Hyperon Semi-Leptonic Decays

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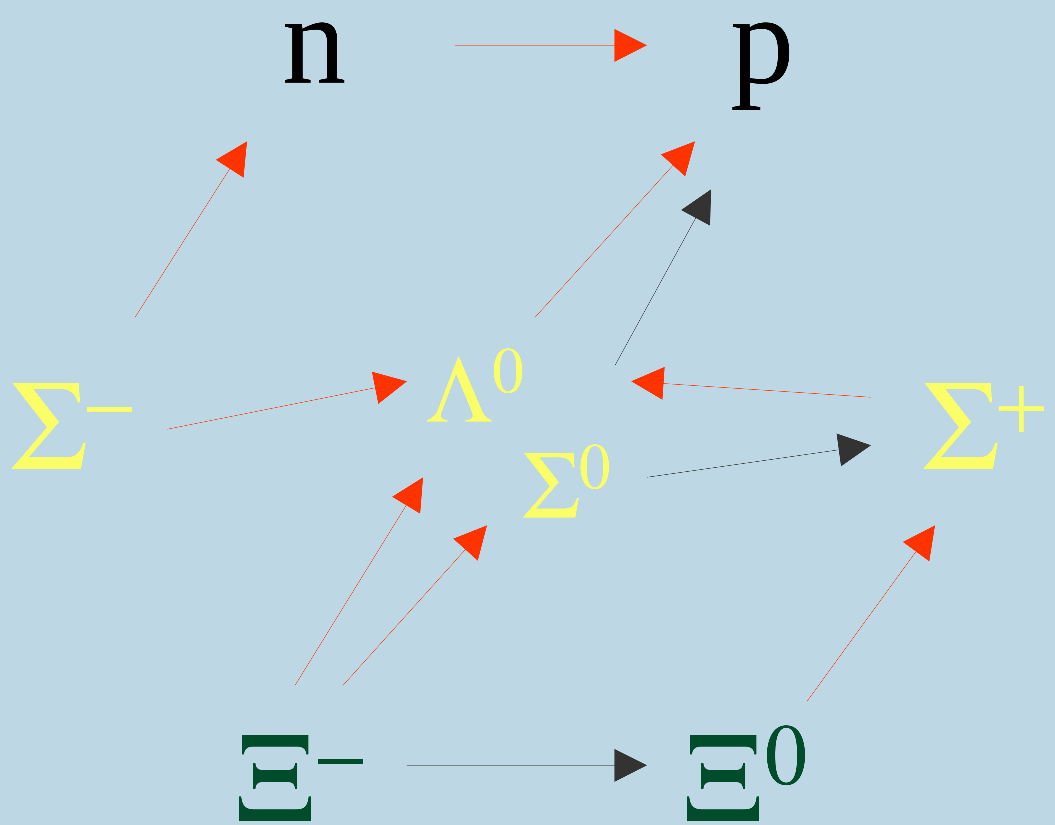
Outline

- HSD’s in Cabibbo Model.
- Precision Measurements of Lambda Beta Decay.
- Negative Sigma Beta Decay, FNAL(E715).
- CERN(WA2) results: A Cabibbo fit.
- Status of V_{us} in HSD Cabibbo fits.
- Neutral Cascade Beta Decay, KTEV.
- Conclusion.

Hyperon Semi-Leptonic Decays

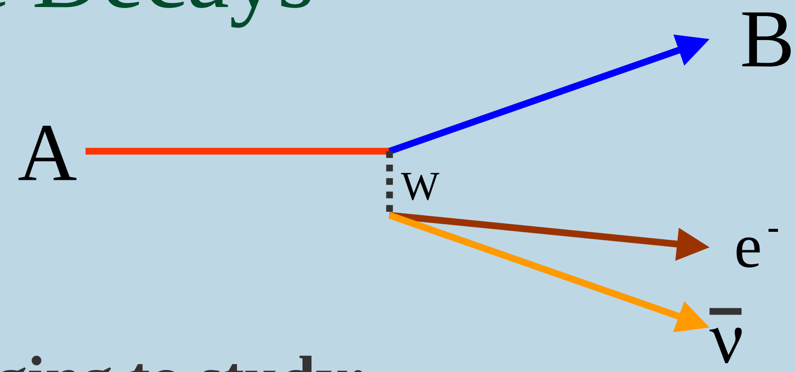
- **Cabibbo Model explains HSD based on flavor SU(3) symmetry.**
- **Three free parameters θ_c, F and D in the model.**
- **Excellent prediction power.**
- **Experimental data are in good agreement with the model.**
- **SU(3) is a not a perfect symmetry and the symmetry breaking effects are expected to be seen in HSD.**
- **Several models try to explain the deviations from the experiment with various symmetry breaking mechanisms.**

Allowed Baryon Beta Decays



Hyperon Semi-Leptonic Decays

$$A \rightarrow B \; e^{-} \; \overline{\nu}_e$$



HSD's are experimentally challenging to study:

•High flux polarized hyperon beams are needed for precision experiments.

•Small Branching Ratios (10^{-3} - 10^{-5}), hence limited statistics.

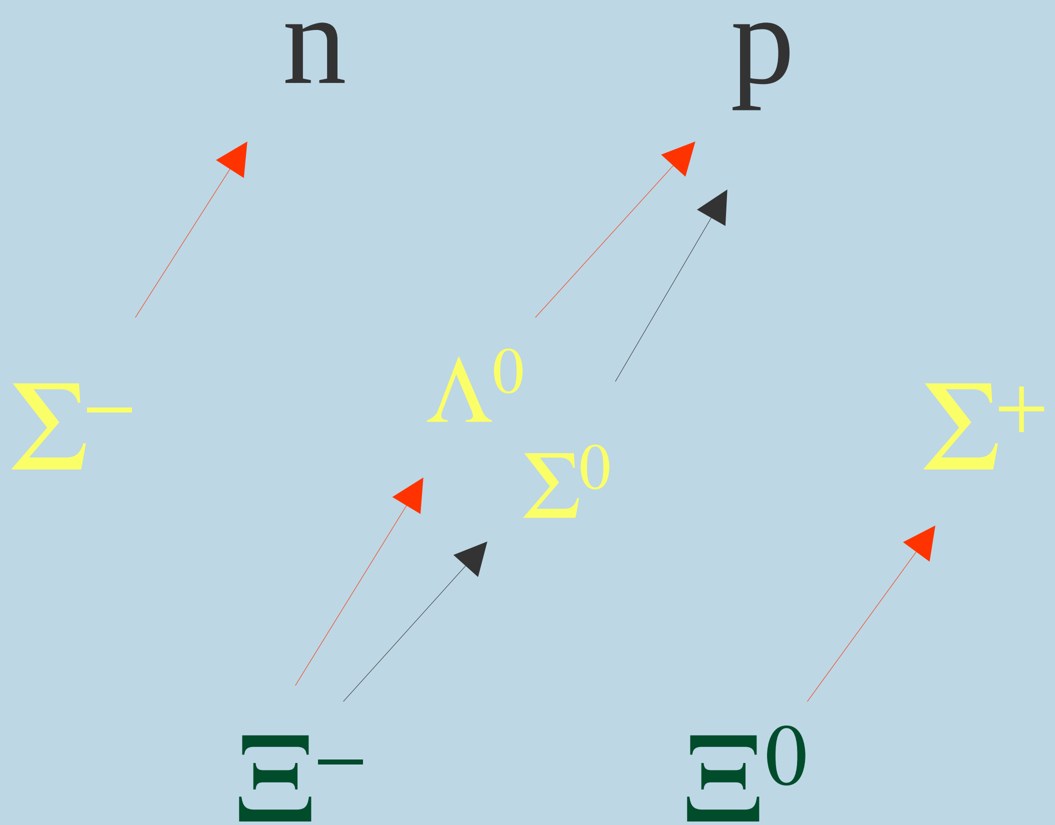
•High Background level, especially the dominant two-body decay exists for some HSD's:

$$A \rightarrow B\pi^{-}$$

Hyperon Semi-Leptonic Decay Rates

Decay	BR	Events	two-body
$\Lambda \rightarrow p\bar{e}\,\nu$	$8.32\text{x}10^{-4}$	20 k	Y
$\Sigma^{-} \rightarrow n e^{-}\nu$	$1.02\text{x}10^{-3}$	4.1 k	Y
$\Sigma^{-} \rightarrow \Lambda e^{-}\nu$	$5.73\text{x}10^{-5}$	1.8 k	N
$\Sigma^{+} \rightarrow \Lambda e^{+}\nu$	$2.0\text{x}10^{-5}$	21	N
$\Xi^{-} \rightarrow \Lambda e^{-}\nu$	$5.63\text{x}10^{-4}$	2868	N
$\Xi^{-} \rightarrow \Sigma^{0} e^{-}\nu$	$8.7\text{x}10^{-5}$	154	N
$\Xi^{0} \rightarrow \Sigma^{+} e^{-}\nu$	$2.71\text{x}10^{-4}$	176	N
$\Xi^{-} \rightarrow \Xi^{0} e^{-}\nu$	$<2.3\text{x}10^{-3}$	0	N

Allowed Hyperon Muonic Decays



Hyperon Muonic Decays

Decay	Branching Ratio	Events
$\Sigma^- \rightarrow n\mu^-\nu$	$4.5\text{x}10^{-4}$	174
$\Lambda \rightarrow p\mu^-\nu$	$5.17\text{x}10^{-4}$	28
$\Xi^- \rightarrow \Lambda\mu^-\nu$	$3.5\text{x}10^{-4}$	1

Semi-Leptonic Decay of Baryons

$A(p_A) \rightarrow B(p_B) + l + \nu \quad , \quad q = p_A - p_B$

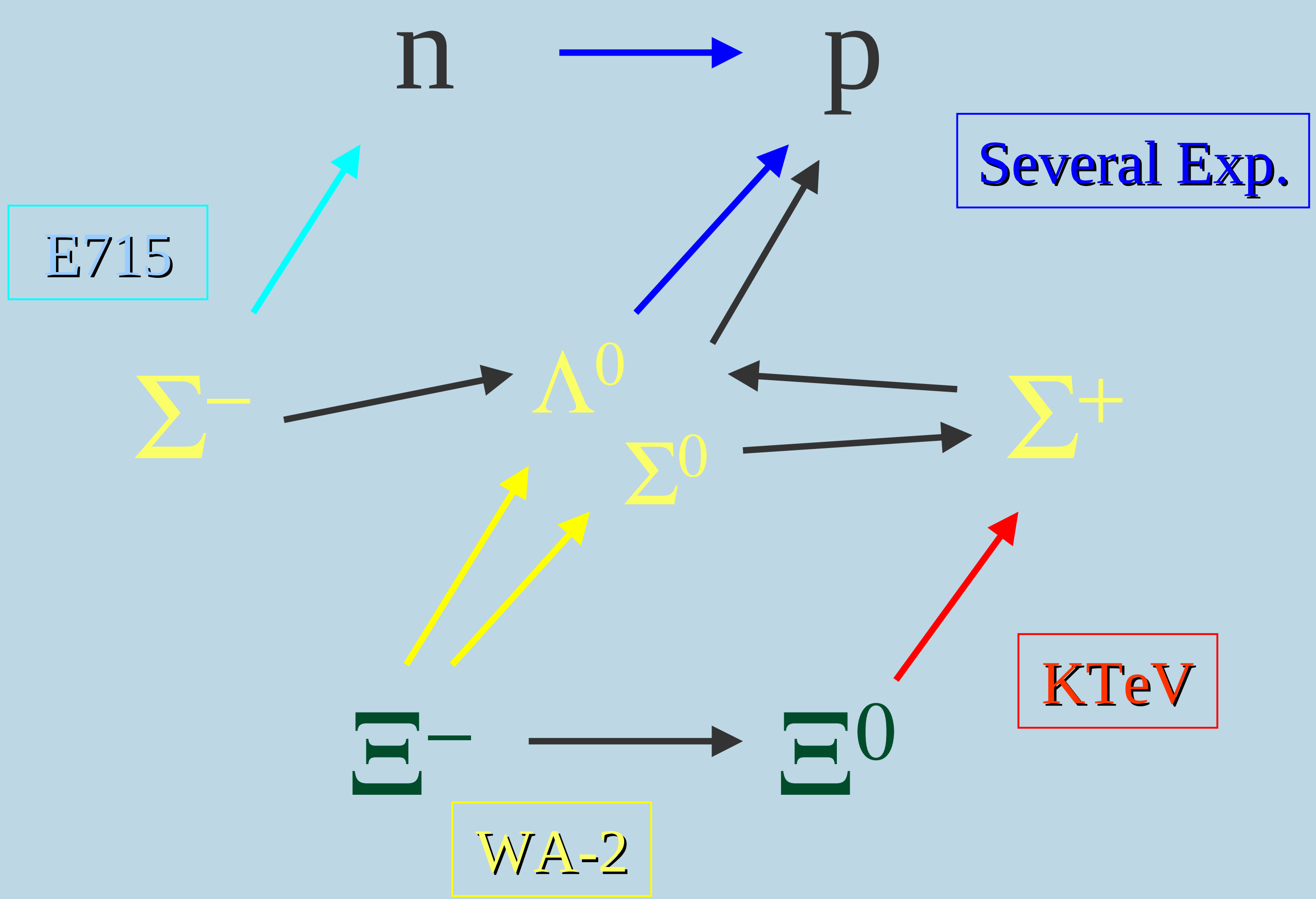
$\underline{M} = 2^{1/2}\, G \langle B|\, J^\mu \,| A\rangle\, u_l(\bar{p}_l)\, \gamma_\mu(1+\gamma_5)\, v_\nu(p_\nu)$

$$\langle B |\; J^\mu \,| A\rangle = \bar{u}_B \,\{ f_1(q^2)\gamma^\mu + i\frac{f_2(q^2)}{M}\sigma^{\mu\nu} q_\nu + \frac{f_3(q^2)}{M} q^\mu$$

$$g_1(q^2)\gamma^\mu\gamma_5 + i\,\frac{g_2(q^2)}{M}\sigma^{\mu\nu}\gamma_5 q_\nu + \frac{g_3(q^2)}{M}\gamma_5 q^\mu \,\}\, u_A$$

- All 6 form factors are real, assuming time reversal invariance.
- f_1 and f_2 can be fixed through the CVC hypothesis.
- $g_2 = 0$ in the SM (no second class currents).
- f_3 and g_3 are suppressed by the mass of the lepton and can be neglected in the case of electrons.
- q^2 dependence of f_1 and g_1 may need be to be considered.

Beta Decay Form-factors



Hyperon Beta Form Factors

Decay	scale	f_1	g_1
$n \rightarrow p e \nu$	V_{ud}	1	D+F
$\Lambda \rightarrow p e^- \nu$	V_{us}	$-\sqrt{3/2}$	$-\sqrt{1/6}$ (D+3F)
$\Sigma^- \rightarrow n e^- \nu$	V_{us}	-1	D-F
$\Sigma^- \rightarrow \Lambda e^- \nu$	V_{ud}	0	$\sqrt{2/3}$ D
$\Sigma^+ \rightarrow \Lambda e^+ \nu$	V_{ud}	0	$\sqrt{2/3}$ D
$\Xi^- \rightarrow \Lambda e^- \nu$	V_{us}	$\sqrt{3/2}$	$-\sqrt{1/6}$ (D-3F)
$\Xi^- \rightarrow \Xi^0 e^- \nu$	V_{ud}	-1	D-F
$\Xi^0 \rightarrow \Sigma^+ e^- \nu$	V_{us}	1	D+F
$\Xi^- \rightarrow \Sigma^0 e^- \nu$	V_{us}	$\sqrt{1/2}$	$\sqrt{1/2}$(D+F)

Hyperon Semi-Leptonic Decays

Form factors can be extracted from integrated observables:

- **Total decay rate (or Branching Ratio).**
- **e-ν angular correlation in the CM of decaying baryon.**
- **Polarization of the decay baryon in its own CM for unpolarized beam.**
- **Asymmetry parameters of the decay products (e, ν and decay baryon) for polarized beam.**

$\Lambda \rightarrow p + e^- + \bar{\nu}_e$

- The first and well studied hyperon beta decay.
- Can be produced with high statistics.
- Good place to search for second-class currents.

Early tests of the Cabibbo Model with polarized Lambda's:

Althoff, et. al. (CERN) 1972 — $\left|\frac{g_1}{f_1}\right| = 0.64 \pm 0.6$ Measuring ν correlation coef.

Lindquist, et. al. (ANL) 1977 — $\frac{g_1}{f_1} = 0.53^{+0.11}_{-0.09}$ Measuring all correlation coef. as well as e-ν correlation.

$\Lambda \rightarrow p + e^- + \bar{\nu}_e$

- **Precise studies of the decay with hyperon beams:**

Wise, et. al. (BNL)
1981

$$\left|\frac{g_1}{f_1}\right| = 0.734 \pm 0.031$$ **Measuring e-ν correlation.**

Bourquin, et. al. (CERN)
1983

$$\frac{g_1}{f_1} = 0.70 \pm 0.03$$ **from** $\Xi^- \rightarrow \Lambda \pi^-$

Dworkin, et. al. (FNAL)
1990

$$\frac{g_1}{f_1} = 0.731 \pm 0.013$$ **Measuring e-ν correlation.**

- **Excellent agreement with Cabibbo prediction.**

$\Sigma^- \rightarrow n + e^- + \bar{\nu}_e$ **An important test of Cabibbo Model**

- The only beta decay for which Cabibbo Model predicts a negative g_1 / f_1 .

- Fits on beta decay data predict a large negative value of electron asymmetry $\alpha_e = -0.51 \pm 0.04$

- Previous Σ^- polarized experiments failed to confirm this test.

- WA2 (CERN) group favored the negative sign from the shape of the electron spectrum.

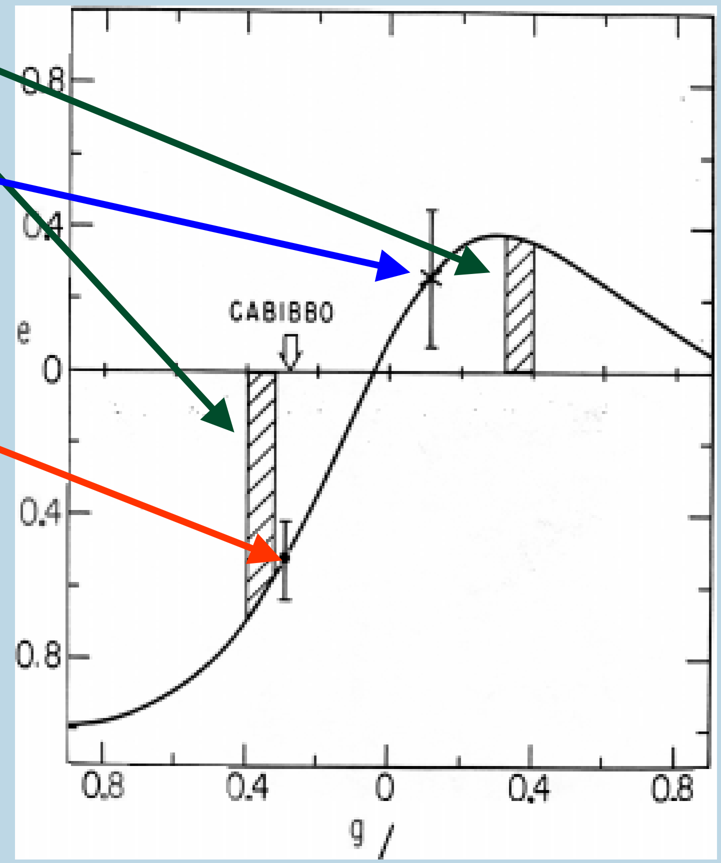
- E715 (FNAL) measurement collected about 50k events of this decay with a high flux polarized beam from the Tevatron.

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

Previous Σ^- unpolarized experiments

Previous Σ^- polarized experiments

E715 (FNAL) measurement



$\alpha_e = -0.519 \pm 0.102$

$g_1 / f_1 = -0.328 \pm 0.019$

CERN (WA2) Experiment

- **A magnetic channel selected 100 GeV/c negative particles produced in the forward direction by 200 GeV/c protons on BeO.**

- **A DISC Cerenkov counter identified Σ^- and Ξ^- concurrently.**

- **Measured BR and form factors for beta decays of Σ^-, Ξ^- and Λ :**

$$\Lambda \rightarrow p e^- \nu$$

$$\Sigma^- \rightarrow n e^- \nu$$

$$\Sigma^- \rightarrow \Lambda e^- \nu$$

$$\Xi^- \rightarrow \Lambda e^- \nu$$

$$\Xi^- \rightarrow \Sigma^0 e^- \nu$$

CERN (WA2) Experiment

- **Cabibbo fits on these measurements results in:**

F = 0.477$\pm$0.012, D = 0.756$\pm$0.011

and $\sin\theta_C$ = 0.231$\pm$0.003 (Bourquin et.al. 1983)

- **Excellent fit with all measurements from a single experiment, within the error bars.**

- **Still a good fit when they added the n lifetime measurements.**

- **However, the measured Cabibbo angle disagrees with the K sector:**

$$\mathrm{Sin}\,\theta_C = 0.2196 \pm 0.0023 \quad \text{(PDG98)}$$

CERN (WA2) Experiment: Cabibbo angle controversy

- Some recent attempts incorporate second order SU(3) breaking corrections to WA2 data which gives more consistent values of $|V_{us}|$ with the Kaon sector. (A. Garcia's talk)

- PDG chooses not to use the hyperon values of $|V_{us}|$.

- How reliable the experimental values are?

Physics Motivation For Cascade Beta Decay

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

- ☯ SU(3) copy of $n \rightarrow p e \nu_e$ (ddu $\rightarrow$ duu)

- ☯ Another test of Cabibbo Model.
- ☯ Any flavor SU(3) symmetry breaking indications?

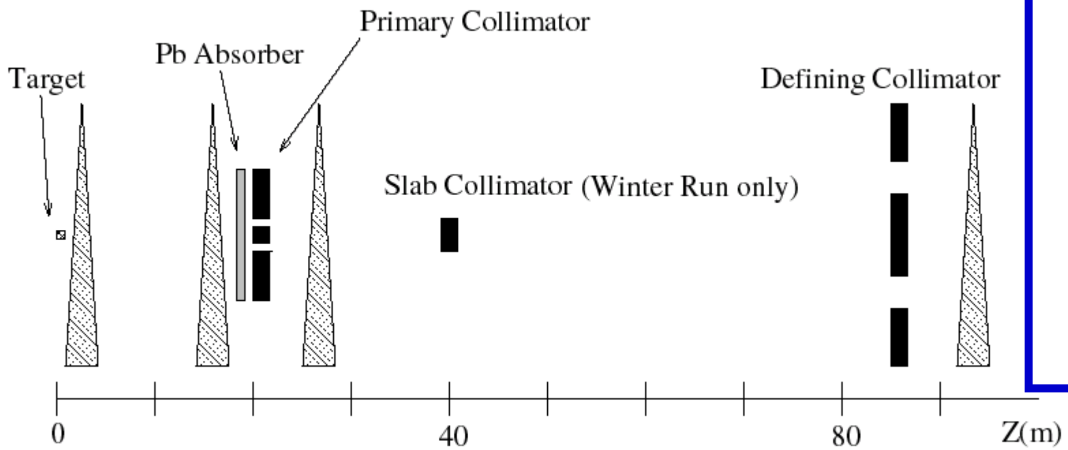
- ☯ Large V&A form factor amplitudes.

- ☯ ~ 100% equivalent polarized Ξ^0 beam .

- ☯ No competing two body decay with the same final state baryon

  ($\Xi^0 \not\rightarrow \Sigma^+ \pi^-$)

Unique possibility to probe this kind of decay at KTeV



KTeV Detector

KTeV Beam

Proton Beam Energy: 800 GeV

Proton Intensity: 3.0-5.0E12

Vertical Targeting Angle -4.8 mrad

Horizontal Targeting Angle <0.02mrad

Beam Size (winter) 0.5mrad x 0.5mrad
(summer) 0.7mrad x 0.7mrad

Target: BeO (30.5 cm long)

4 Sweeping Magnets and

3 Collimators define

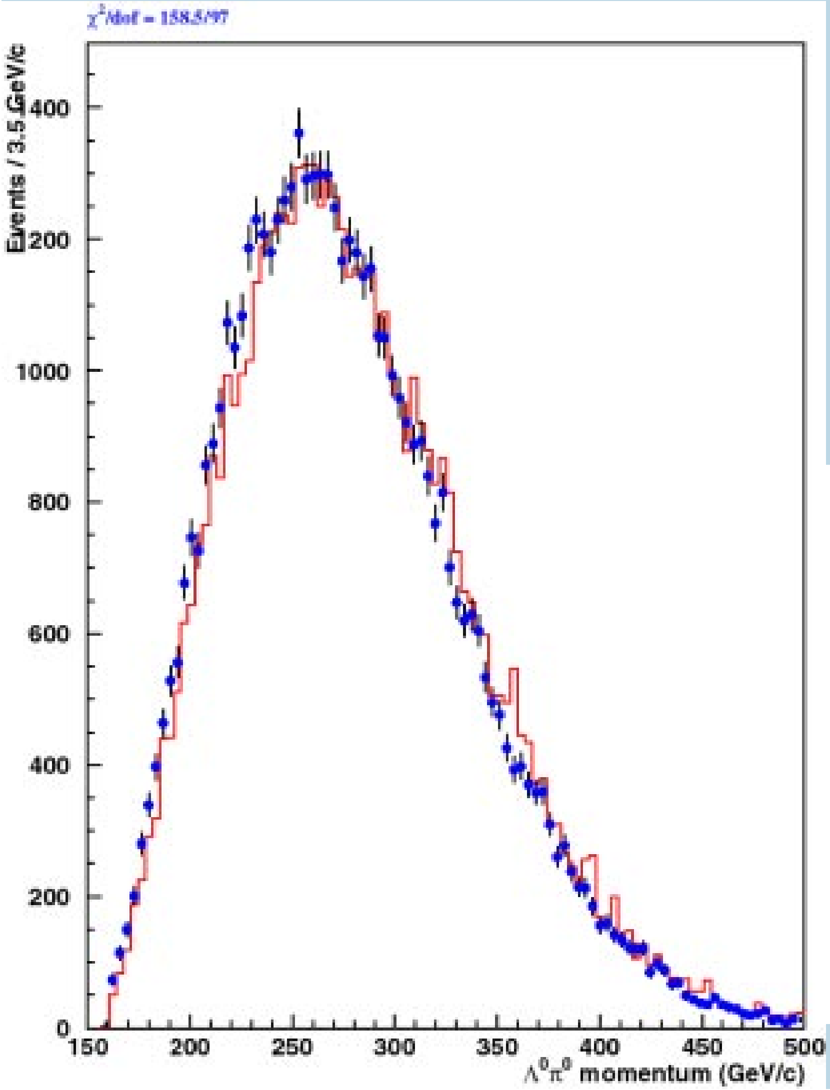
two parallel neutral beams.

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

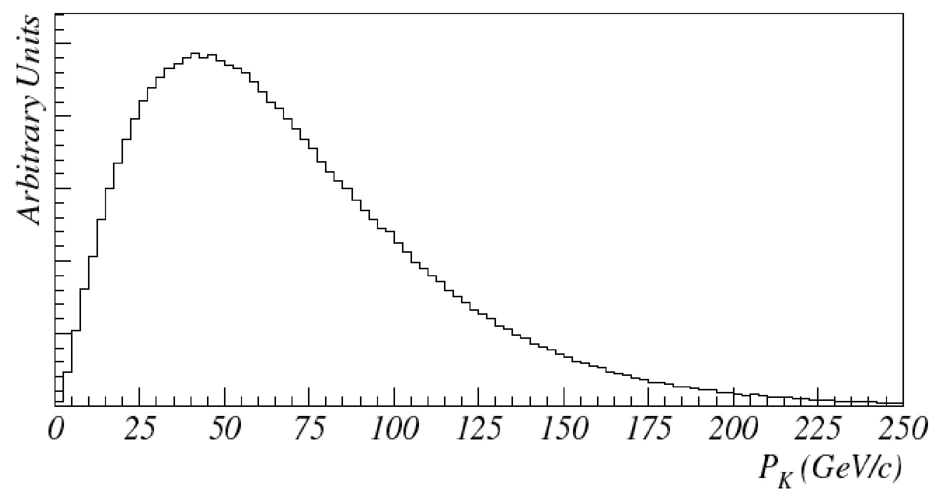
Mean Lifetime ($c\tau$) of the Neutral Particles at KTeV:

K_L	15.5 m
K_S	2.7 cm
Λ	7.9 cm
Ξ^0	8.7 cm

Ξ^0 Momentum Spectrum



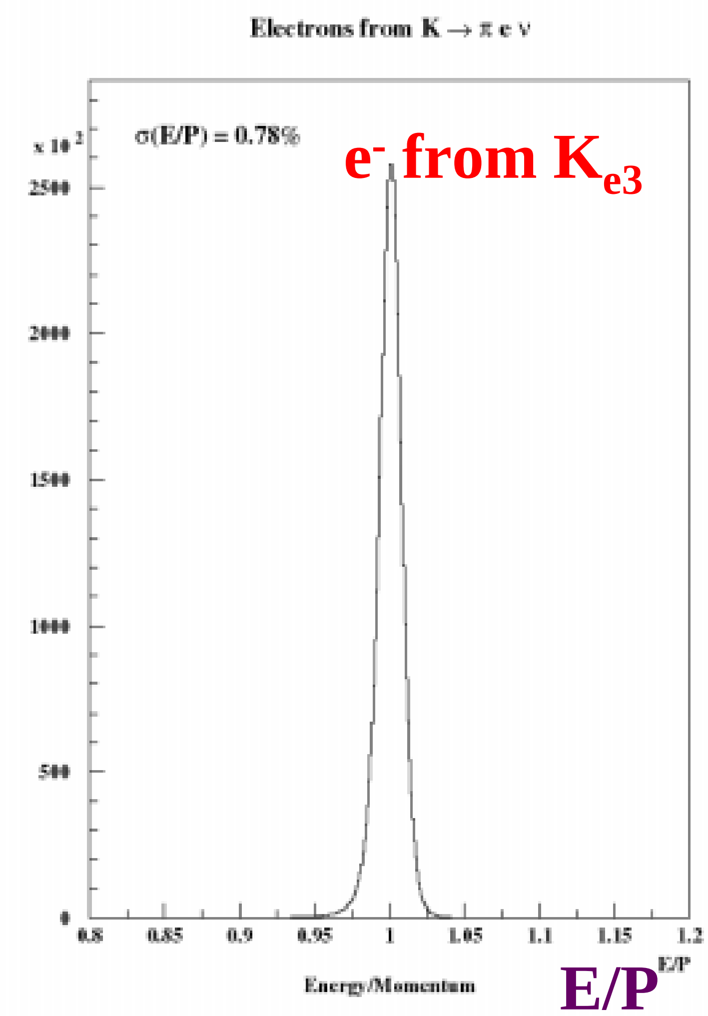
K_L Momentum Spectrum

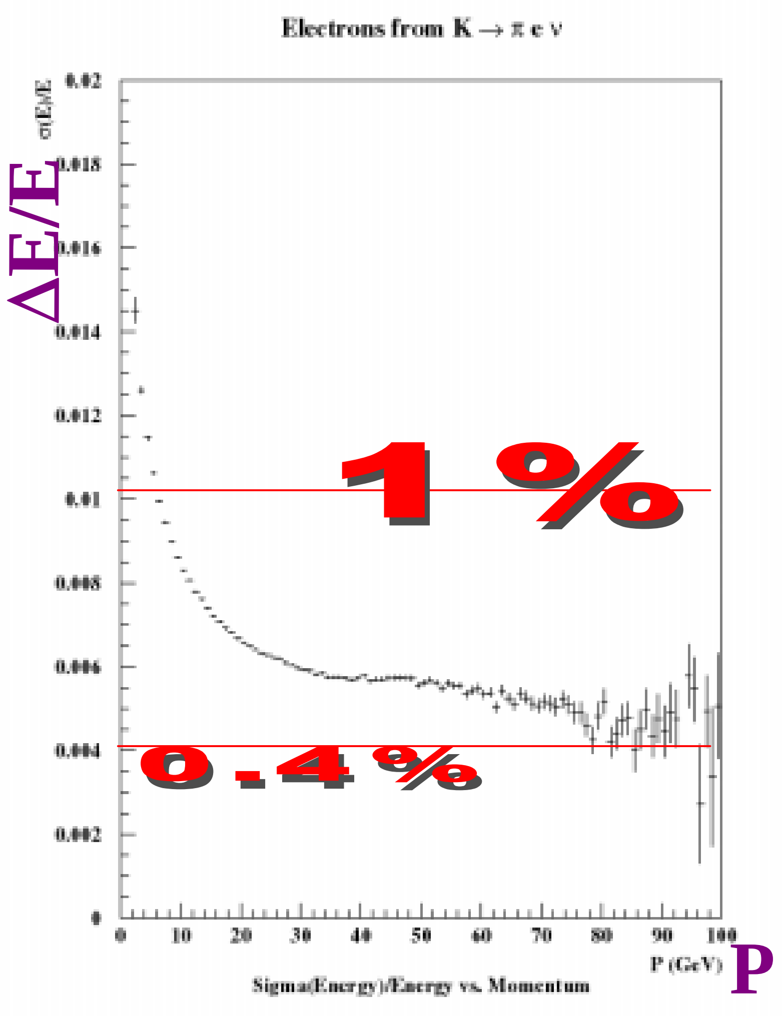


The CsI Electromagnetic Calorimeter

3100 blocks of pure CsI Crystals, 50 cm (~ 27 X_0) long.
2232 inner crystals size: 2.5x2.5 cm
and the 868 outer ones: 5.0x5.0 cm

Position resolution < 1mm
Energy resolution < 1%
for E > 5 GeV
electron/pion rejection of 500:1





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

$\quad\quad \hookrightarrow p + \pi^0$

Branching Ratio Measurement

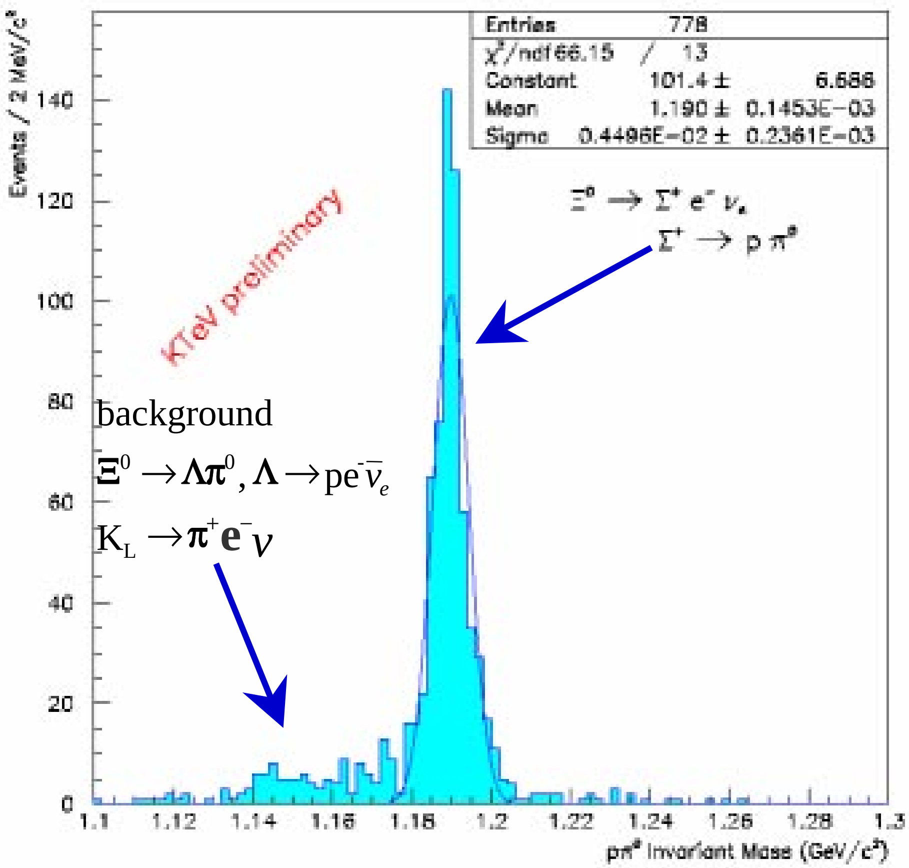
Signal = 626 ± 25 events

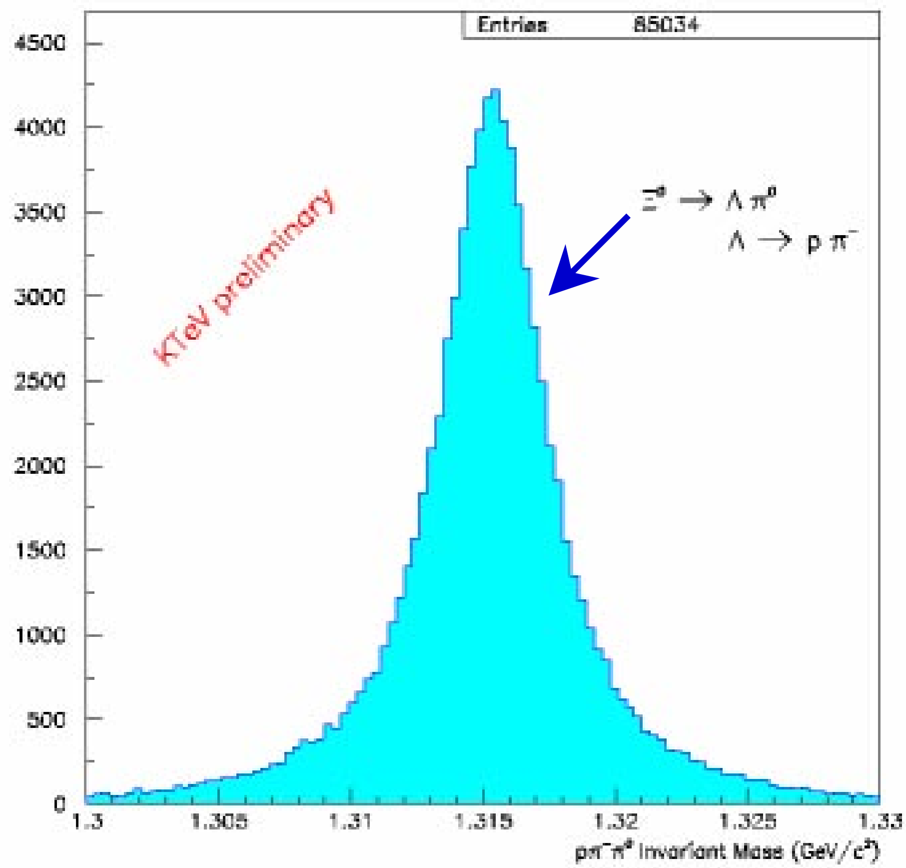
Background = 60 ± 8 events

B.R = (2.54 ± 0.11 ± 0.16) x 10^{-4}
Stat Sys

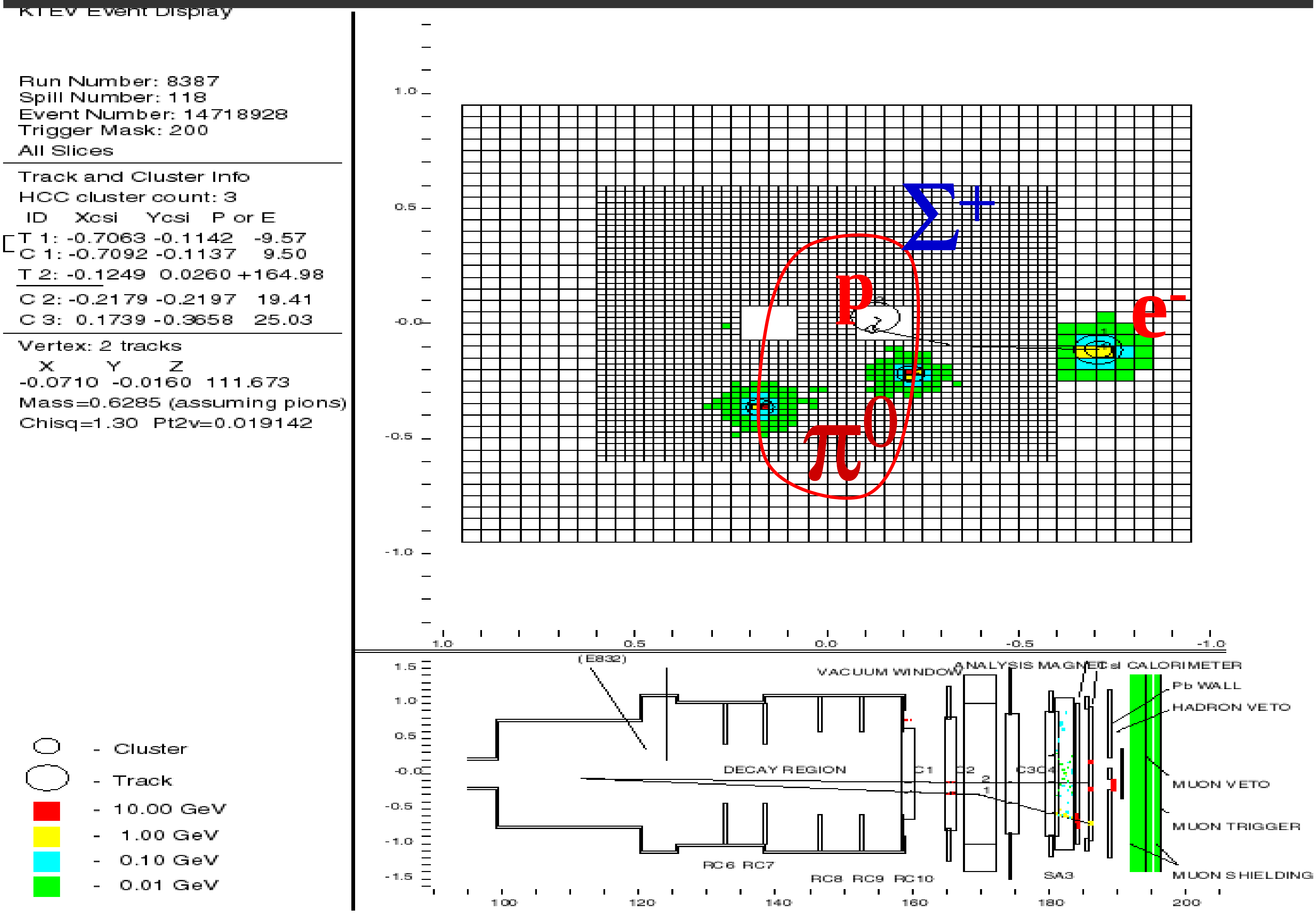
KTeV first measured B.R = (2.71 ± 0.22 ± 0.31) x 10^{-4}

Theoretical SU(3) predicted B.R = (2.61 ± 0.11) x 10^{-4}





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



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

KTeV measurements:

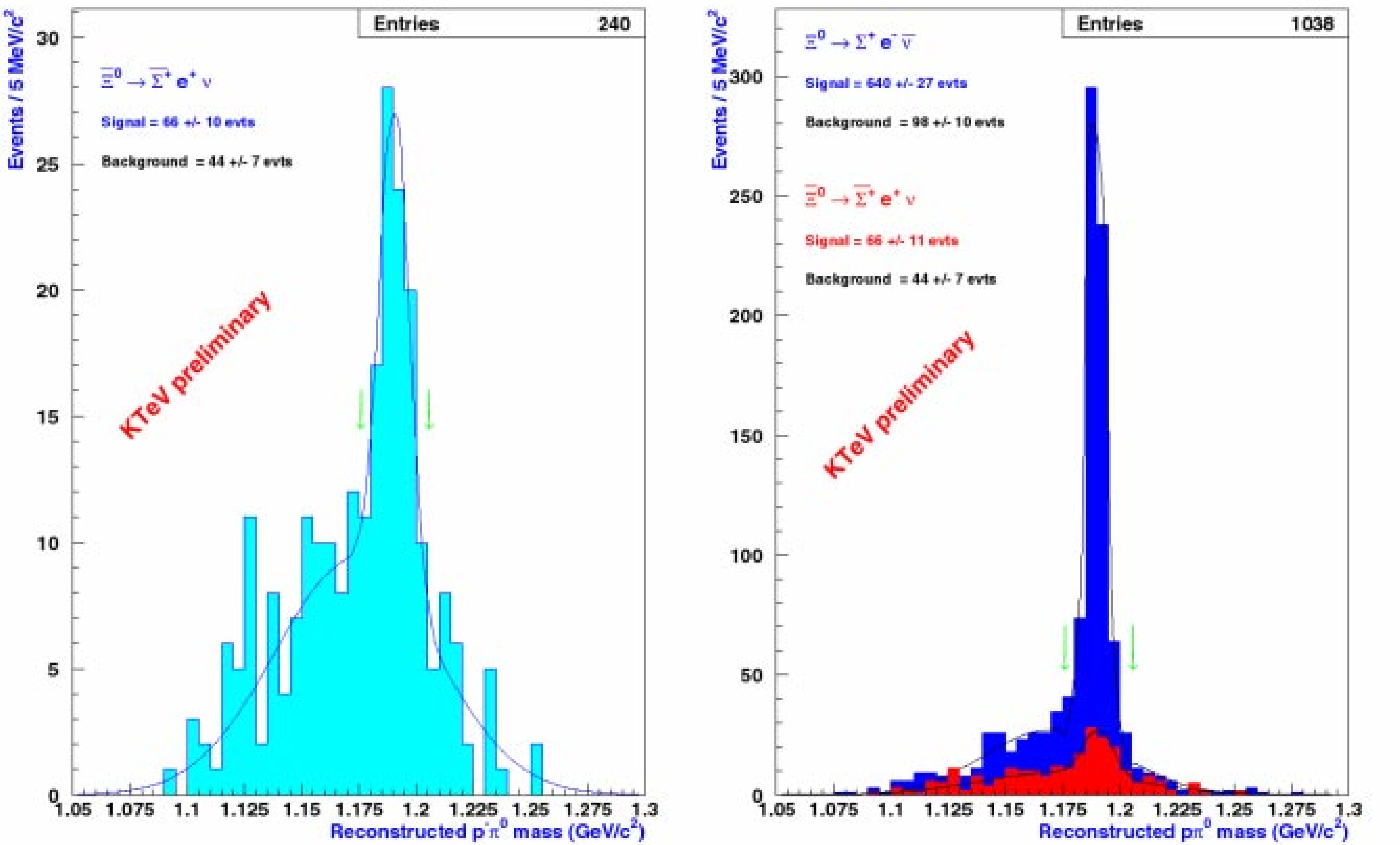
(DPF99) B.R = $(2.54 \pm 0.11 \pm 0.16) \times 10^{-4}$

(S. Bright's talk) $$\frac{g_1}{f_1} = 1.24^{+0.20}_{-0.17} \pm 0.07$$

$$\frac{f_2}{f_1} = 1.9 \pm 1.3 \pm 0.7$$

$$\frac{g_2}{f_1} = -1.4^{+2.2}_{-1.9} \pm 0.5$$

Anti- Cascade Beta Decay

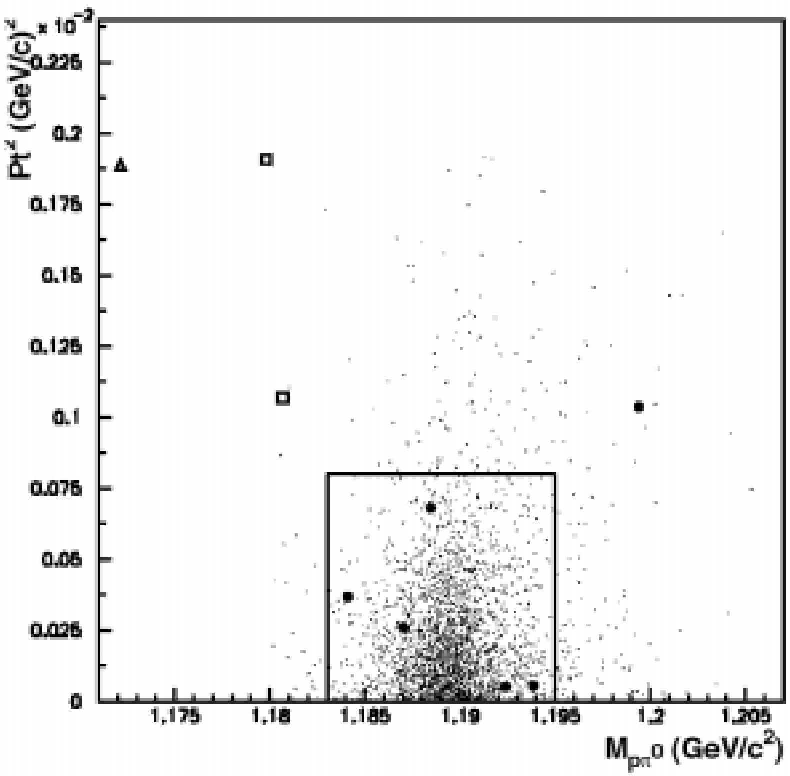


$\Xi^0 \rightarrow \Sigma^+ + \mu^- + \bar{\nu}_\mu$

$\quad\quad \hookrightarrow p + \pi^0$

Branching Ratio Measurement

- Five Candidate Events in the 90% cut box.
- $\Xi^0 \rightarrow \Sigma^+ + e^- + \bar{\nu}_e$ Used as the normalization mode.

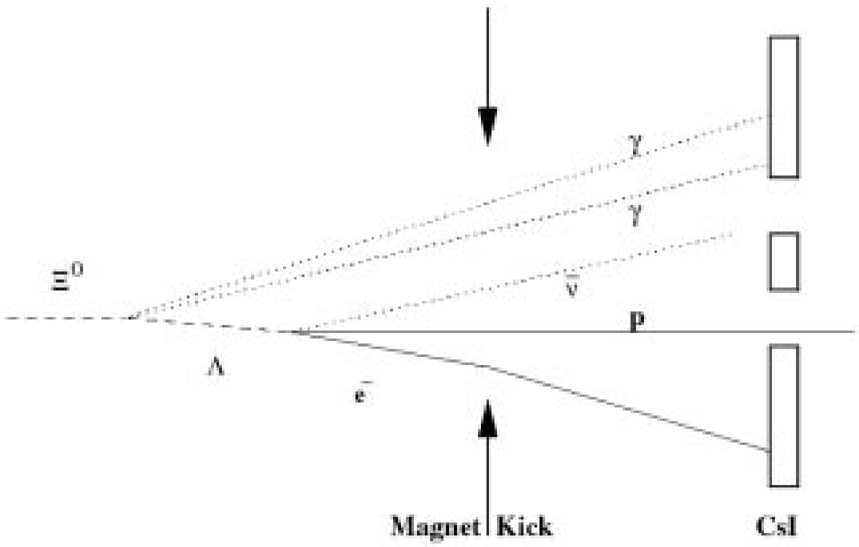


$$BR = (2.6 \begin{smallmatrix} +2.7 \\ -1.7 \end{smallmatrix} + 0.6) \times 10^{-6}$$

Stat Sys

Theoretical S(U3) Prediction:

2.3×10^{-6}



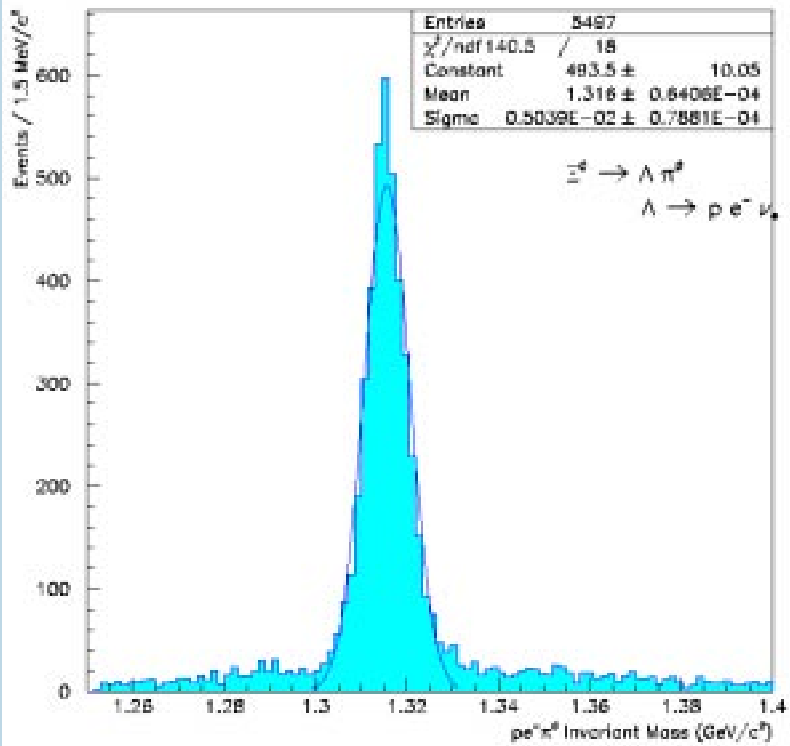
$$\Xi^0 \rightarrow \Lambda + \pi^0$$
$$\hookrightarrow p + e^- + \bar{\nu}_e$$

Same final state as Cascade Beta Decay, but a different decay topology.

4229 +/- 65 Events over about 11% background.

Can be used as the flux normalization mode

for Cascade Beta Decay.



Conclusions

- **36 years after its birth, the Cabibbo Model explains HSD successfully**

- **Small deviations from the theory should either be resolved by experiments or explained by theory.**

- **HSD is still an open field to search for SU(3) symmetry**
- **breaking effects and second-class currents.**

- **More precision measurements are needed.**