How Unitarity in the CKM Matrix of quark interactions was proven correct

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Intent of this talk is to inspire young scientists in particle physics that they can do new things in large experiments.

CKM Matrix of quark interactions:

Each element of the CKM matrix describes the weak-force interaction strength between those two types of quarks denoted in the subscripts.

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Unitarity means that the square-root of the sum of all the elements squared in any given row or column should be equal to 1:

$$\sqrt{(V_{ud}^2 + V_{us}^2 + V_{ub}^2)} = 1$$

If it was not 1 then this could have been explained as a unexpected origin of CP violation.

If it was more than 1 then probability theory of quantum interactions would have been violated

If less than 1 then some interactions might be suppressed or forbidden.

V_{us} in CKM matrix

- Historically the Value for V_{us} was from K_{l3} decays of old bubble chamber experiments, having an average of 0.2165 +/- 0.0004
- Tau lepton decays produced a larger V_{us} of 0.2216 +/- 0.0015
- Hyperon Decays could also measure V_{us} but at the time, circa 1996, it was not taken into the PDG average due to a concern they were not able to measure a fundamental weak force parameter due to the large strong force potential inside Baryons.

V_{us} in CKM matrix

Using 1996 values for:

$V_{ud} = 0.9749$

$V_{us} = 0.2165$

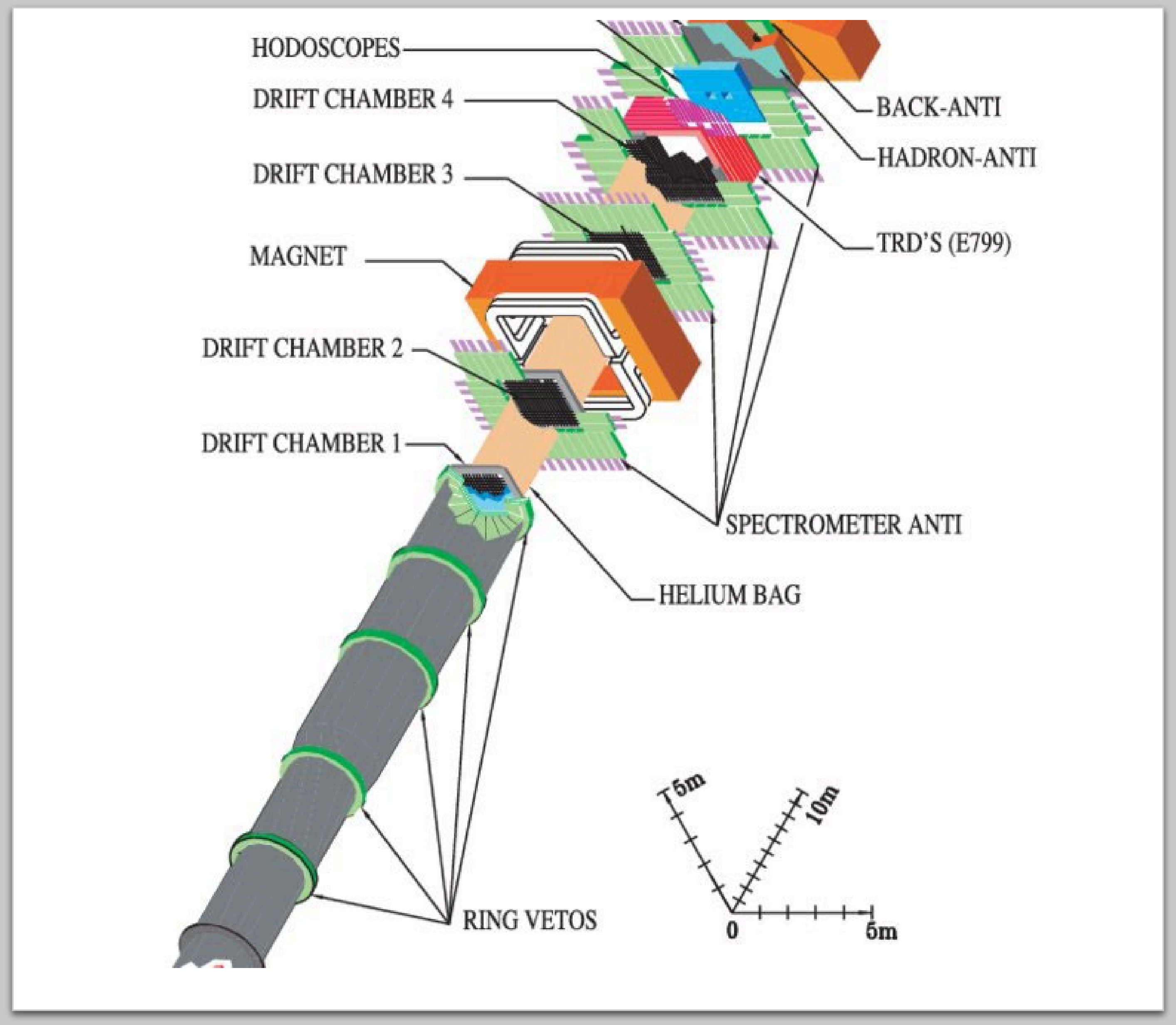
$V_{ub} = 0.0035$

Using: $\sqrt{(V_{ud}^2 + V_{us}^2 + V_{ub}^2)} = 0.9987 \pm 0.0004$

Which was <u>not</u> consistent with 1 and could have been a sign of new unexplained physics, or an unexplained origin of CP violation.

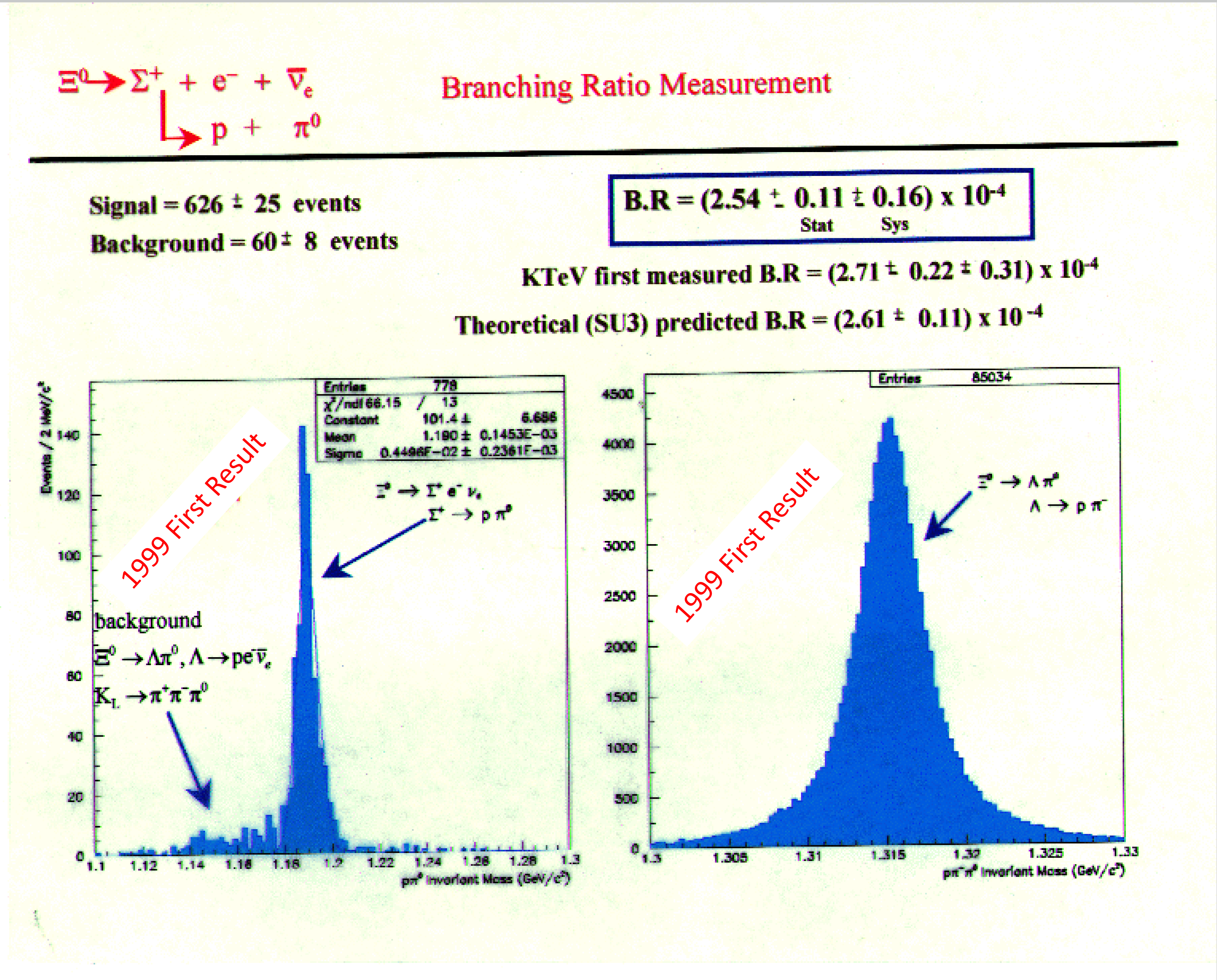
KTeV experiment

- Designed in 1992 as a neutral Kaon experiment.
- Lambda Hyperon Beta Decays were planned from the beginning.
- But in 1993 I was able to add another way to study new particle physics with a Ξ^0 Beta decay study into the experiment.



Ξ^0 Beta Decay

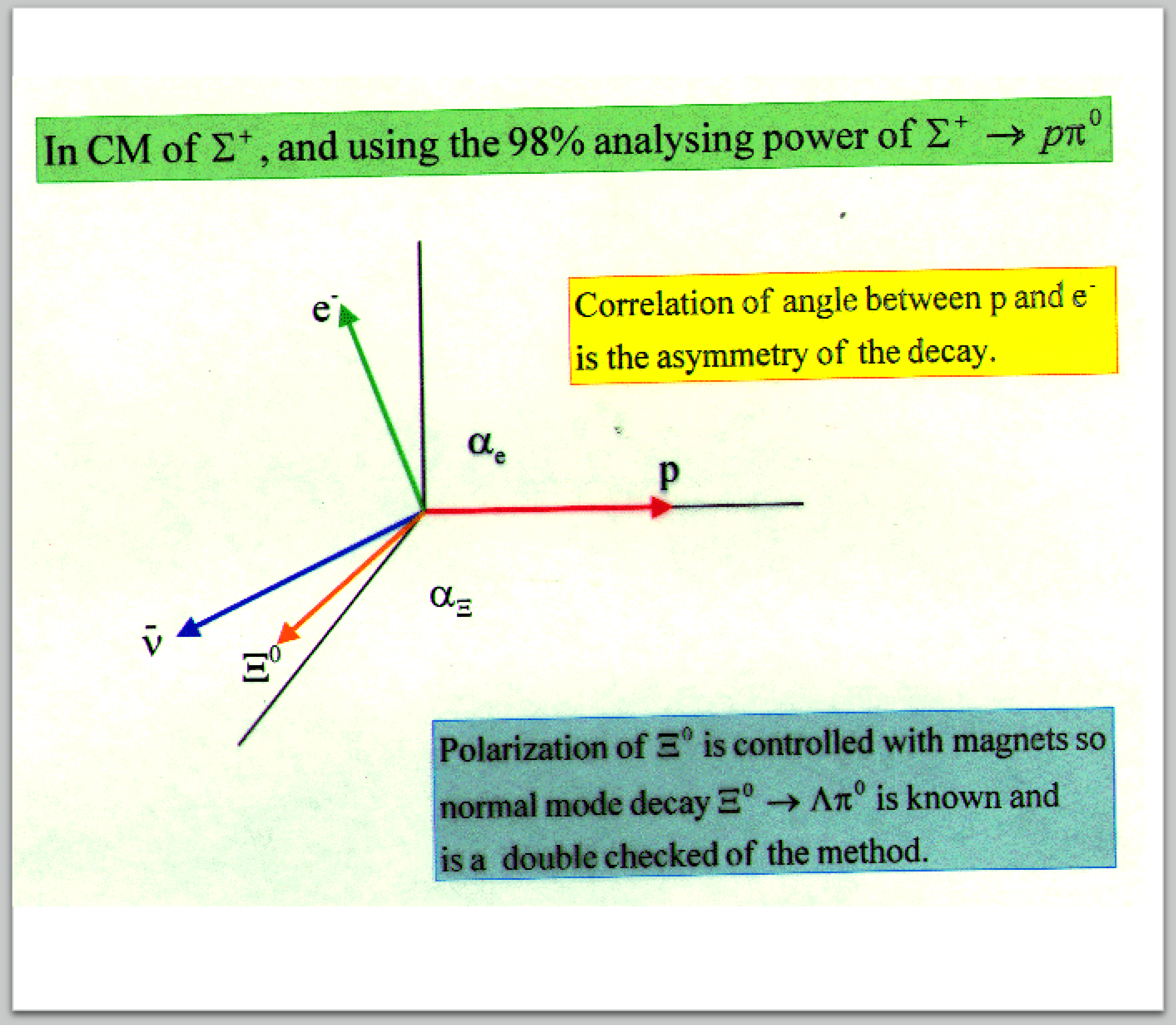
- This new Hyperon Beta Decay we were only able to collect ~600 events and it was next to and had little background under it.
- I even had to pay 3,600$ for 4 photo-tubes from my personal savings since we could not afford them from the tight KTeV budget for trigger paddle sensors.



Ref: N. Solomey et al., A proposal for Hyperon Physics at KTeV", Univ. of Chicago note EFI 93-25, April 1993.

Ξ^0 Beta Decay

- The importance of this Ξ^0 Hyperon Beta Decay is the 98% analyzing power of the Σ^+ secondary decay.

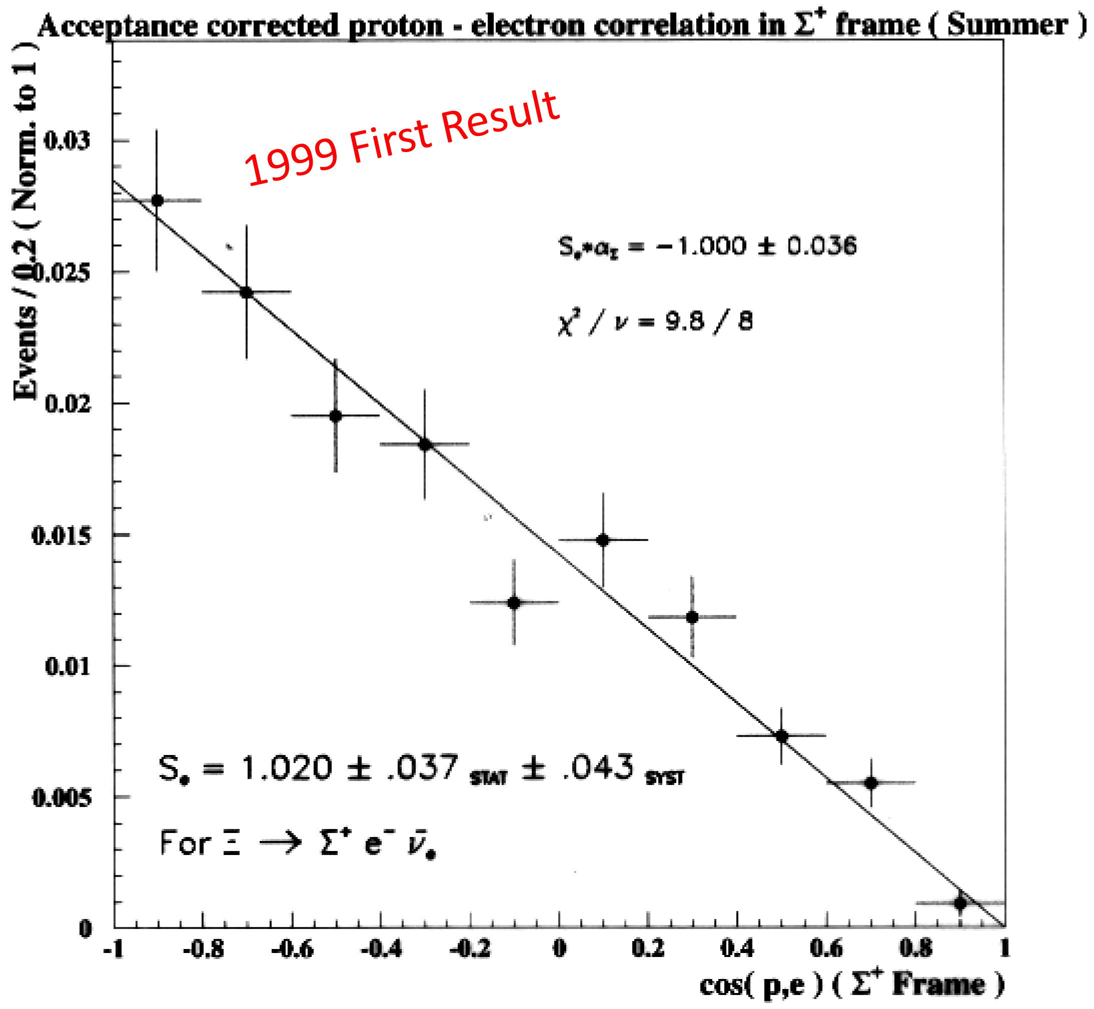


Ξ^0 Beta Decay

- This Hyperon Beta Decay results was clean and that made it even more powerful since it did not sit on top of a background of contamination.

Ref: A. Affolder et al., Observation of the decay Ξ^0 into Σ^+ e^- ν, Phys. Rev Letters, V82, #3751 (1999).

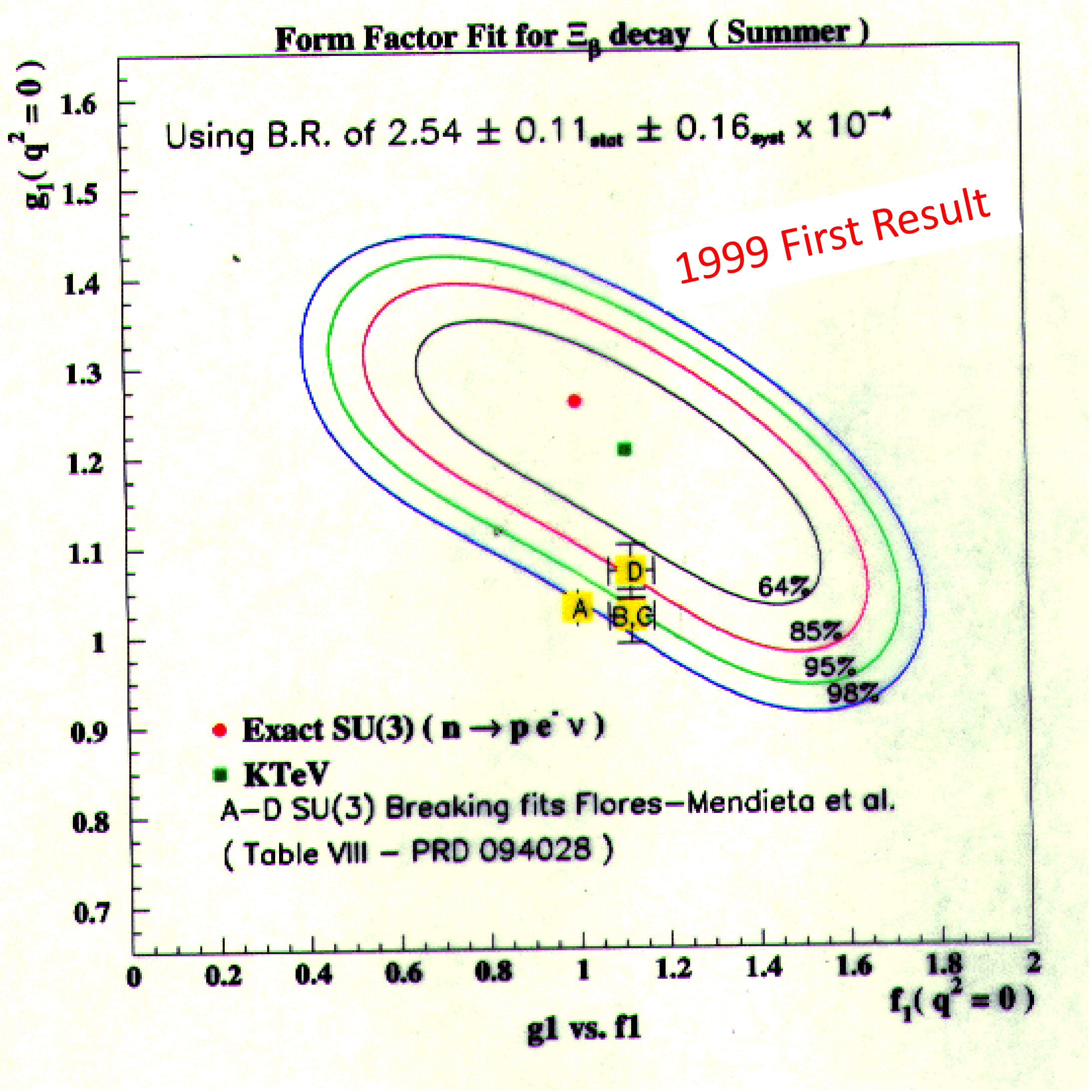
Ref: A. Alanvi-Harait et al., First Measurement of form factors of the decay Ξ^0 into Σ^+ e^- ν, Phys. Rev Letters, V87, #13 (2001).



Ξ^0 Beta Decay

- This Hyperon Beta Decay result allow us to measure a Branching ratio and form factors as shown by green square which is very different than previous V_{us} measurements of A-D fits by Flores-Mendieta PRD094028.
- It implied a new value of V_{us} of 0.2240 +/- 0.0015, this was the first rough number presented in the Summer of 1999 at Kaon-99.

Ref: N. Solomey, Recent Results in Weak Hyperon Decays, Chapter 44 of Kaon Physics, edited by J. Rosner and B. Winstein, University of Chicago Press 2001, presented at Kaon 1999 conference, Chicago.



Ξ^0 Beta Decay

Criticisms:

- At the time of this 1999 conference presentation and subsequent refereed publication review doubt was raised:
  1. How could a complex Baryon be able to measure a fundamental weak interaction parameter, would not the strong force distort weak interaction strengths.
  2. The old V_{us} result was from K+ decay of a bubble chamber and had to be correct due to full tracking, was the claim.

Endorsements:

- Others like theoretical physicist Prof. Sandip Pakvasa of Univ. of Hawaii though it should be fundamental like his prediction for CP violation in Hyperons.
- Prof. Julie Thompson of Univ. of Pittsburgh, quoted this Ξ^0 Hyperon beta decay result for one of the reasons to preform her K^+ BNL E865 experiment to verify or refute it.

Ξ^0 Beta Decay new V_{us} verified:

A Refined Study:

- Using these new KTeV Hyperon Ξ^0 Beta Decay Results:
  - N. Cabibbo was able to refine V_{us} better than my first presentation and publication:
  - Getting $V_{us} = 0.2250 +/- 0.0047$

Ref: N. Cabibbo et al., Phys. Rev. Lett. 92, 251803 (2004).

Confirmation:

- Two other experimental confirmations were made:

➢ BNL E865 K^+ into $\pi^0 e^+ \nu$ Branching Ratio was 6% higher than expected giving Vus consistent with Unitarity, see A. Sher et al., Phys Rev. D 66, 1 (2002).

➢ KTeV E832 K^0 decays: T. Alexopoulis et al., Phys. Rev. D70:092006 (2004).

Using the new value for V_{us} in CKM matrix

with:

$V_{ud} = 0.9749$
$V_{us} = 0.2245$
$V_{ub} = 0.0035$

Using: $\sqrt{(V_{ud}^2 + V_{us}^2 + V_{ub}^2)} = 1.0002 \pm 0.0002$

Which was consistent with 1 and significantly so, as to prove Unitarity in the CKM matrix of quark interactions

Today Unitarity in the CKM Matrix is important

- It is a guide for the neutrino oscillation matrix, which is more complicated than the quark CKM matrix.
- Using what we learned in quark-quark weak interaction in the CKM matrix and applying it to the neutrino matrix as a guide this allowed an improved understanding of neutrino oscillation.
- This use of the CKM matrix to help understand neutrinos is important for many aspects of future science such as:
  - Searches for CP violation in neutrinos
  - Neutrino and anti-Neutrino comparisons

Conclusion:

- By adding a small additional study to a larger experiment this allowed me to do a new Ξ^0 beta decay study.
- It used only ~625 reconstructed Ξ^0 Hyperon beta decay events.
- However, the 98% analyzing power of the Σ^+ decay into $p^+ \pi^0$ made it more powerful than 100,000 Λ^0 beta decay events which had only 60% analyzing power.
- We were the first to see a change in the value of V_{us} and brought the CKM matrix into Unitarity in 1999, but not confirmed until 2002 by BNL E865 experiment and reconfirmed by KTeV E832 K^0 decays in 2004!

I hope this provides inspiration and determination to the new younger generation of physicists, even if you are working in a large experiment, it is still possible to introduce new ideas and do something fantastically unexpected and important, so your curiosity should be your inspiration and guide!