Hyperon Beta Decay: A (Somewhat Biased) Review

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pbar2000 Workshop
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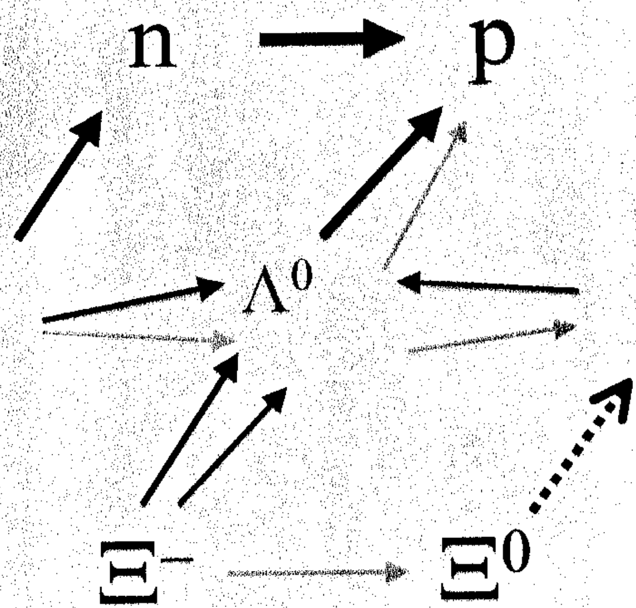
Outline

- Limitation: Only Allowed Octet Baryon Beta Decays
- Phenomenology and Notation
- Cabibbo (CKM) Model
- 1983-84 Review
- Selected "New"Results
- Data Summary 2000
    - Flavor SU(3) Breaking?
    - Determining V_{us} and V_{ud} (the Cabibbo angle)
    - Hints of New Physics?
- Summary and Conclusions

Allowed Baryon Beta Decays



$$\underline{A} \rightarrow \underline{B} + e^{-} + \overline{\nu}$$

$$M = \frac{G_{\mu}}{\sqrt{2}} V_{uj} \langle \underline{B} | J^{\alpha} | \underline{A} \rangle \ell_{\alpha} + ??$$

$$\langle \underline{B} | J^{\alpha} | \underline{A} \rangle =$$

$$\overline{u}(\underline{B}) \left[\underline{f_1(q^2)}\gamma^{\alpha} + \frac{f_2(q^2)}{M_A}\sigma^{\alpha\nu}\gamma_{\nu} + \frac{f_3(q^2)}{M_A} q^{\alpha} + \right.$$

$$\left. \left\{ \underline{g_1(q^2)}\gamma^{\alpha} + \frac{\underline{g_2(q^2)}}{M_A}\sigma^{\alpha\nu}\gamma_{\nu} + \frac{g_3(q^2)}{M_A} q^{\alpha} \right\} \gamma_5 \right] u(\underline{A})$$

$\underline{g_1/f_1}$ = +1.267 for $n \rightarrow pe^{-}\overline{\nu}$ is a "$\underline{V - A}$" Matrix Element.

In V_{uj}, j = d for $\Delta S = 0$ decays, and j = s for $\Delta S = 1$.

$V_{ud} = \cos(\theta_C)$ $\qquad$ $V_{us} \cong \sin(\theta_C)$

Observables

$$\delta \equiv \frac{\Delta M}{M} \equiv \frac{M_A - M_B}{M_A}$$

→ "Parity conserving"

① Rate $= \frac{B.F.}{\tau} \sim G_\mu^2 |V_{uj}|^2 [1+3x^2] |f_1|^2 (1+\epsilon_R)$

$$\Rightarrow x = \frac{(g_1 - \frac{2}{3}\delta g_2)}{f_1}$$

② $\alpha_{e\nu}$ or $E_B \longleftrightarrow x^2)$

③ $E_e \longleftrightarrow \frac{f_2}{f_1}$ at $O(\delta)$

→ Parity violating: $\langle \sigma \cdot p \rangle$

$\{\alpha_e, \alpha_\nu, \alpha_B\}$

$\{S_e, S_\nu, S_B\}$

- $\frac{g_1}{f_1}$ at $O(1)$
- $\frac{g_2}{f_1}$ at $O(\delta)$
- $\frac{f_2}{f_1}$ at $O(\delta)$

1) $\frac{K \to \mu\nu}{\pi \to \mu\nu}$ - $\frac{K \to \pi e \nu}{\pi \to \pi e \nu}$ $\Rightarrow \theta \approx 0.26$

[Maint. $\theta = 0.2196 \pm 0.0023$]

V-1.25A ← 2) use as input { $n \to p e^- \bar{\nu}$; $\Sigma^{\pm} \to \Lambda^0 e \nu$ }

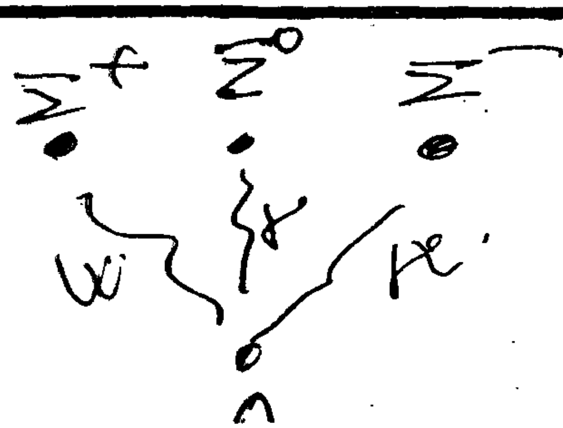
or $\frac{g_1}{f_1} = +1.25$

and predict ⇓

Table I. Predictions for the leptonic decays of hyperons.

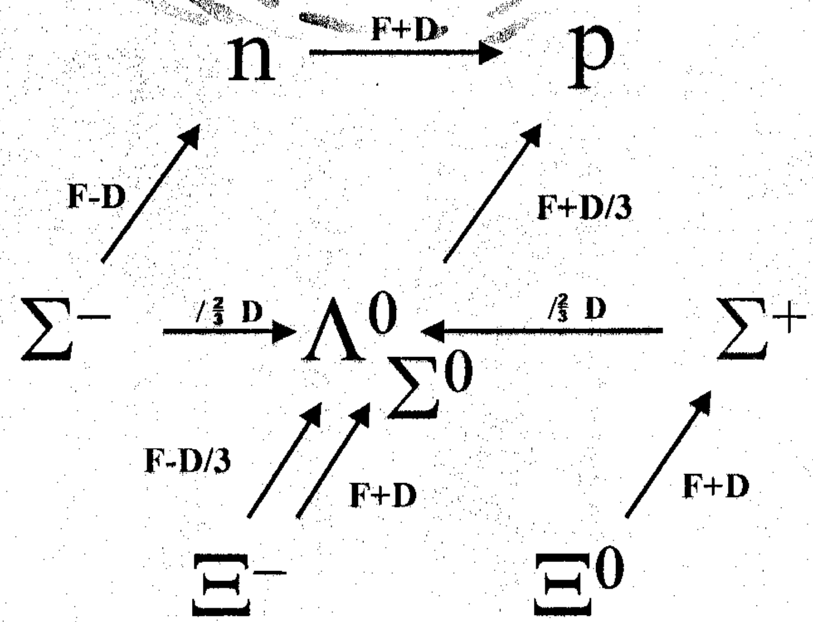
Decay	Branching ratio From reference 2	Branching ratio Present work	Type of interaction
$\Lambda \to p + e^- + \bar{\nu}$	1.4 %	0.75×10^{-3}	$V - 0.72A$
$\Sigma^- \to n + e^- + \bar{\nu}$	5.1 %	1.9×10^{-3}	$V + 0.65A$
$\Xi^- \to \Lambda + e^- + \bar{\nu}$	1.4 %	0.35×10^{-3}	$V + 0.02A$
$\Xi^- \to \Sigma^0 + e^- + \bar{\nu}$	0.14 %	0.07×10^{-3}	$V - 1.25A$
$\Xi^0 \to \Sigma^+ + e^- + \bar{\nu}$	0.28 %	0.26×10^{-3}	$V - 1.25A$

$\frac{g_1}{f_1} < 0$



From Cabibbo's Hyperon '99 talk: Table I from PRL 10, 531 (1963)

Beta Decays in the Baryon Octet



Hyperon Beta Decay: 1983-84 Review

[J.M. Gaillard and G. Sauvage, *Ann. Rev. Nucl. Part. Sci.* **34**, 351 (1984).]

50^{th} Anniversary of Fermi Theory

- **Included *only* CERN SPS (WA2) hyperon data in fits (+ neutron decay: $g_1/f_1 = 1.2390 \pm 0.0090$ from lifetime).**

- **Emphasized need to consistently include radiative corrections and q^2 dependance of f_1 & g_1.**

- **Remarkable success in fitting "most recent data."**

$V_{us} = 0.231 \pm 0.003$	$F/D = 0.631$
$F = 0.477 \pm 0.012$	$F+D = 1.233$
$D = 0.756 \pm 0.011$	$F-D = 0.279$

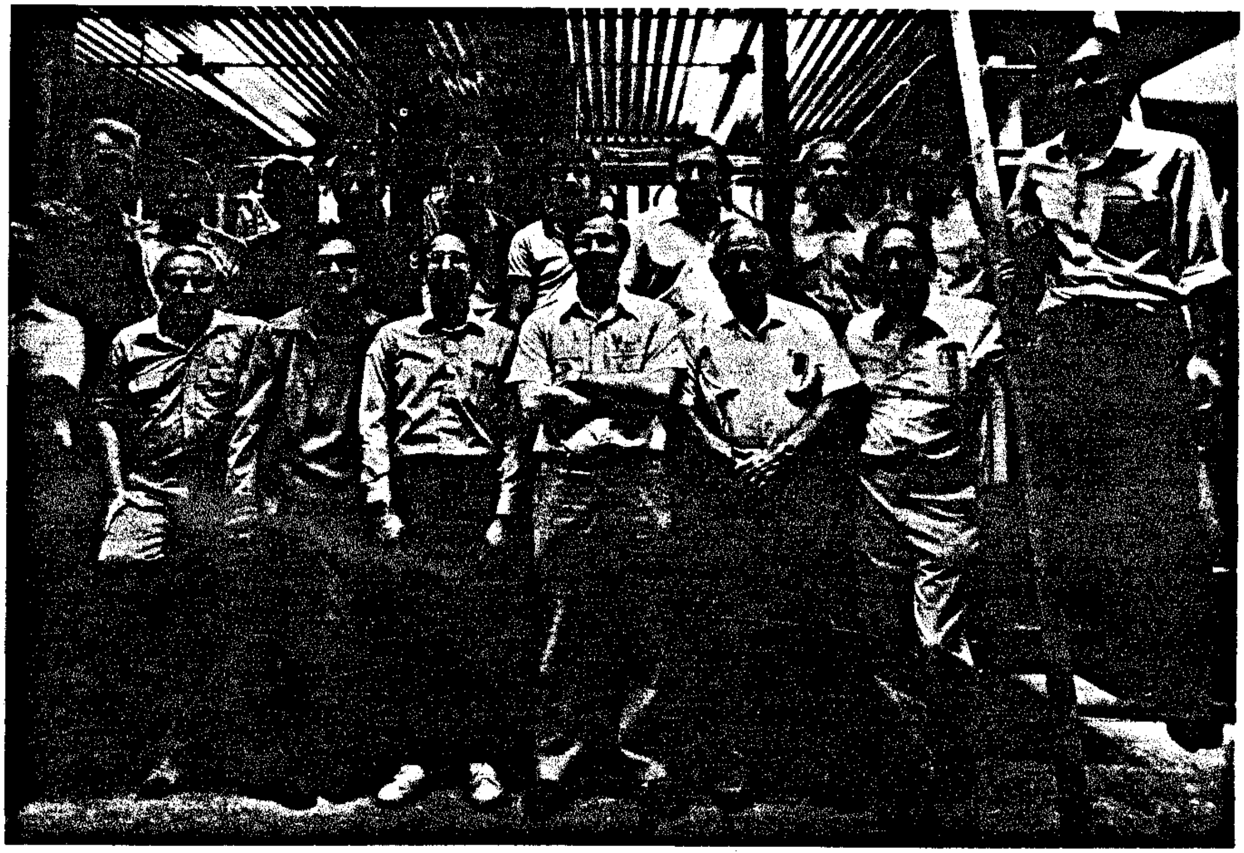
- **$V_{us} = 0.2196 \pm 0.0023$ from Ke3 analysis.**

- **Measurements in** polarized **hyperon beams desirable.**

- Sign of g_1/f_1 in $\Sigma^- \rightarrow ne^-\bar{\nu}$ **is still an open question: "the keystone of the Cabibbo theory."**

- **Effects of flavor SU(3) breaking "yet to be uncovered."**

- **No theoretical ground rules for hunting SU(3) breaking effects.**



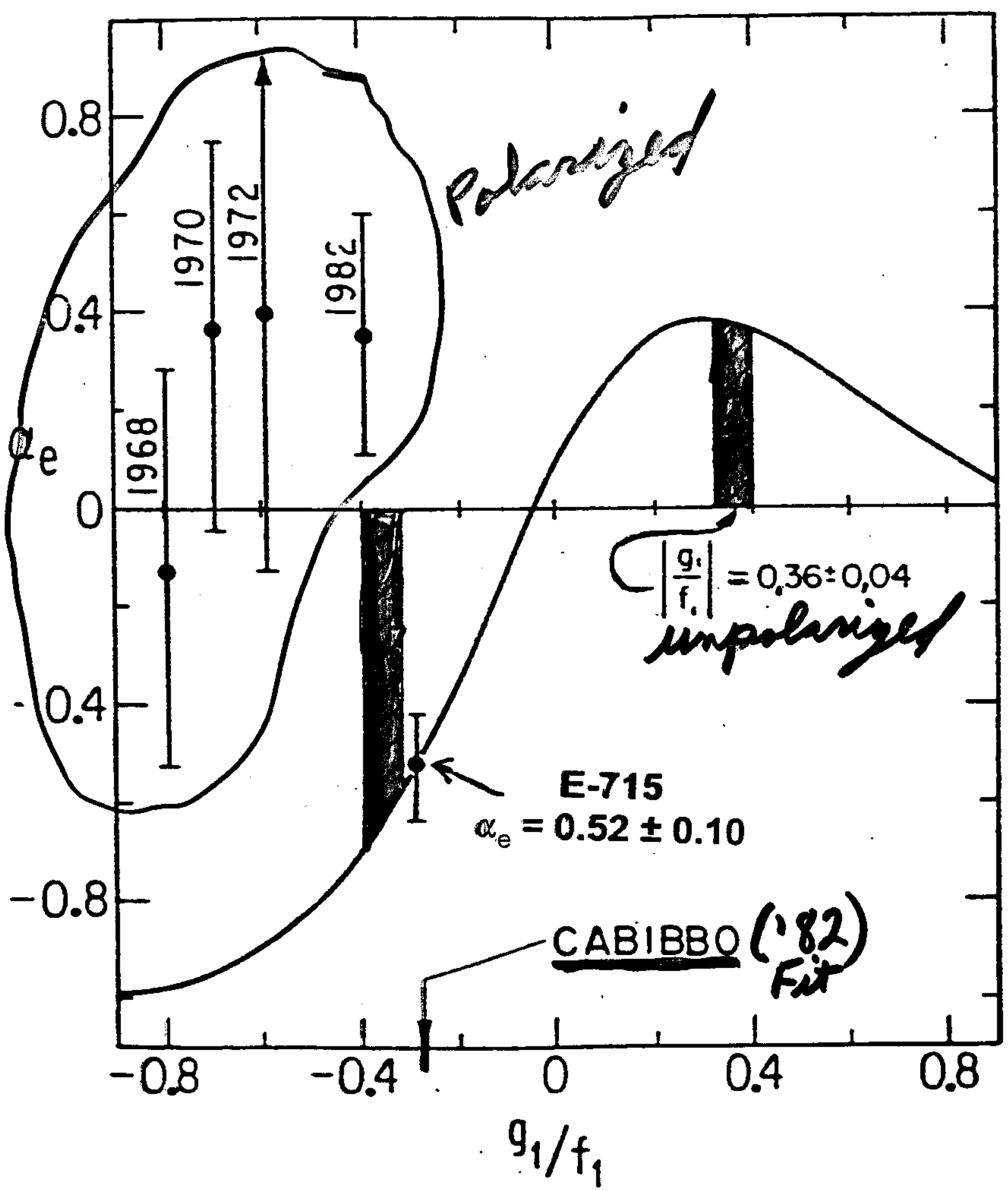
E 715 IS HONORED AND PROUD TO BE

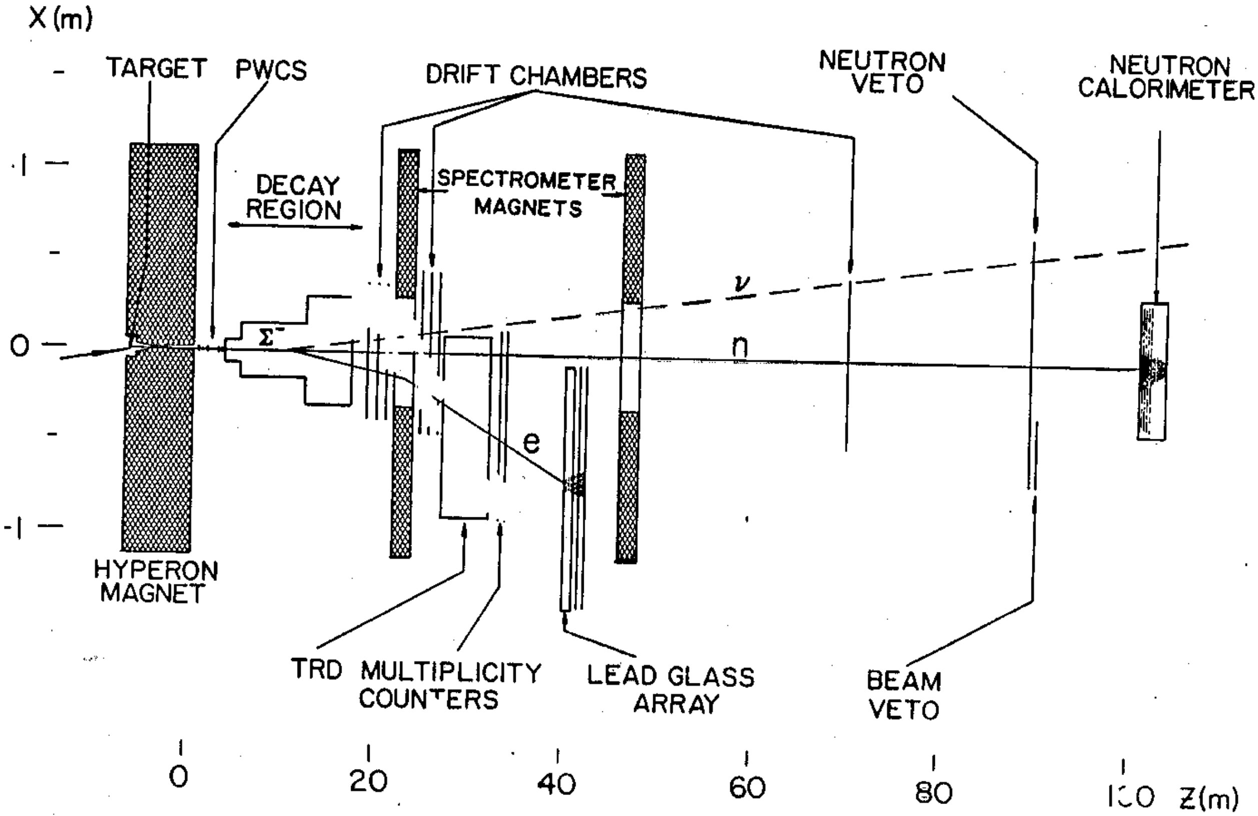
THE FIRST ENERGY SAVER USER

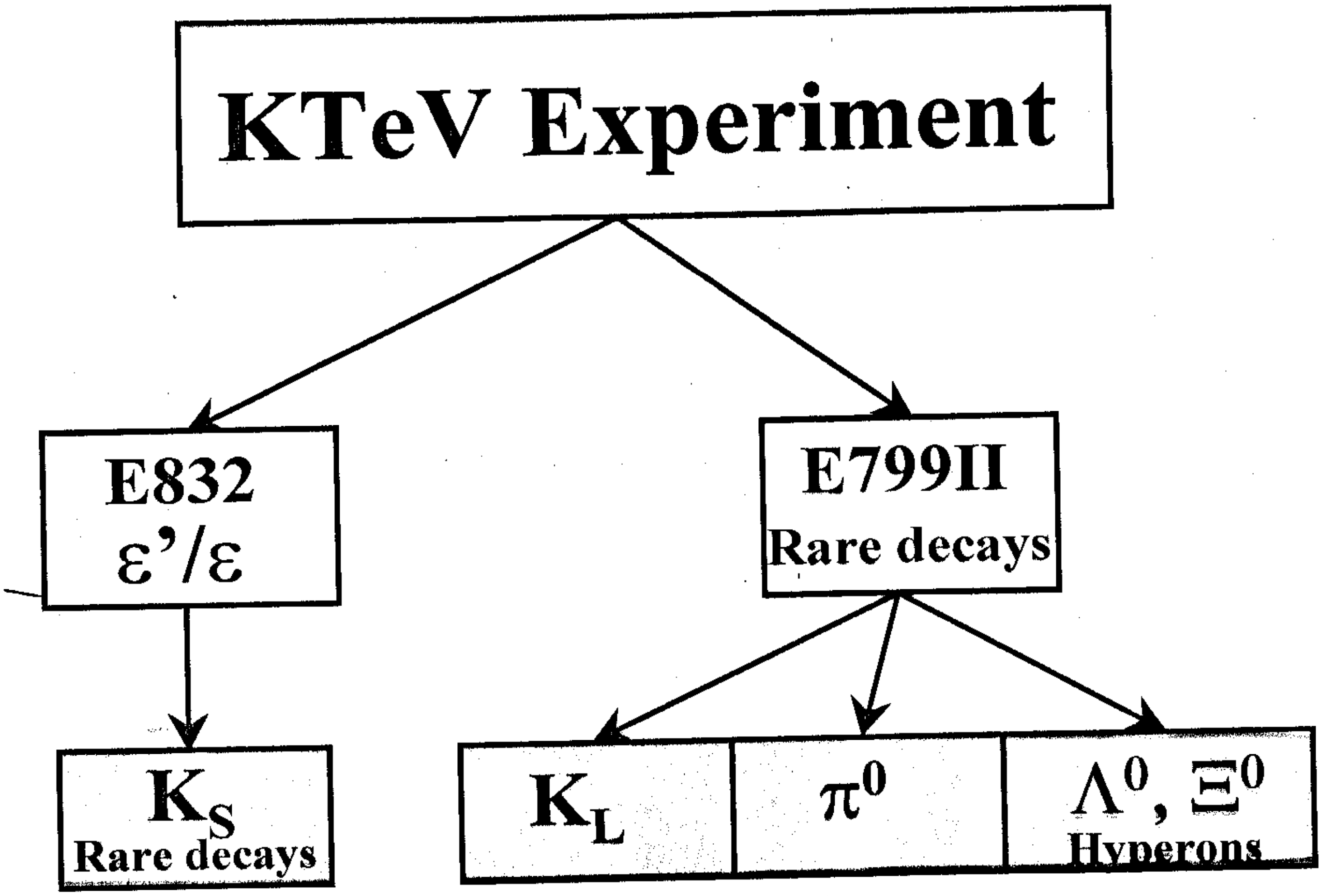
OCTOBER 1, 1983

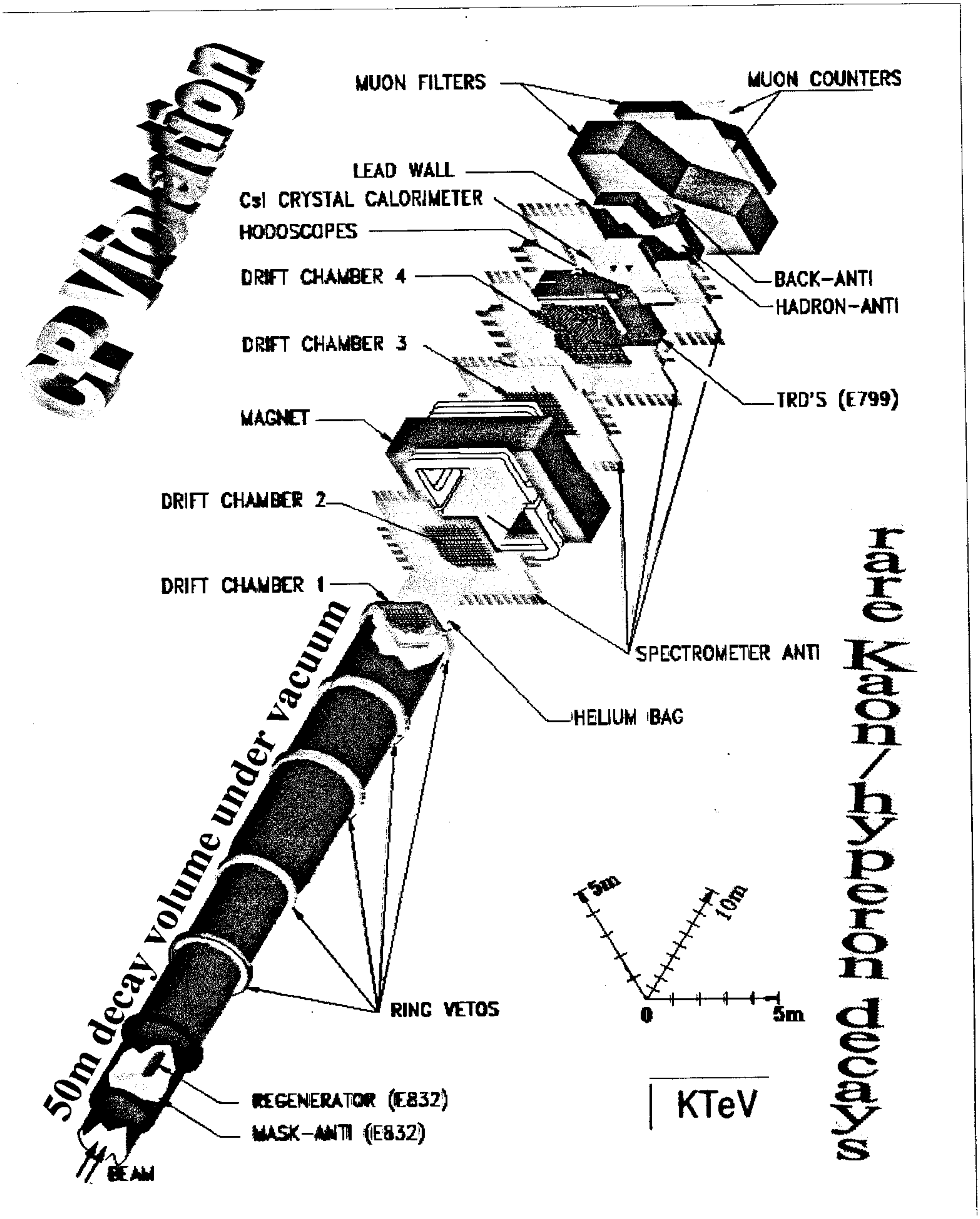
THANK YOU FERMILAB!

$\Sigma^- \rightarrow n e^- \bar{\nu}$



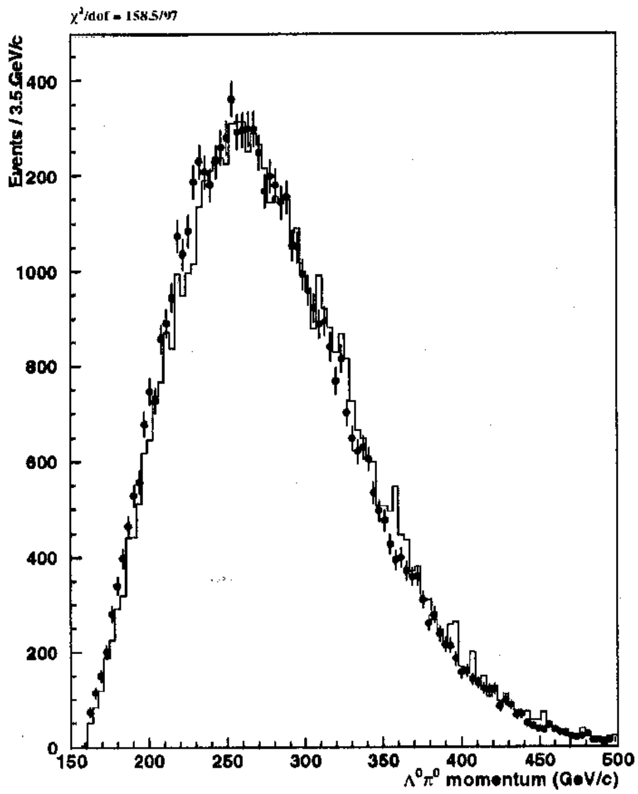

X (m)
TARGET
PWCS
DRIFT CHAMBERS
NEUTRON VETO
NEUTRON CALORIMETER
DECAY REGION
SPECTROMETER MAGNETS
Σ⁻
ν
n
e
1
0
-1
HYPERON MAGNET
TRD
MULTIPLICITY COUNTERS
LEAD GLASS ARRAY
BEAM VETO
0
20
40
60
80
100
Z(m)


KTeV Experiment
E832
ε'/ε
E799II
Rare decays
K_S
Rare decays
K_L
π^0
Λ^0, Ξ^0
Hyperons

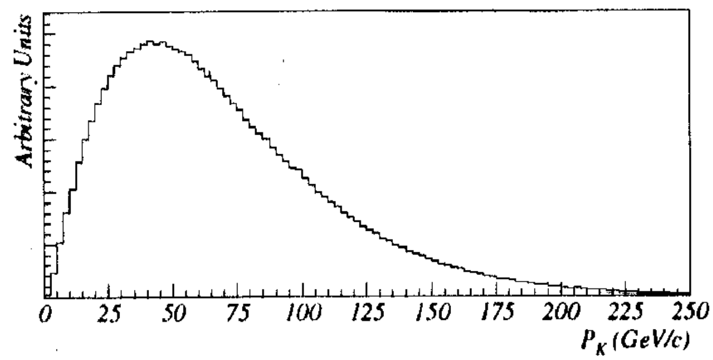

CP Violation
rare Kaon/hyperon decays
50m decay volume under vacuum
MUON FILTERS
MUON COUNTERS
LEAD WALL
CsI CRYSTAL CALORIMETER
HODOSCOPES
DRIFT CHAMBER 4
DRIFT CHAMBER 3
MAGNET
DRIFT CHAMBER 2
DRIFT CHAMBER 1
BACK-ANTI
HADRON-ANTI
TRD'S (E799)
SPECTROMETER ANTI
HELIUM BAG
RING VETOS
REGENERATOR (E832)
MASK-ANTI (E832)
BEAM
5m
10m
0
5m
KTeV

Only highest momentum Λs and Ξ^0s reach the decay volume.

Ξ^0 Momentum Spectrum



K_L Momentum Spectrum



Physics Motivation For Cascade Beta Decay

$\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}$ (ssu $\rightarrow$ suu) $\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}$

$\hookrightarrow p\pi^0$

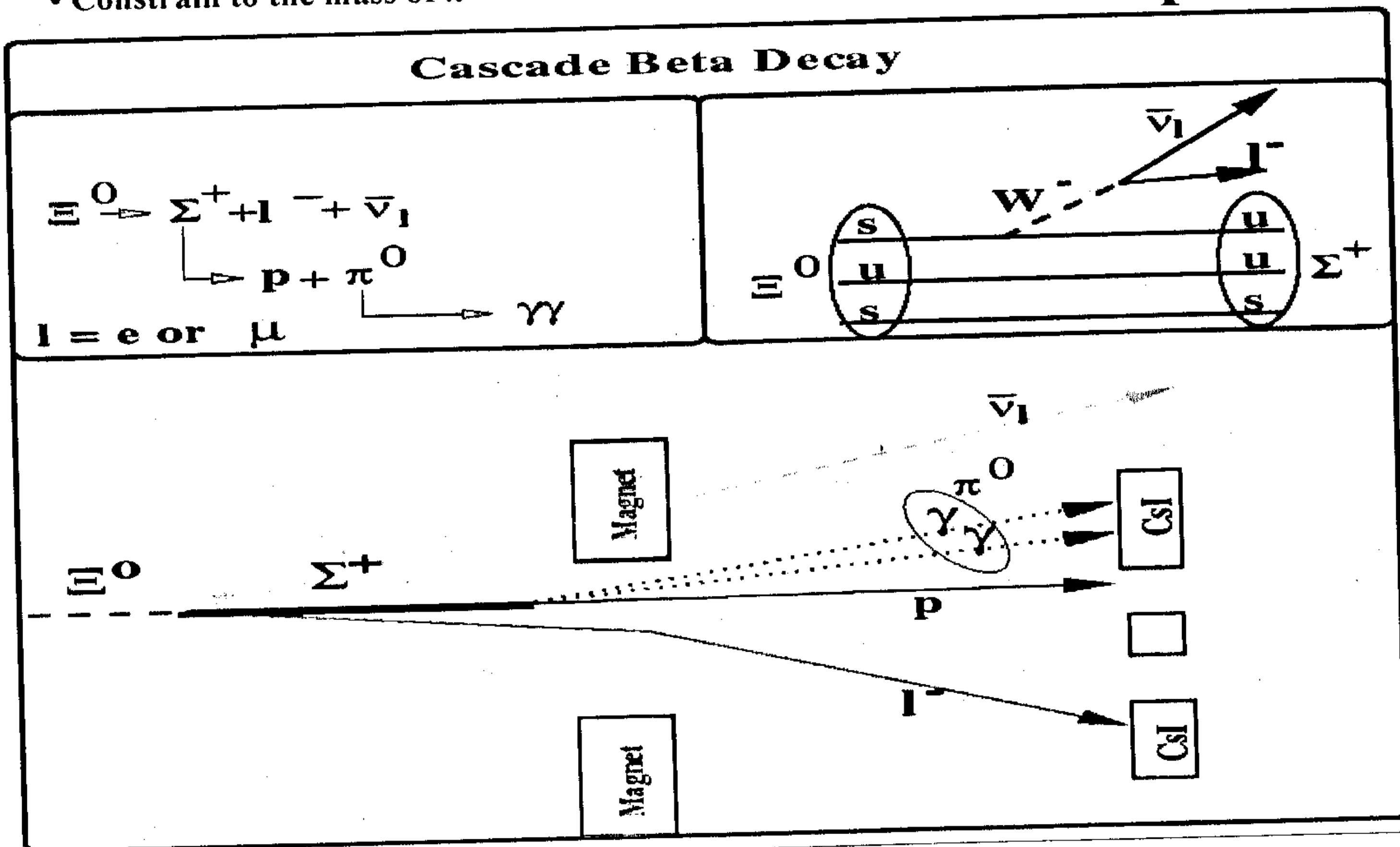
$\hookrightarrow \gamma\gamma$

- ✓ Never Seen (before KTeV) – Possible Surprise
- ✓ SU(3) copy of $n \rightarrow p e \nu_e$ (ddu $\rightarrow$ duu) $\left(\frac{g_1}{f_1} = +1.267\right)$
- ✓ Clear Window on SU(3) Symmetry Breaking
- ✓ Clarify V_{us} Comparison: Kaons *vs.* Hyperons?
- ✓ ~ 100% "Equivalent Polarization"
- ✓ Comparable Vector & Axial Vector Contributions
- ✓ No Similar Competing Two-Body Decay [$\Xi^0 \not\rightarrow \Sigma^+ \pi^-$]

08/28/00 MON 12:01 FAX 630 840 6311 FERMILAB 13 NORTH 015

Reconstruction of $\Xi^0 \longrightarrow \Sigma^+ e^- \bar{\nu}_e$, $\Sigma^+ \rightarrow p\pi^0$

- Constrain to the mass of π^0



$\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e$ Event Display

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

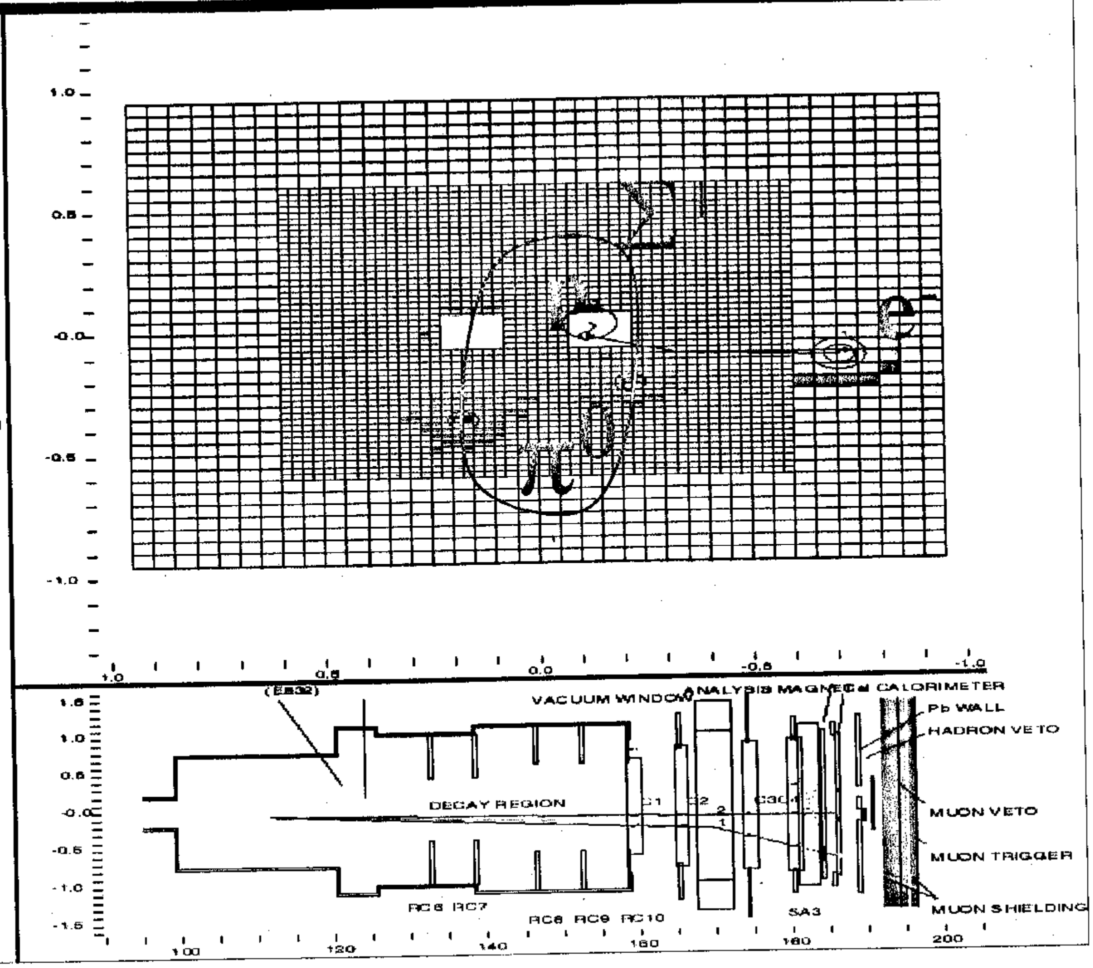
Track and Cluster Info
HCC cluster count: 3

ID	Xcsl	Ycsl	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

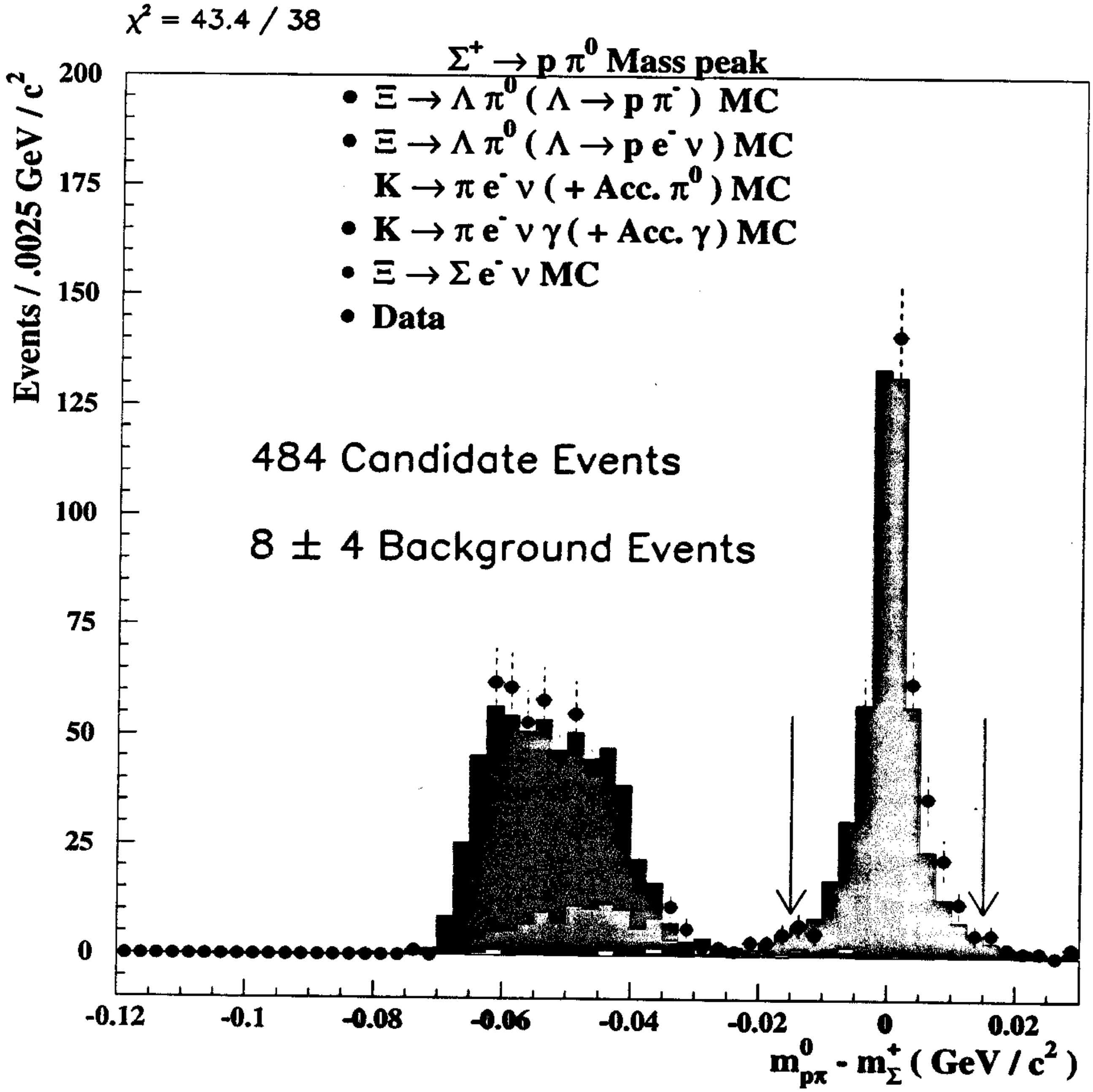
Vertex: 2 tracks

X	Y	Z
-0.0710	-0.0160	111.673

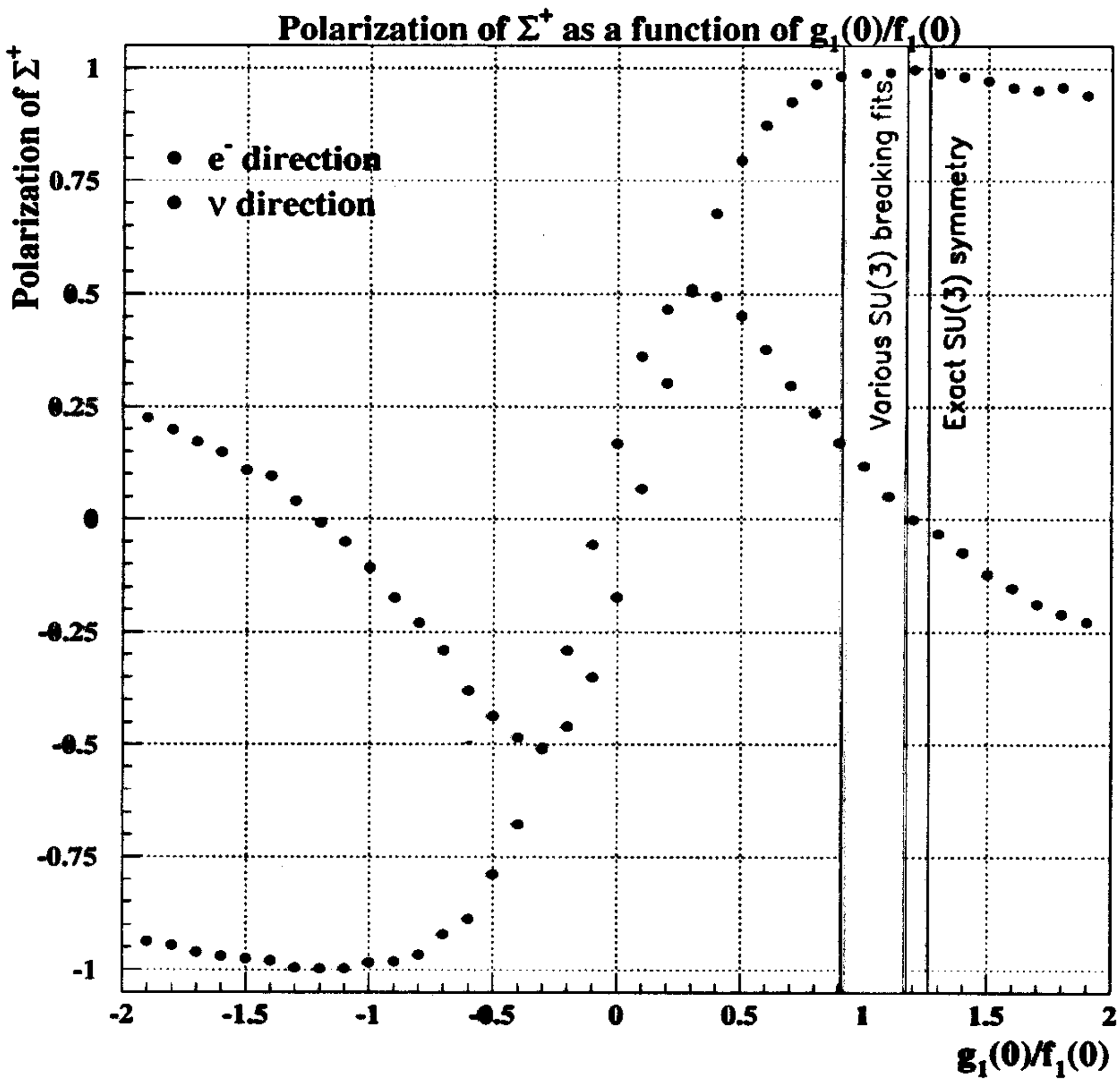
Mass=0.6285 (assuming pions)
Chisq=1.30 Pt2v=0.019142



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

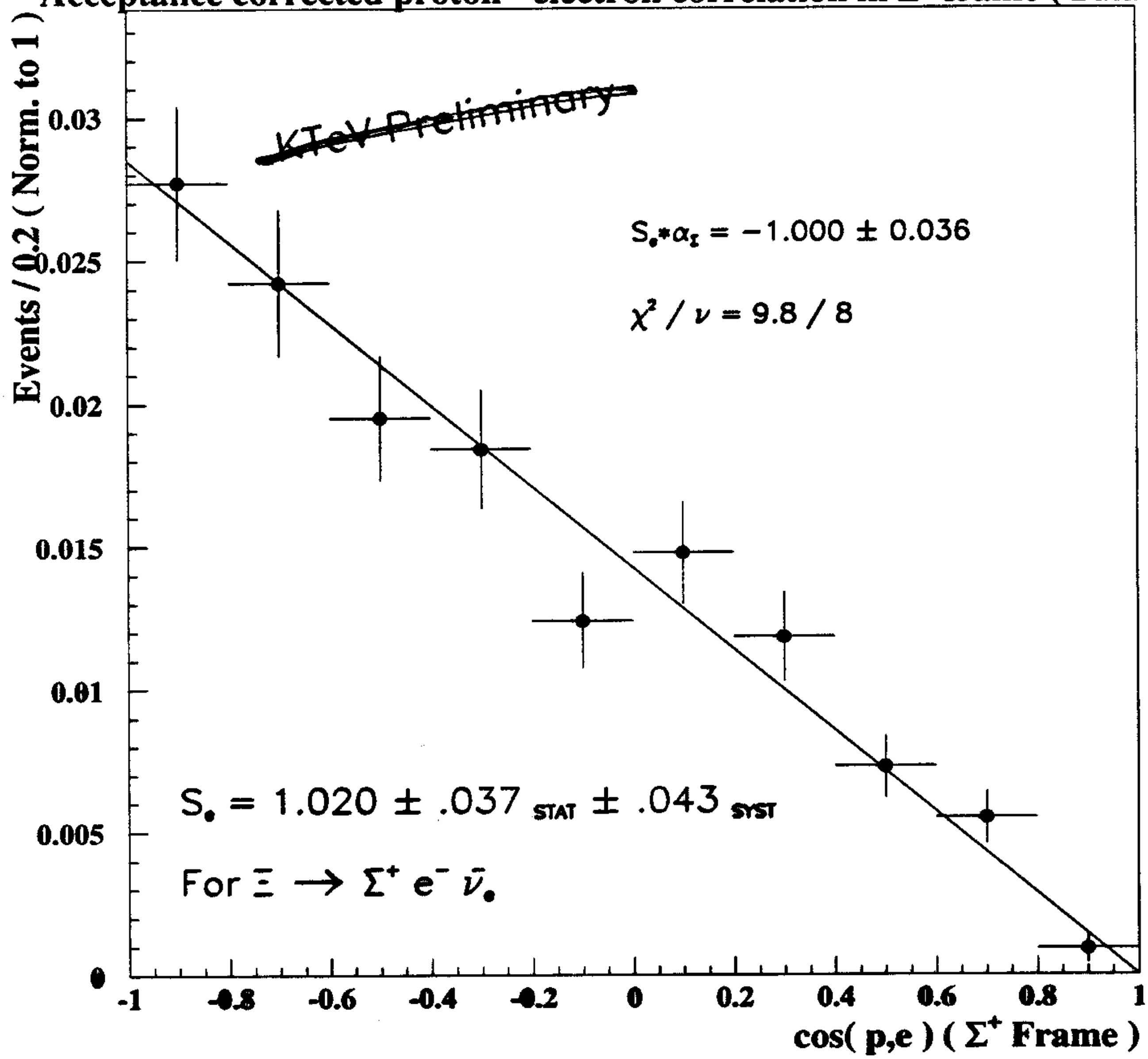


χ^2 = 43.4 / 38
$\Sigma^+ \rightarrow p\,\pi^0$ Mass peak
$\Xi \rightarrow \Lambda\,\pi^0\,(\Lambda \rightarrow p\,\pi^-)$ MC
$\Xi \rightarrow \Lambda\,\pi^0\,(\Lambda \rightarrow p\,e^-\,\nu)$ MC
$K \rightarrow \pi\,e^-\,\nu\,(+\,\mathrm{Acc.}\,\pi^0)$ MC
$K \rightarrow \pi\,e^-\,\nu\,\gamma\,(+\,\mathrm{Acc.}\,\gamma)$ MC
$\Xi \rightarrow \Sigma\,e^-\,\nu$ 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)



Polarization of Σ⁺ as a function of g₁(0)/f₁(0)
Polarization of Σ⁺
e⁻ direction
ν direction
Various SU(3) breaking fits
Exact SU(3) symmetry
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
g₁(0)/f₁(0)

Acceptance corrected proton - electron correlation in Σ^+ frame (Summer)



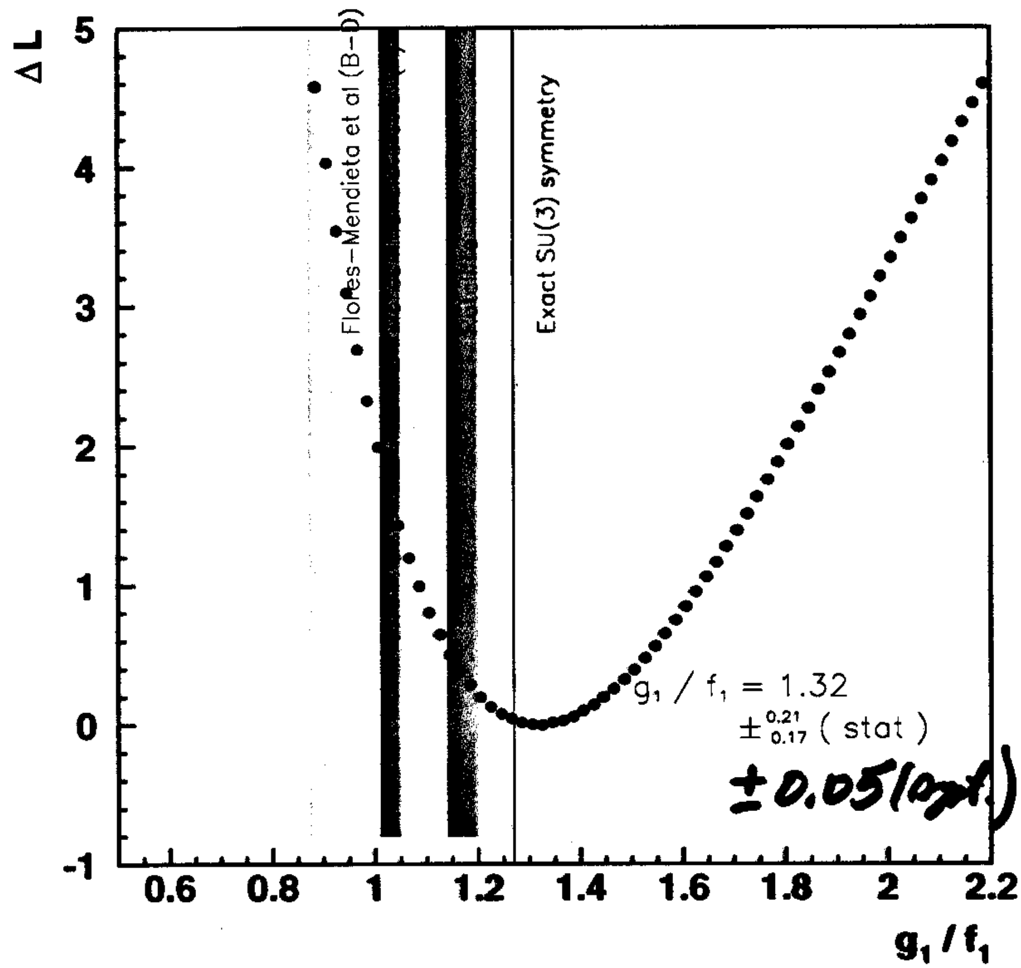
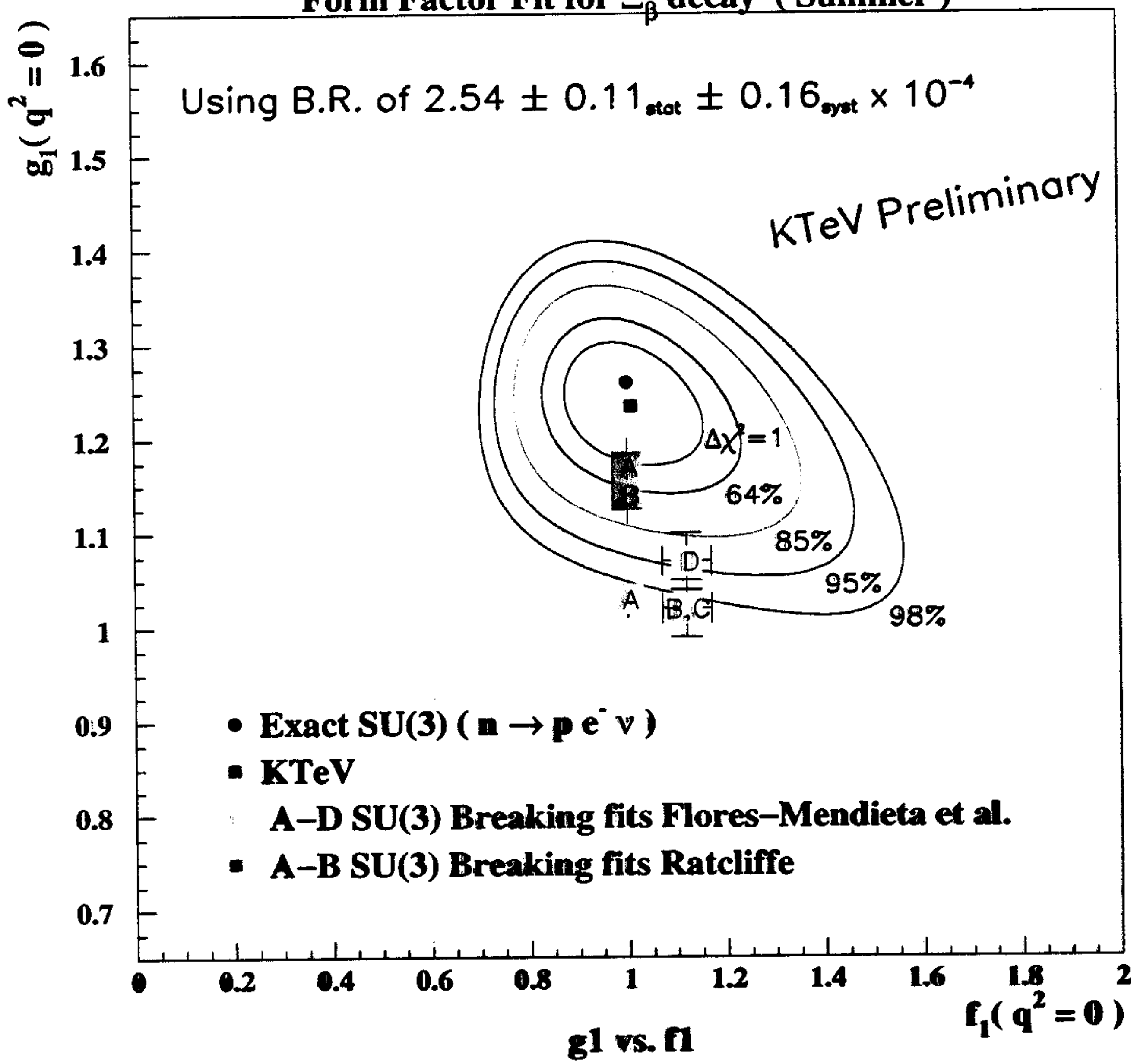


Figure 53. Maximum Likelihood fit to g_1/f_1 corrected for background.

9.4.1 Correcting for Background

Our best background estimate with this selection criteria is 7.4 ± 3.7 events (about 2 ± 1% of the signal), the background being almost entirely due to $K_L \to \pi^+ e^- \bar{\nu}_e$ and $K_L \to \pi^+ e^- \bar{\nu}_e \gamma$ decays. We estimate the effect of this background by adding MC background events to MC signal events and observing the change in the measured value of g_1/f_1 in the MC samples. We used 30 'data sized' $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ Monte Carlo samples

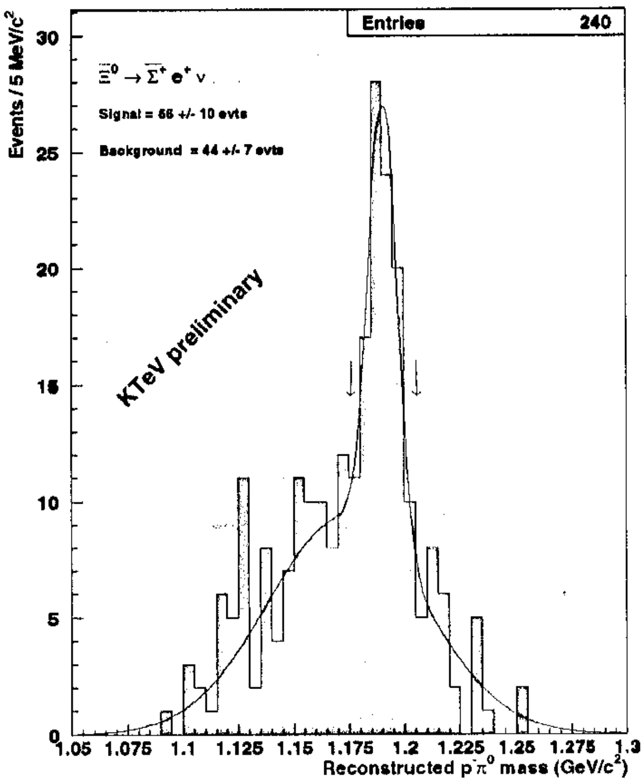
Form Factor Fit for Ξ_β decay (Summer)

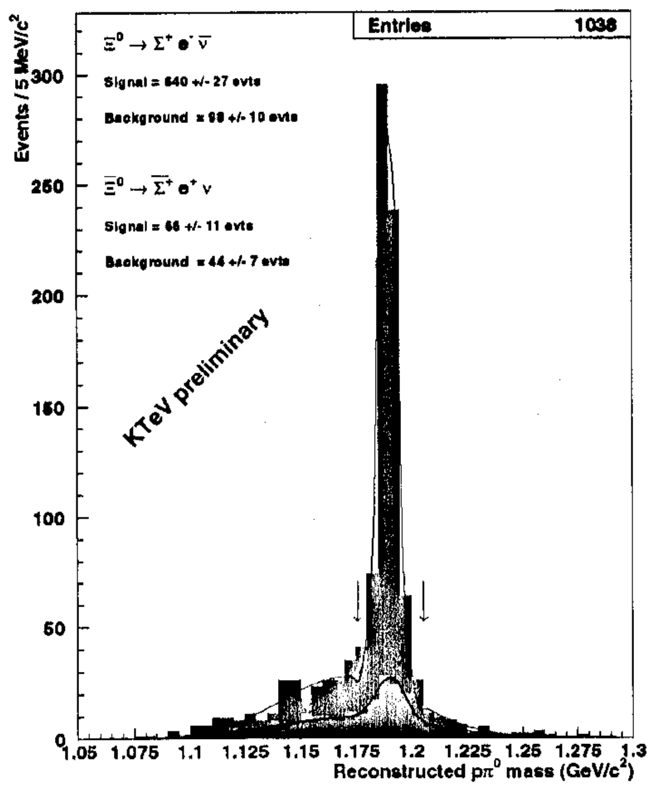


PRD 58-094028 (1998)

PRD 59-014038 (1999)

Anti-Cascade Beta Decay





Octet Baryon Beta Decay
Data Summary **2000**

Decay Process	Lifetime (sec)	Branching Fraction	Rate (μsec^{-1})	g_1/f_1
$n \rightarrow pe^- \overline{\nu}$	886.7 (1.9)*	1	1.1278(24) E-9	1.2670(35)‡
$\Lambda \rightarrow pe^- \overline{\nu}$	2.632 (20) E-10§	0.832(14) E-3	3.161(58)	0.718 (15)
$\Sigma^- \rightarrow ne^- \overline{\nu}$	1.479 (11) E-10†	1.017(34) E-3	6.88(24)	-0.340 (17)
$\Sigma^- \rightarrow \Lambda e^- \overline{\nu}$	1.479 (11) E-10†	0.0573(27) E-3	0.387(18)	f_1/g_1 = 0.01(10)**
$\Sigma^+ \rightarrow \Lambda e^+ \nu$	0.8018 (26) E-10	0.020(5) E-3	0.250(63)	
$\Xi^- \rightarrow \Lambda e^- \overline{\nu}$	1.639 (15) E-10	0.563(31) E-3	3.44(19)	0.25(5)
$\Xi^- \rightarrow \Sigma^0 e^- \overline{\nu}$	1.639 (15) E-10	0.087(17) E-3	0.53(10)	
$\Xi^0 \rightarrow \Sigma^+ e^- \overline{\nu}$	2.900 (90) E-10	0.254(19) E-3	0.876(71)	1.32 (+.22/-.18)

*S = 1.2 ‡S = 1.9 §S = 1.6 †S = 1.3 **S = 1.5

Octet Baryon Beta Decay
"Analysis" 2000

Decay Process	Calculated		Measured	
	Rate (μsec^{-1})	g_1/f_1	Rate (μsec^{-1})	g_1/f_1
$n \rightarrow pe^- \bar{\nu}$	—	*input* F + D	1.2278(24) E-9	*1.2670(35)*
$\Lambda \rightarrow pe^- \bar{\nu}$	3.173(32) [3.106(78)]	0.731(6) F + ⅓D	3.161(58)	0.718 (15)
$\Sigma^- \rightarrow ne^- \bar{\nu}$	6.42(17) [6.42(17)]	*input* F - D	6.88(24)	*-0.340 (17)*
$\Sigma^- \rightarrow \Lambda e^- \bar{\nu}$	0.343(9)	0.656(7)* $\sqrt{2/3}$D	0.387(18)	f_1/g_1 = 0.01(10)**
$\Sigma^+ \rightarrow \Lambda e^+ \nu$	0.202(5)	0.656(7)* $\sqrt{2/3}$D	0.250(63)	
$\Xi^- \rightarrow \Lambda e^- \bar{\nu}$	2.84(4) [3.03(19)]	0.196(12) F - ⅓D	3.44(19)	0.250(50)
$\Xi^- \rightarrow \Sigma^0 e^- \bar{\nu}$	0.361(2)	1.2670(35) F + D	0.53(10)	
$\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}$	0.909(41)	1.2670(35) F + D	0.876(71)	1.32 (+.22/-.18)

*$f_1 = 0$ & g_1 tabulated

Λβ Physics Motivation

~55,000 unpolarized decays

+

Standard Model Concepts

⇓

$A_\nu = 0.974 \pm 0.004$

~1,700 polarized decays

$A_\nu = 0.821 \pm 0.060$

35,000 Events with 40% pol.

$A_\nu = ?? \pm 0.02$

$V_{us}(K_{\ell 3}) = V_{us}(B_{\ell 3})$?

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$?

Note: $|V_{ub}|^2 \sim 10^{-5}$

Source	V_{us} Value	Unitarity $V^U_{ud} = (1 - \lvert V_{us}\rvert^2)^{1/2}$
K_{e3}	0.2196(23)	0.9756(5)
K_{e3} and $K_{\mu 3}$	0.2188(16)	0.9758(3.5)
B_{e3} ($\Delta f_1 = 0$)	0.2258(27)	0.9742(6)
B_{e3} ($\Delta f_1 > 0$)	0.2176(26)	0.9760(5)
B_{e3} ($1/N_c$, $\Delta f_1 > 0$)	0.2194(23)	0.9756(5)
		Measured V_{ud}
Nuclear ft Values	—	0.9740(5) (10)
New Neutron Decay	—	0.9728(12)
PDG 2000 Average	—	0.9735(8)

Conclusions 2000

- Results for the "last" hyperon beta decay: $\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}$.
- Sign of g_1/f_1 in $\Sigma^- \rightarrow n e^- \bar{\nu}$ conclusively established.
- Consistent data for $\Sigma^- \rightarrow n e^- \bar{\nu}$ and $\Lambda \rightarrow p e^- \bar{\nu}$.
- New V_{ud} value from $n \rightarrow p e^- \bar{\nu}$.
- No flavor SU(3) breaking seen in g_1/f_1 measurements.

  $F+D = 1.2670 \pm 0.0035$ $\quad F = 0.4635 \pm 0.0087$

  $F-D = -0.3400 \pm 0.0170$ $\quad D = 0.8035 \pm 0.0087$

  $F/D = 0.569$
- $V_{us} = 0.2196 \pm 0.0023$ from Ke3 analysis unchanged.
- Measurements with polarized hyperons are still desirable.
  - Neutrino asymmetry (α_ν) in $\Lambda \rightarrow p e^- \bar{\nu}$. ← KTeV
  - Charge Symmetry in $\Sigma^\pm \rightarrow \Lambda e^\pm \nu$ (Cabibbo).
  - More precise $\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}$ for SU(3) breaking. ← NA48'
  - More precise $\Xi^- \rightarrow \Lambda e^- \bar{\nu}$ and $\Sigma^- \rightarrow \Lambda e^- \bar{\nu}$.
- Bread and butter: verify/improve lifetimes and masses.
- More precise V_{us} from $\Sigma^- \rightarrow n e^- \bar{\nu}$ and $\Lambda \rightarrow p e^- \bar{\nu}$?

EXP. Conductions.

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50th Anniversary of Fermi Theory

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