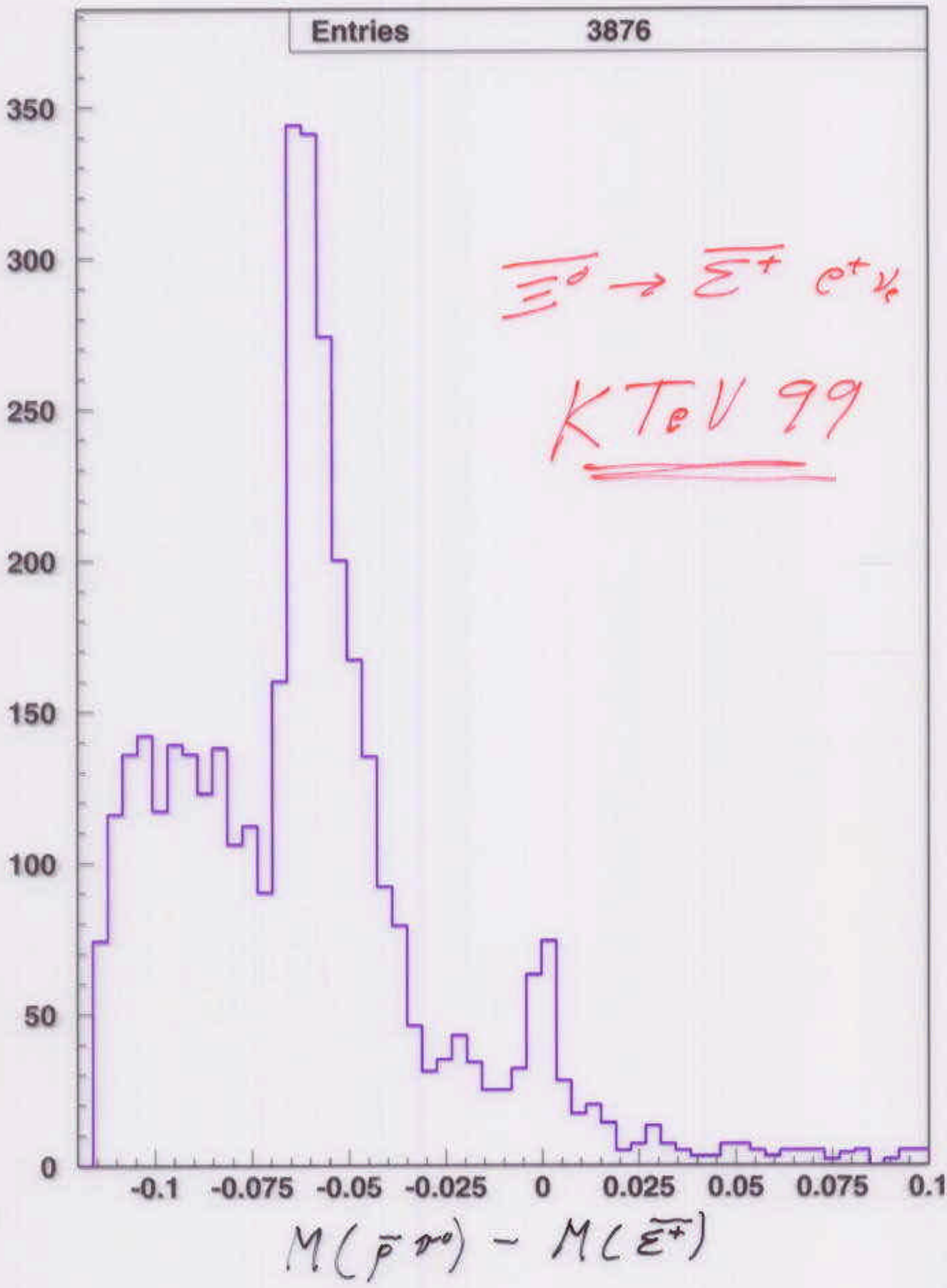
$$= 3.5\ (+2 / -1.6\,\text{stat.} + .5 / -1.0\,\text{sys.}) \times 10^{-6}$$

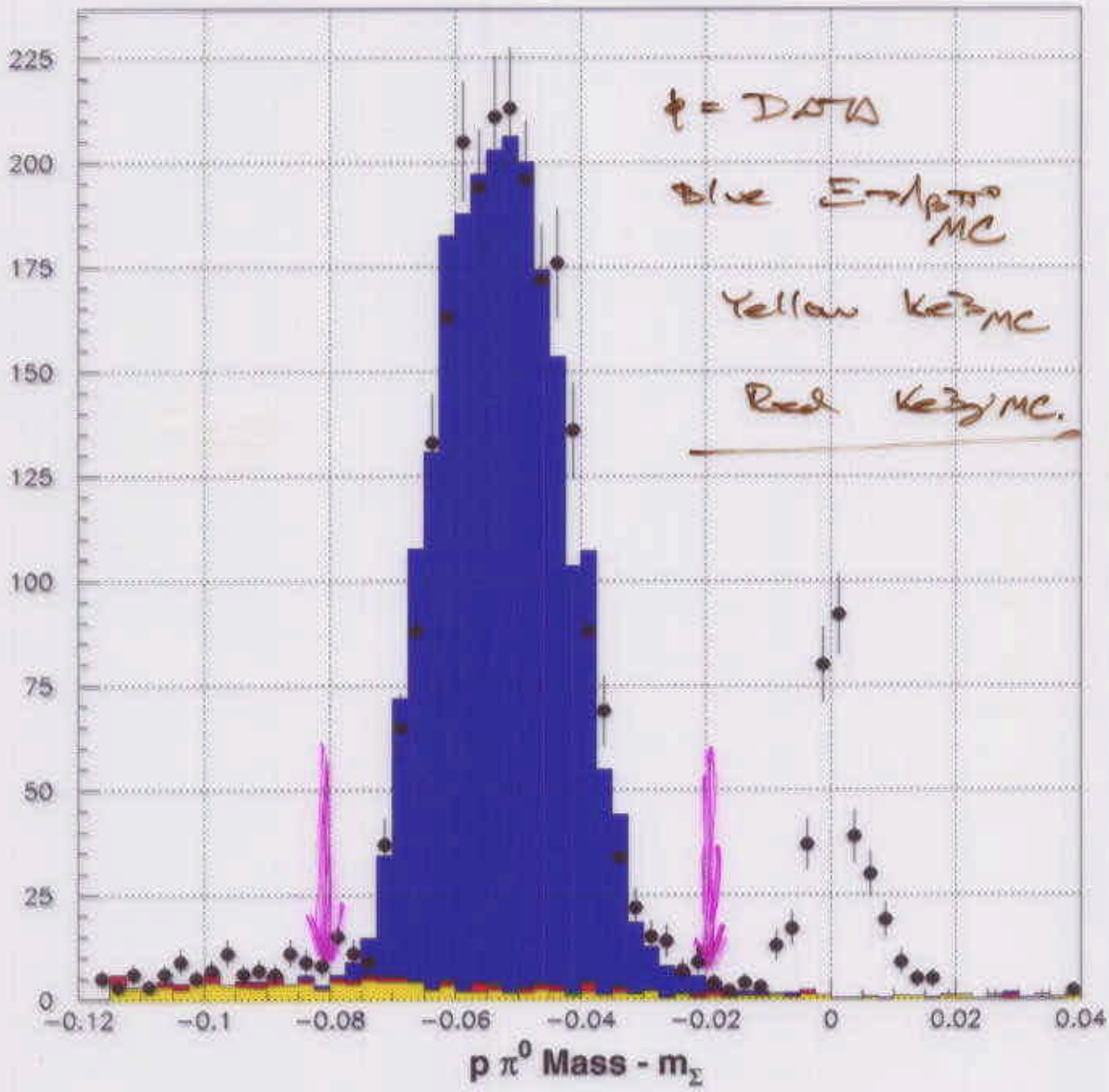
- Theoretical prediction: 2.3×10^{-6}

Conclusions

- The KTeV experiment has, for the first time measured Ξ^0 beta decay form factors
- The results are in excellent agreement with exact Cabibbo SU(3) predictions
- The results agree better with exact SU(3) than with various attempts to include effects of SU(3) symmetry breaking


Entries 18255
1200
1000
800
600
400
200
0
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
$\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$
KTeV 99
$M(p\pi^0) - M(\Sigma^+)$


Entries 3876
350
300
250
200
150
100
50
0
-0.1
-0.075
-0.05
-0.025
0
0.025
0.05
0.075
0.1
$\bar{\Xi}^0 \to \bar{\Sigma}^+ e^+ \nu_e$
KTeV 99
$M(\bar{p}\pi^0) - M(\bar{\Sigma}^+)$



$N_{events} = 2282$

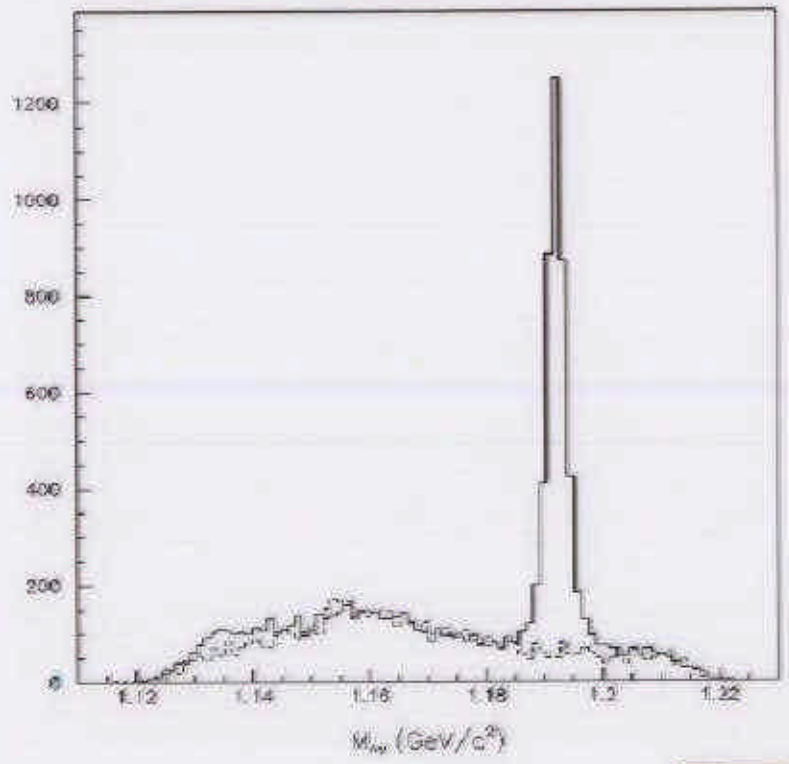
$N_{BKG} = 120 \pm 30$ (MOSTLY Ke3)

Latest WRHD World Results

Mode	BR(x 10^3)	α	# Events	Year	Group
$\Sigma^+ \rightarrow p\,\gamma$	1.20 +/- 0.08	-0.72 +/- 0.09	31901	1994	FNAL
$\Lambda \rightarrow n\,\gamma$	1.75 +/- 0.15	na	1816	1993	BNL
$\Xi^o \rightarrow \Lambda\,\gamma$	1.06 +/- 0.16	0.43 +/- 0.44	87	1990	FNAL
$\Xi^o \rightarrow \Sigma^o\,\gamma$	3.56 +/- 0.43	0.20 +/- 0.32	85	1989	FNAL *
$\Xi^- \rightarrow \Sigma^-\,\gamma$	0.12 +/- 0.02	1.0 +/- 1.3	211	1994	FNAL
$\Omega^- \rightarrow \Xi^-\,\gamma$	< 0.46	na	na	1994	FNAL

* Asymmetry incorrectly calculated

Preliminary Result for BR($\Xi^o \rightarrow \Sigma^o \gamma$)

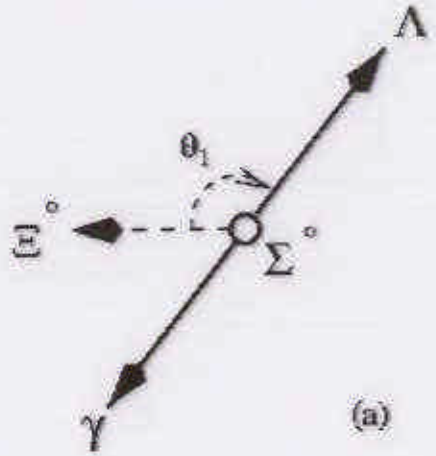


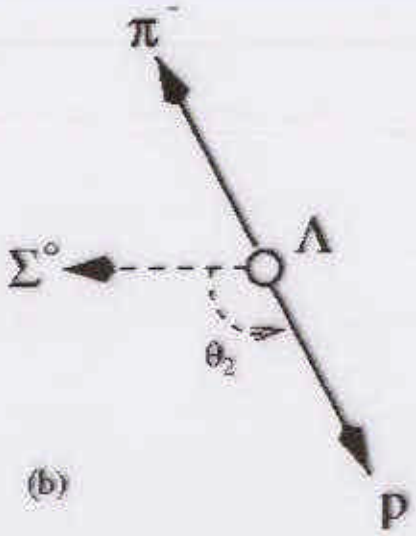
Number of events is 4048 on top of an irreducible background of 804 normal mode events.

BR($\Xi^o \rightarrow \Sigma^o \gamma$) = (3.34 +/– 0.12) x 10^{-3}

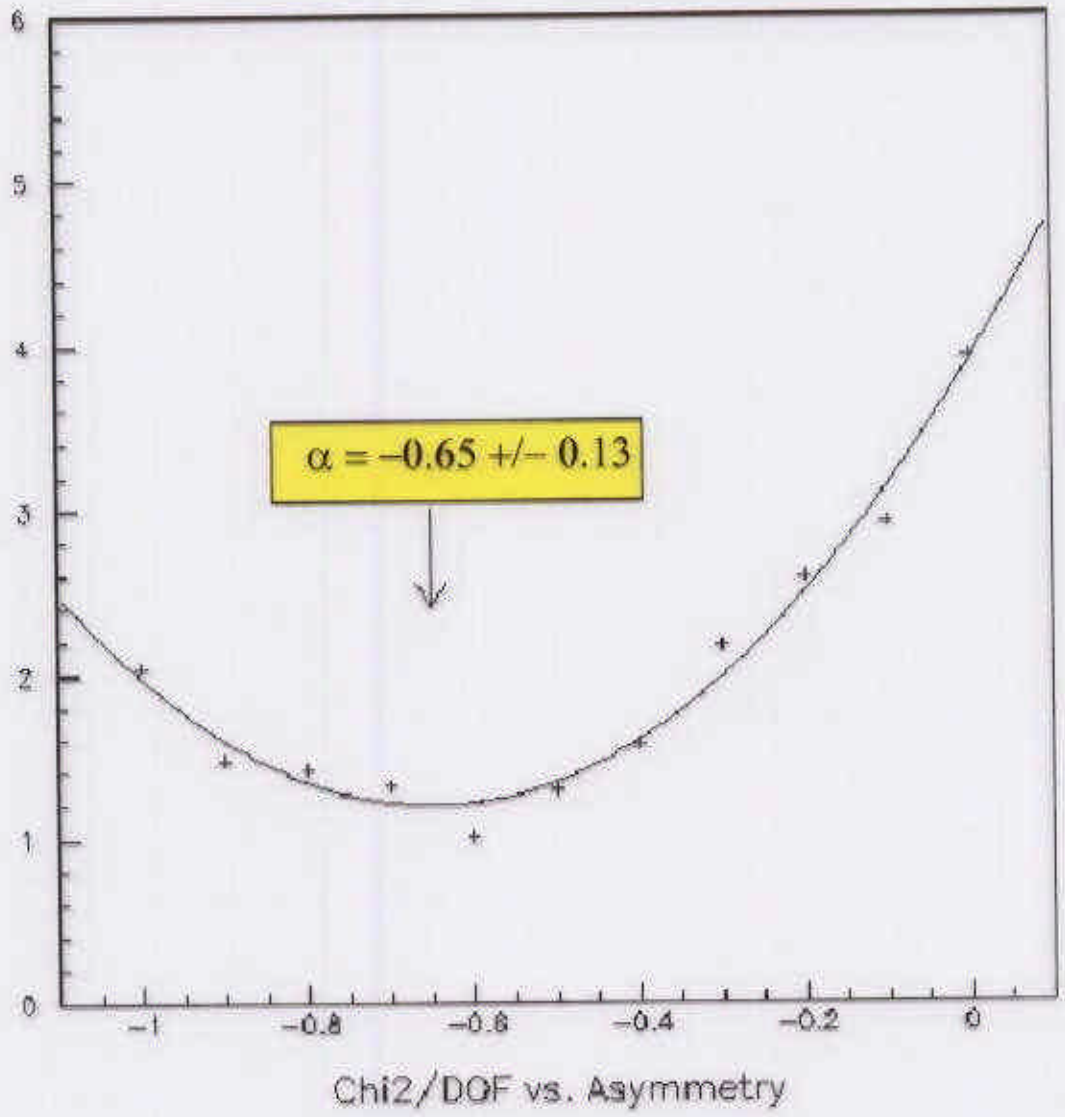
Measuring $\alpha_{\Xi->\Sigma\gamma}$

- Three stages of decay are taken into account - the only decay where this is true.
- Depolarization of -1/3 occurs in the decay $\Sigma->\Lambda\gamma$, which was not taken into account in the previous measurement (Teige 89).

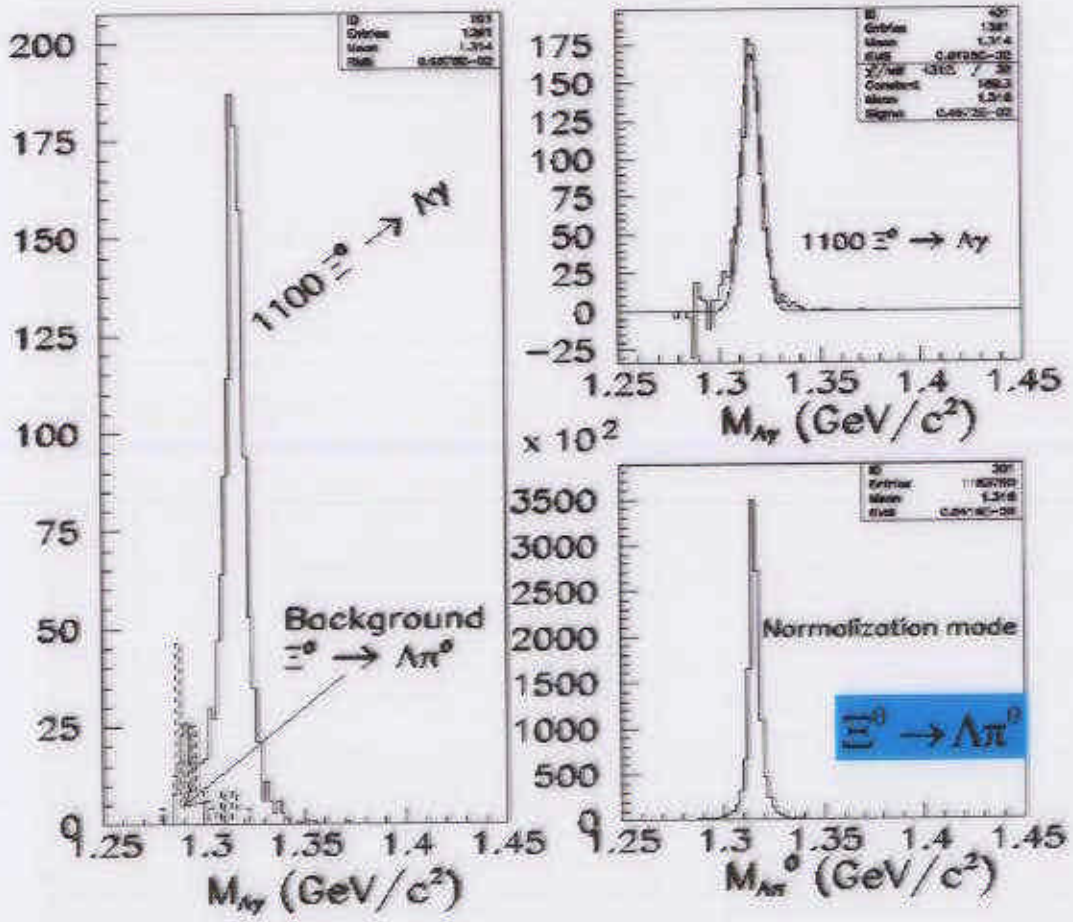




Preliminary Result for $\alpha_{\Xi^- \to \Sigma\gamma}$



Preliminary BR calculation of $\Xi^o \to \Lambda\gamma$



Winter'97 data

(Contained 1 cluster data)

$$N(\Lambda\gamma) = 1{,}100 \pm 33 \text{ evts}$$

$$N(\Lambda\pi^0) = 1{,}130{,}000 \pm 1063 \text{ evts}$$

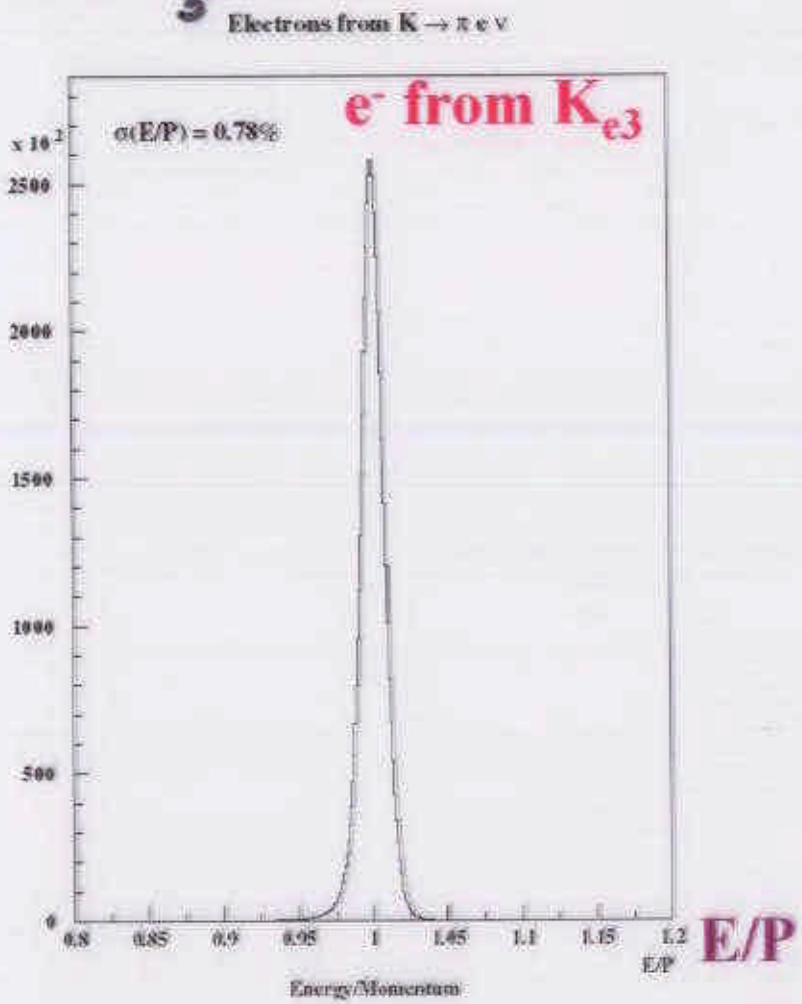
$$\frac{BR(\Lambda\gamma)}{BR(\Lambda\pi^o)} = (0.94 \pm 0.04)\text{x}10^{-3}$$

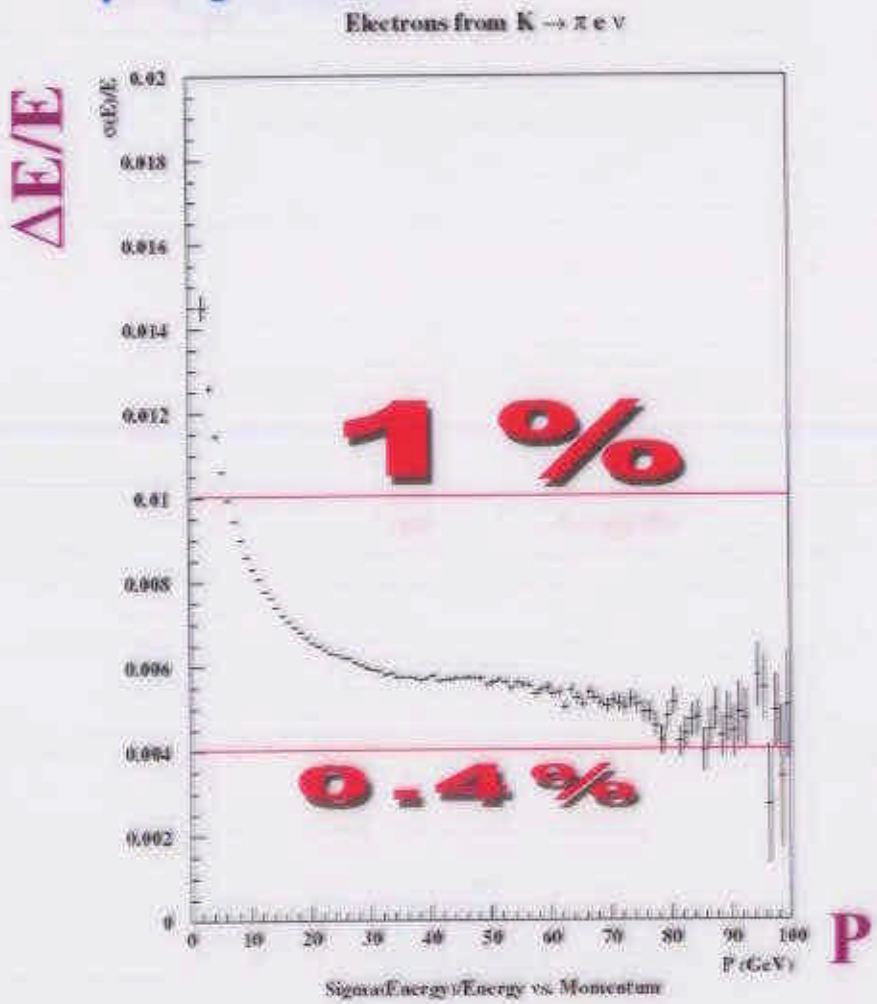
(stat only)

$$BR_{PDG} = [1.06 \pm 0.16]\text{x}10^{-3}$$

KTeV Detector Highlights

- ✓ **Pure CsI EM Calorimeter**
  - Position resolution < 1mm
  - Energy resolution < 1%
  - for E > ~~10~~ 5 GeV
- ✓ **Drift Chambers**
  - Position resolution ~ 100μm
- ✓ **Photon Veto system**
- ✓ **μ-system**





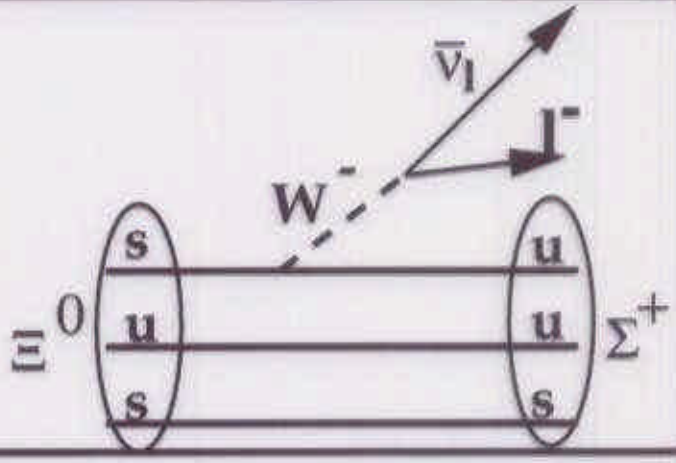
Cascade Beta Decay

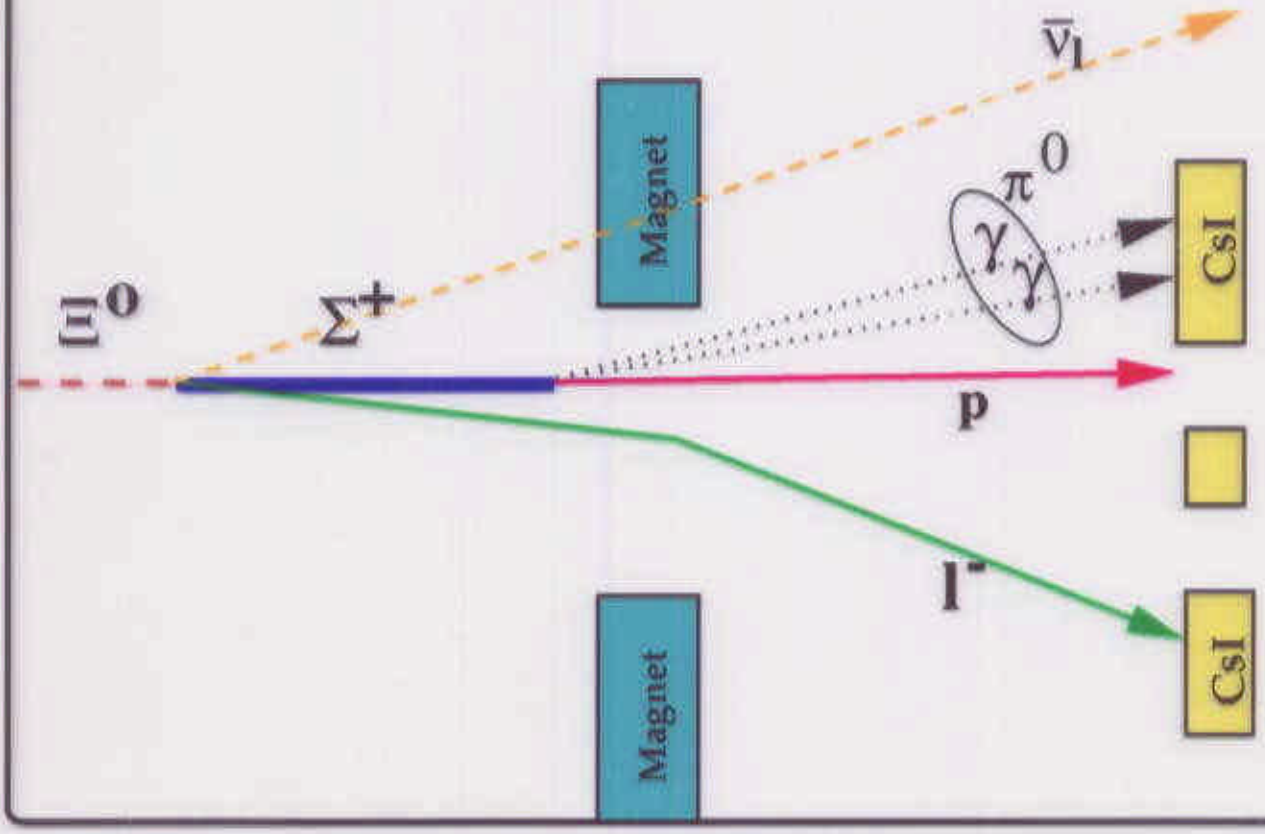
$\Xi^0 \rightarrow \Sigma^+ + l^- + \bar{\nu}_l$

$\hookrightarrow p + \pi^0$

$\hookrightarrow \gamma\gamma$

$l = e$ or μ





A typical $\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e$ event

KTEV Event Display

Run Number: 8387
Spill Number: 118
Event Number: 14718928
Trigger Mask: 200
All Slices

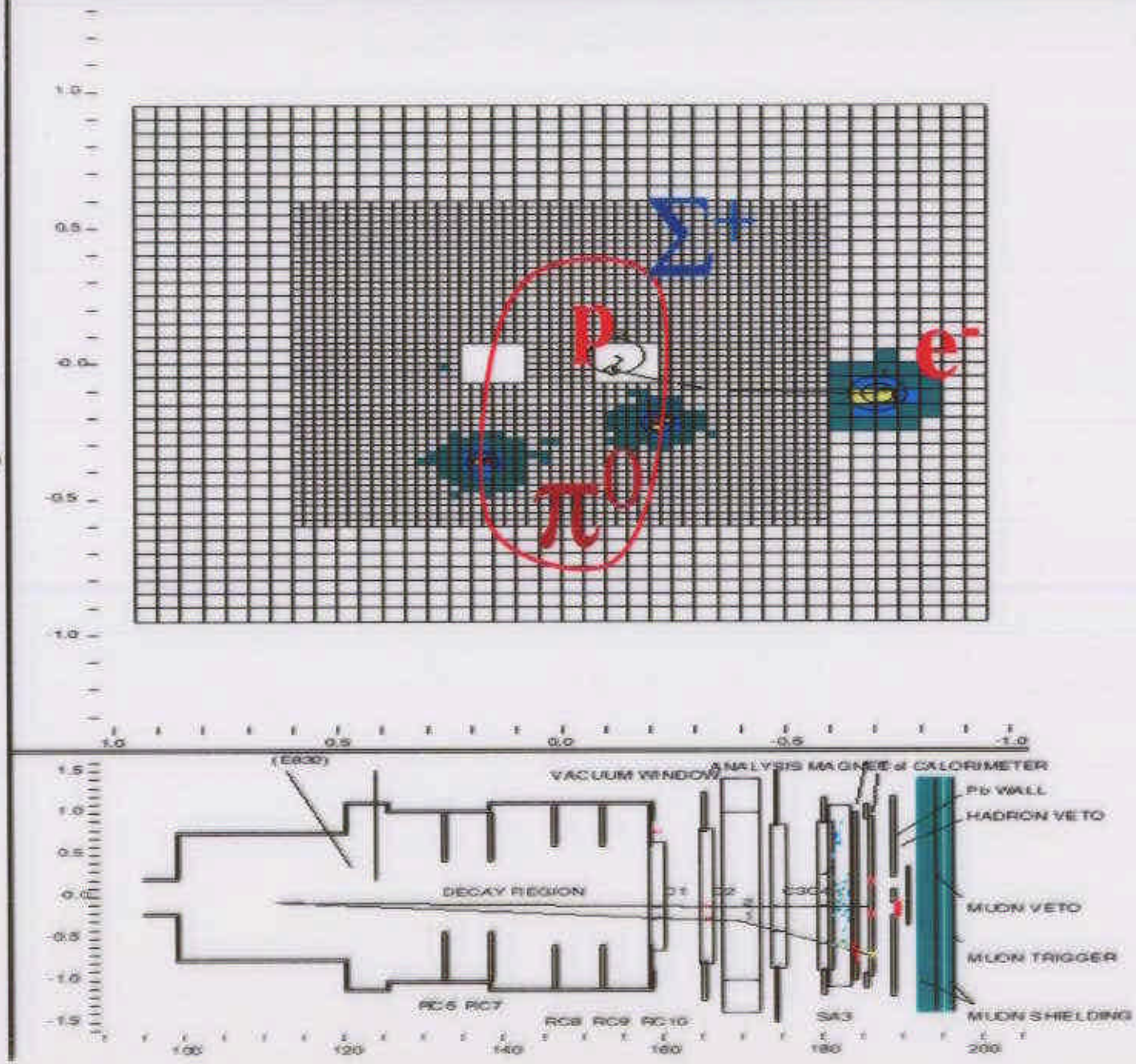
Track and Cluster Info
HCC cluster count: 3

ID	Xcsi	Ycsi	P or E
T 1:	-0.7063	-0.1142	-9.57
C 1:	-0.7092	-0.1137	9.50
T 2:	-0.1249	0.0260	+164.98
C 2:	-0.2179	-0.2197	19.41
C 3:	0.1739	-0.3658	25.03

Vertex: 2 tracks

X	Y	Z
-0.0710	-0.0160	111.673

Mass=0.6285 (assuming pions)
Chisq=1.30 Pt2v=0.019142



- Cluster
- Track
- 10.00 GeV
- 1.00 GeV
- 0.10 GeV
- 0.01 GeV

Neutral Hyperon Decays:

- Semi-leptonic decays:

$$\Xi^0 \rightarrow \Sigma^+ \mathbf{e}^- \nu_e \qquad \Xi^0 \rightarrow \Sigma^+ \mu^- \nu_\mu$$

$$\Lambda \rightarrow \mathbf{p}\, \mathbf{e}^- \nu_e \qquad \Lambda \rightarrow \mathbf{p}\, \mu^- \nu_\mu$$

- Radiative decays:

$$\Xi^0 \rightarrow \Lambda^0 \gamma \qquad \Xi^0 \rightarrow \Sigma^0 \gamma$$

$$\Xi^0 \rightarrow \Lambda^0 \pi^0 \gamma \qquad \Lambda \rightarrow \mathbf{p}\, \pi^- \gamma$$

Semi-leptonic Ξ^0 Decays

- Beta decay branching ratio
  2.6×10^{-4}
  (+/-0.11 stat.
  +/-0.16 sys.)

- Muon decay branching ratio
  3.5×10^{-6}
  (+2 -1 stat.
  +0.5 -1 sys.)

- Form factors
  - f1 = 0.99
    +/- 0.14
  - g1 = 1.32
    +0.21 -0.17 stat.
    +/- 0.05 sys.
  - f2 = 2.0
    +/-1.2 stat.
    +/-0.5 sys.
  - g2 = -1.7
    +2.1 -2.0 stat.
    +/- 0.5 sys.

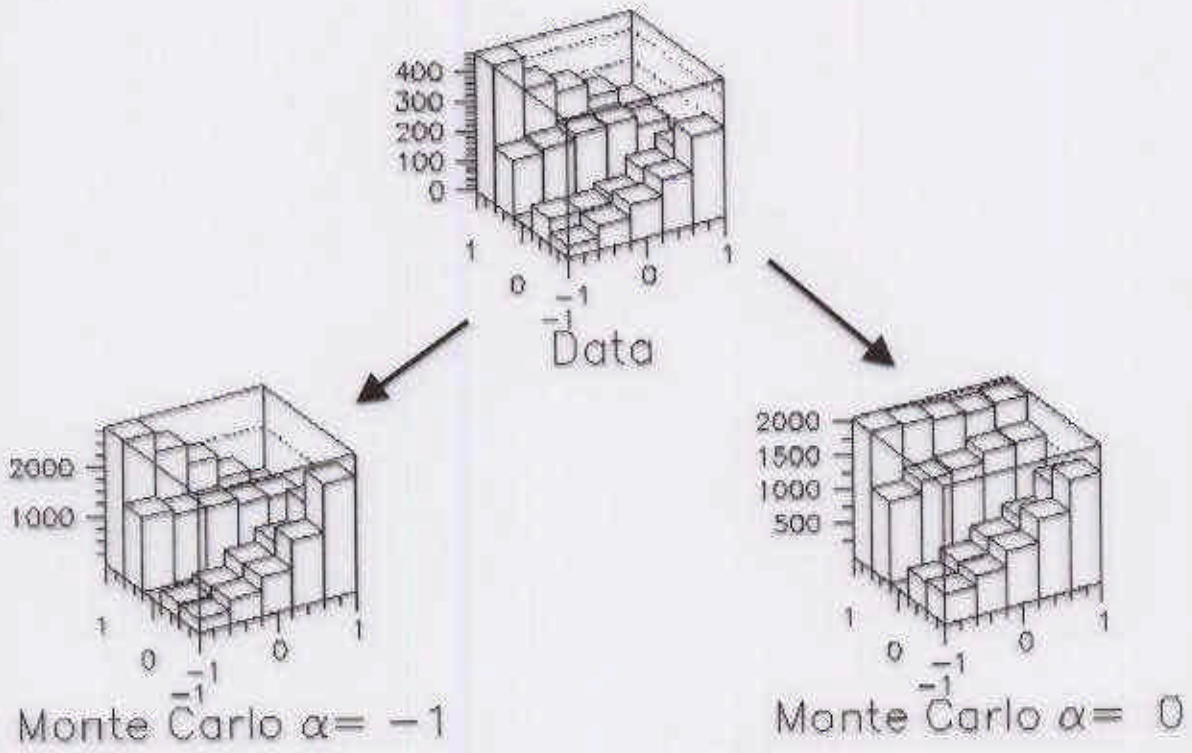
KTeV 1997 data final results

Weak Radiative Hyperon Decays

- WRHD are 1st order weak transitions of hyperons with photon emission: $A \rightarrow B\gamma$.
- Only BR and photon emission asymmetry (α) to be measured.
- Only 1 asymmetry has been accurately measured and it violates the Hara's Theorem expectation of minimal asymmetry: $\alpha(\Sigma \rightarrow p\gamma) = -0.76 +/- 0.08$
- Difficulties in the theory arise at the intersection of the quark model and hadron level language. Penguin diagrams and internal W exchange can play important roles:

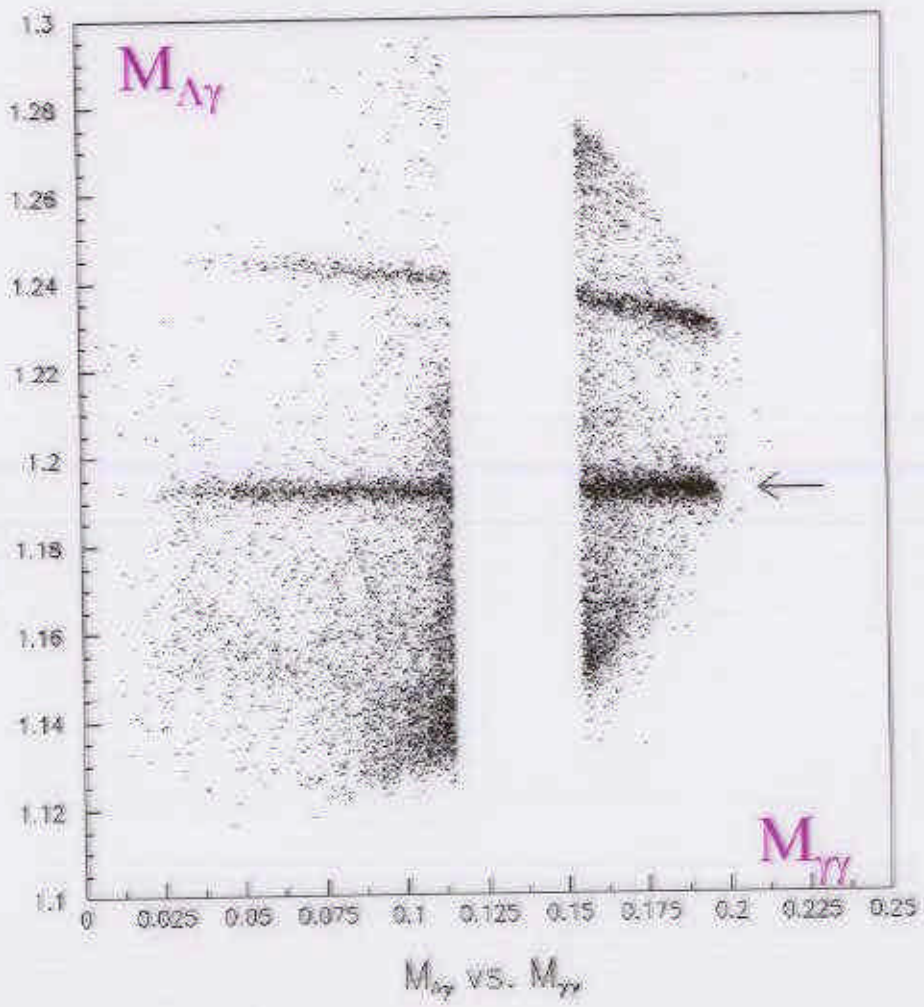
Measuring $\alpha_{\Xi->\Sigma\gamma}$

Compare 2 dimensional angular distribution between data and Monte Carlo with various asymmetry values.

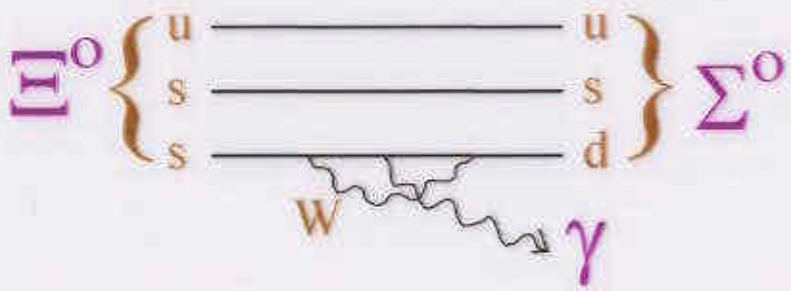


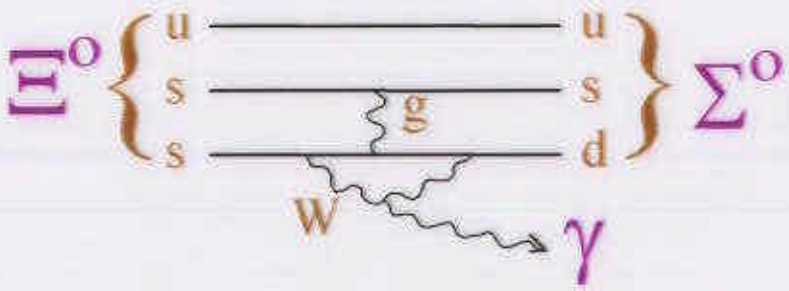
Reconstructing $\Xi^o \rightarrow \Sigma^o \gamma$ in KTeV

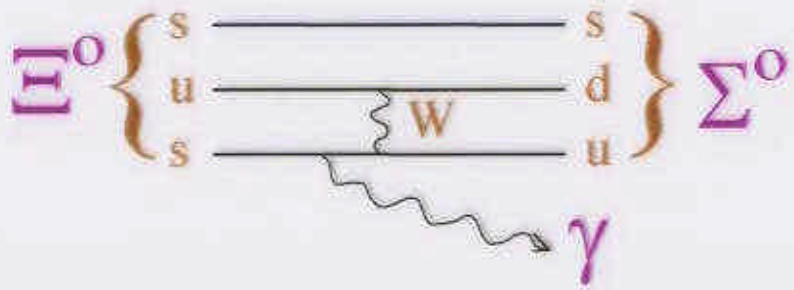
- Select events with 2 extra neutral clusters.
- Impose Ξ^o mass constraint and select for events from target.
- Look at invariant mass of $\Lambda\gamma$ and $\gamma\gamma$ combinations.



$\Xi^o \rightarrow \Sigma^o + \gamma$ Diagrams







Occurs for hyperons containing a u quark