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$K^+ \to \pi^0 e^+ \nu$ Branching Ratio from E865

A.A. Poblaguev for E865 Collaboration

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A. Sher et al., Phys. Rev. Lett. **91***, 261802 (2003)*

A. Sher, Ph.D thesis, University of Pittsburgh (2002)
http://scipp.ucsc.edu/˜sasha/thesis/th_ke3.ps

$K^+ \to e^+\nu_e\pi^0$ matrix element

$$\begin{aligned}\mathcal{M}_{K\to e\nu\pi^0} = \frac{G_F V_{us}}{2} \Big\{ & [f_+(t)(p_K+p_\pi)^\mu + f_-(t)(p_K-p_\pi)^\mu]\ \bar{e}\gamma^\mu(1+\gamma^5)\nu \\ & + 2M_K f_S\ \bar{e}(1+\gamma^5)\nu \\ & + \frac{2f_T}{M_K} p_K^\lambda p_\pi^\mu\ \bar{e}\sigma^{\lambda\mu}(1+\gamma^5)\nu \Big\}\end{aligned}$$

$$t = (p_K - p_\pi)^2 = (p_e + p_\nu)^2 = M_K^2 + m_\pi^2 - 2M_K E_\pi$$

- In the Standard Model f_S=f_T=0

$$\begin{aligned} f_S/f_+(0) &= 0.0017 \pm 0.0014_{stat} \pm 0.0009_{syst} \pm 0.0053_{theor} \\ f_T/f_+(0) &= -0.0007 \pm 0.0071_{stat} \pm 0.002_{syst} \qquad (K^-_{\mu 3}, \text{ISTRA+}, 2004)\end{aligned}$$

  Contribution of f_S and f_T to Branching Ratio $< 0.1\%$

- f_- is suppressed by small electron mass

$$f_-(p_K - p_\pi)^\mu\, \bar{e}\gamma^\mu(1+\gamma^5)\nu = f_- m_e\, \bar{e}(1+\gamma^5)\nu$$

- $f_+(t) = f_+(0)[1 + \lambda_+ t/m^2_{\pi^0}]$

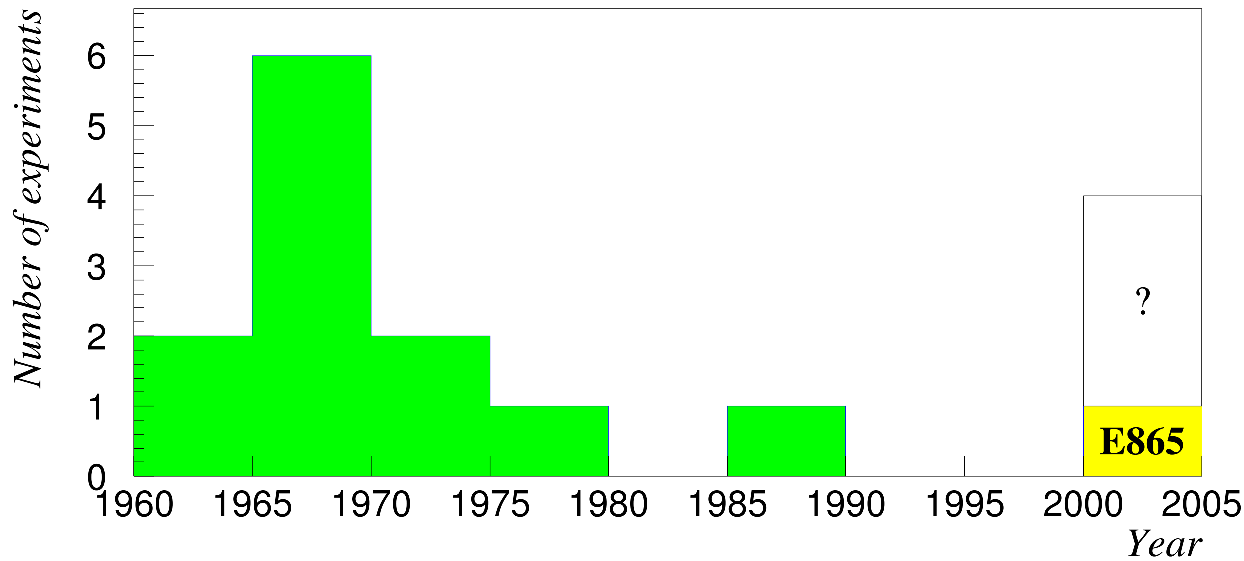
$$\begin{aligned} f_+(0) &= 1 + \delta \quad (\delta \ll 1, \quad \text{Ademollo} - \text{Gatto theorem}) \\ \lambda_+ &= 0.0282 \pm 0.0027 \quad (\text{PDG2002 fit})\end{aligned}$$

$$d\Gamma = C(E_e, E_\pi)|f_+(0)V_{us}|^2(1+\lambda_+ t/m^2_{\pi^0})^2\, dE_e dE_\pi$$

Radiative Corrections:

- E.S. Ginsberg, Phys. Rev. **162**, 1570 (1967).
- V. Cirigliano *et. al.*, Eur. Phys. J. C **23**, 121 (2002). (Fortran code available)
- V. Bytev *et. al.*, Eur. Phys. J. C **27**, 57 (2003).

$K^+ \to e^+ \nu_e \pi^0$ Decay Rate Measurements



$$BR(K^+ \to e^+ \nu \pi) = (4.87 \pm 0.06)\% \quad \text{(PDG2002)}$$

$$\frac{\sigma(V_{us})}{V_{us}} = 0.5 \frac{\sigma(\Gamma)}{\Gamma} \oplus 0.047 \frac{\sigma(\lambda_+)}{\lambda_+} \oplus \frac{\sigma(f_+(0))}{f_+(0)}$$

$$\frac{\sigma(V_{us})}{V_{us}} = 0.61\% \oplus 0.45\% \oplus 0.85\%$$

Why do we need to remeasure K^+_{e3} decay rate ?

CKM Matrix Unitarity

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

- $|V_{ub}| = (3.6 \pm 0.7) \cdot 10^{-3}, \quad |V_{ub}|^2 \ll 0.0001$
  (from B-meson decays.)
- $|V_{us}| = 0.2196 \pm 0.0026, \quad |V_{us}|^2 = 0.0482 \pm 0.0011$
  (from K_{e3} decays, $|V_{us}|^{K^0_{e3}} \approx |V_{us}|^{K^+_{e3}}$)
- $|V_{ud}| = 0.9740 \pm 0.0005, \quad |V_{ud}|^2 = 0.9487 \pm 0.0010$

$\|V_{ud}\|$	$\sum \|V_{ui}\|^2$	Method
0.9740 ± 0.0005	0.9968 ± 0.0014	Nuclear superallowed Fermi beta decays
0.9805 ± 0.0021	1.0095 ± 0.0043	Neutron decay (1990)
0.9757 ± 0.0019	1.0001 ± 0.0040	Neutron decay (PDG2002)
0.9717 ± 0.0013	0.9924 ± 0.0028	Neutron decay (G_A/G_V from PERKEO 2002)
0.9716 ± 0.0039	0.9922 ± 0.0087	Pion beta decay (PIBETA)

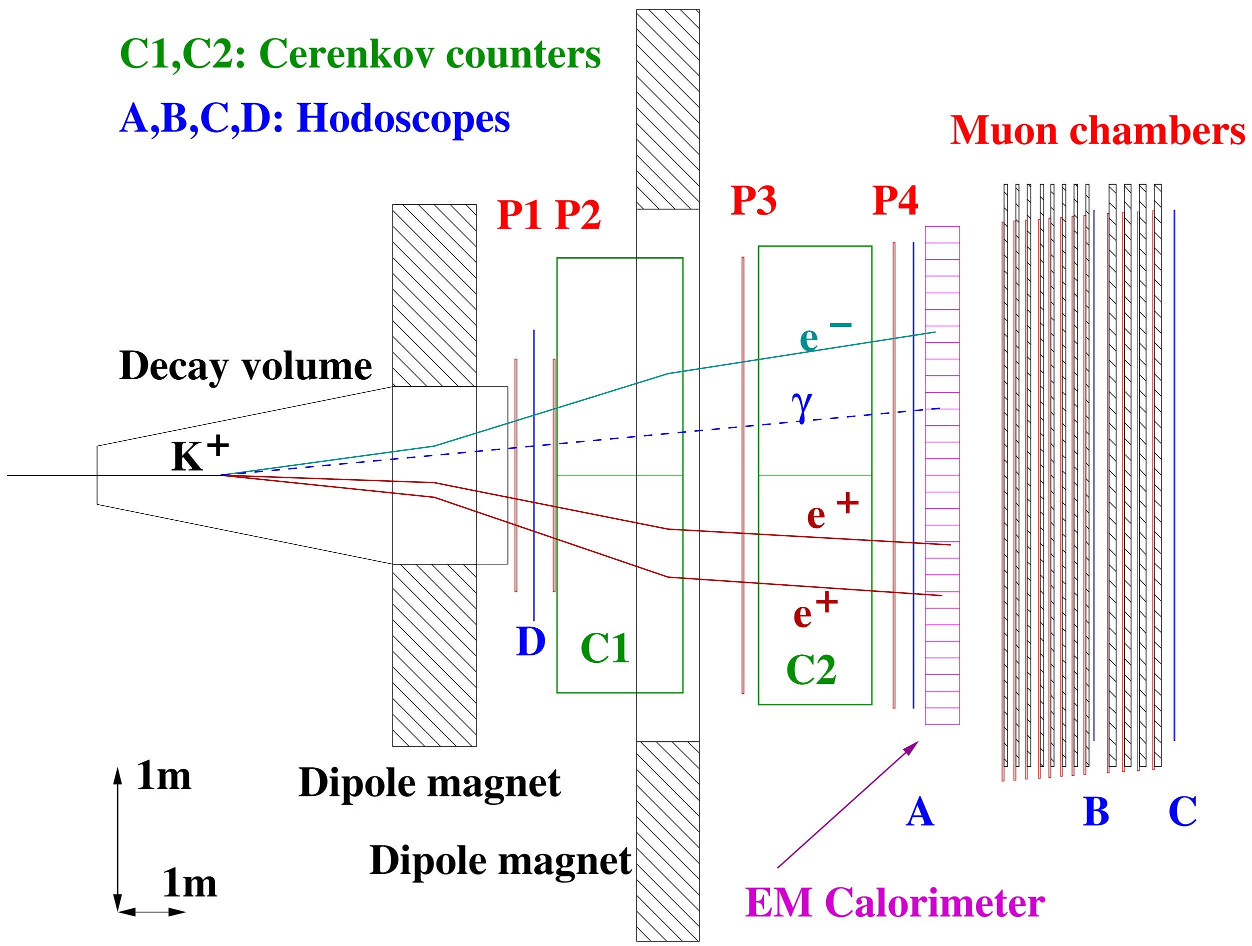
$$|V_{ud}|^2_{\text{nucl.}} + |V_{us}|^2 + |V_{ub}|^2 = 0.9968 \pm 0.0014$$

(2.3 standard deviations from unitarity)

In the last decade, "improvements" in V_{ud} did not improve CKM unitarity. What if V_{us} is wrong ?

Almost all K^+_{e3} decay rate experiments have been done 30–40 years ago with low statistics. A new experiment is needed.

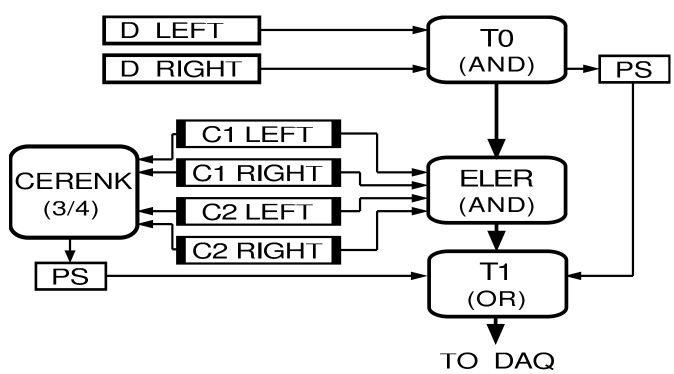
E865 at AGS



- Designed to search for the decay $K^+ \to \pi^+\mu^+e^-$ (LFV) at the level of 10^{-11}.
- Beam: 6 GeV/c; 10^8 K^+; 2×10^9 π^+; 1.7×10^9 p per 2.8 second AGS pulse. Intensity was reduced by factor 10 in K_{e3} decay rate measurement
- No kaon flux measurement
- Three charged particles are required in final state.

What was detected ?

- **Searched process (K_{e3}):**
  $K^+ \to e^+\nu\pi^0_D; \quad \pi^0_D \to e^+e^-\gamma$
- **Normalization decays (K_{dal}):**
  $K^+ \to \pi^+\pi^0_D \; + \; \mu^+\nu\pi^0_D \; + \; \pi^+\pi^0_D\pi^0$
- **Decay identification**:
  - (Low mass) e^+e^- pair indicate either K_{e3} or K_{dal}
  - Additional positive track identified as e^+ means K_{e3}
  - Photon detection is not required (to reduce systematic error)
- **Trigger 1997**:
  Hits in D, A, Calorimeter (2 clumps), and in all four Cherenkov
  (Not included in final result due to systematic errors)
- **Trigger 1998**:
  - "e^+e^-" (T0×ELER)
  - **"TAU"** (T0, prescaled)
  - **"CERENK"**
    (3 of 4, prescaled)



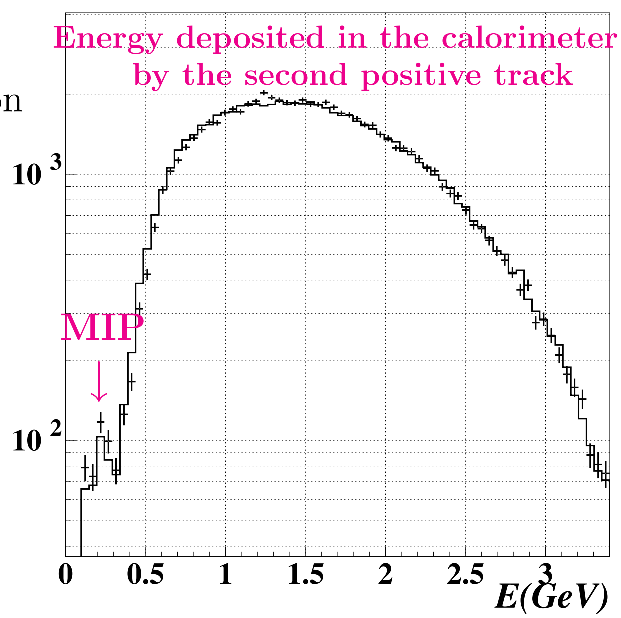
- **Run 1998:**
  - One week dedicated run
  - Reduced beam intensity (10^7 K^+ per 2.8 second AGS pulse)
  - About 50 million trigger collected

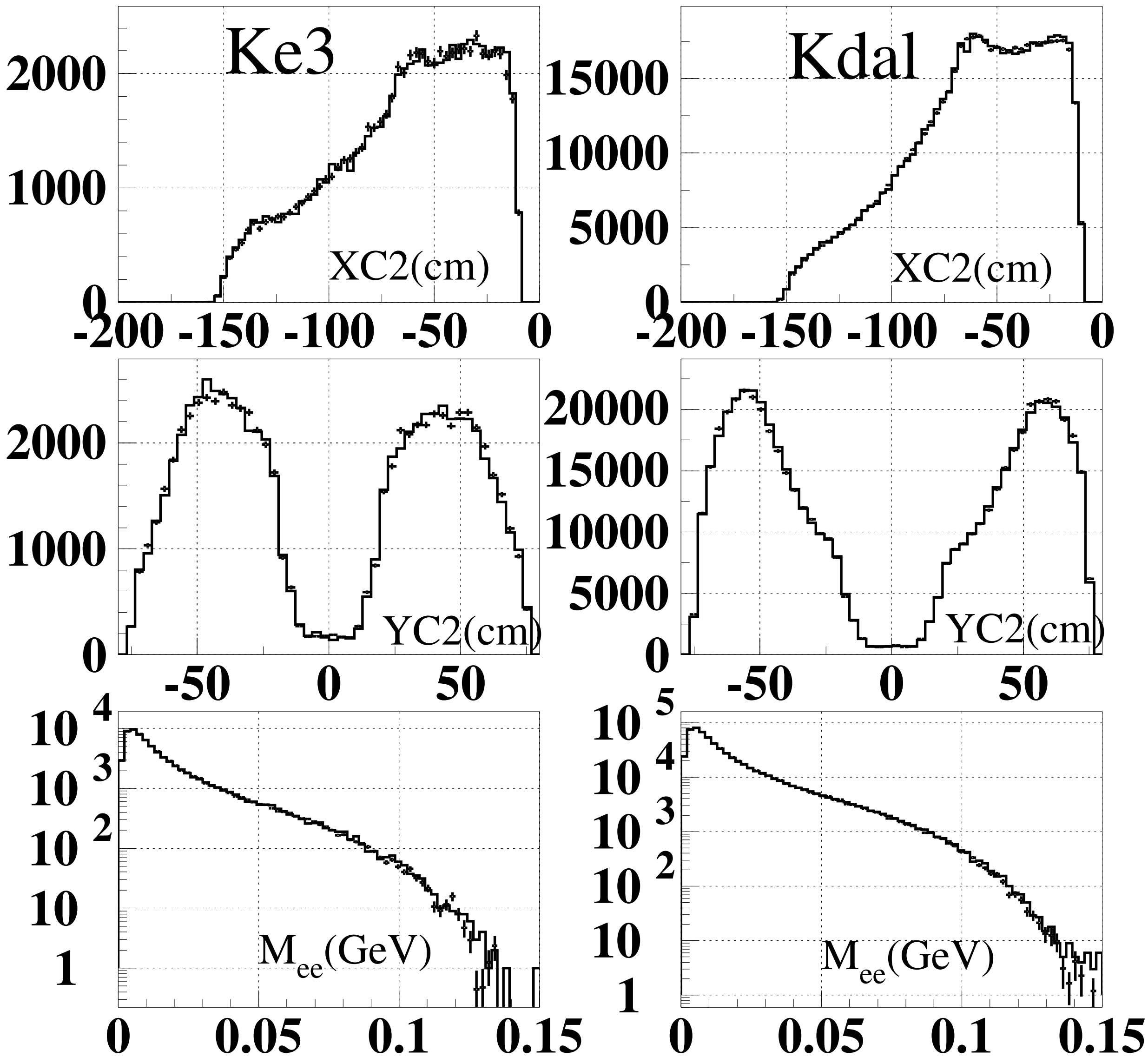
Event selection

- Three tracks, $p < 3.4$ GeV/c, which go through the detector sensitive region and intersecting inside the decay volume.
- Events were rejected if any one Cerenkov photomultiplier could have detected Cerenkov photons from more than one track
- In time signals in both Cerenkov counters for the pair of negative and positive tracks that produces tha smaller M_{ee} invariant mass.
- $M_{ee} < 50$ MeV.
- The second positive track is required to satisfy at least two of the following three conditions:
  - in-time signal in C1
  - in-time signal in C2
  - $E/p > 0.8$ in calorimeter

Contamination:

- **Particle misidentification in K_{e3} sample**
  $(2.49 \pm 0.05_{stat} \pm 0.32_{syst})\%$
  - π^+/μ^+ misidentification as positron
  - $\pi^0 \rightarrow e^+e^-e^+e^-$ in K_{dal} decays
- **Events Overlapping**
  - K_{e3} sample **$(0.25 \pm 0.07)\%$**
  - K_{dal} sample **$(0.12 \pm 0.05)\%$**



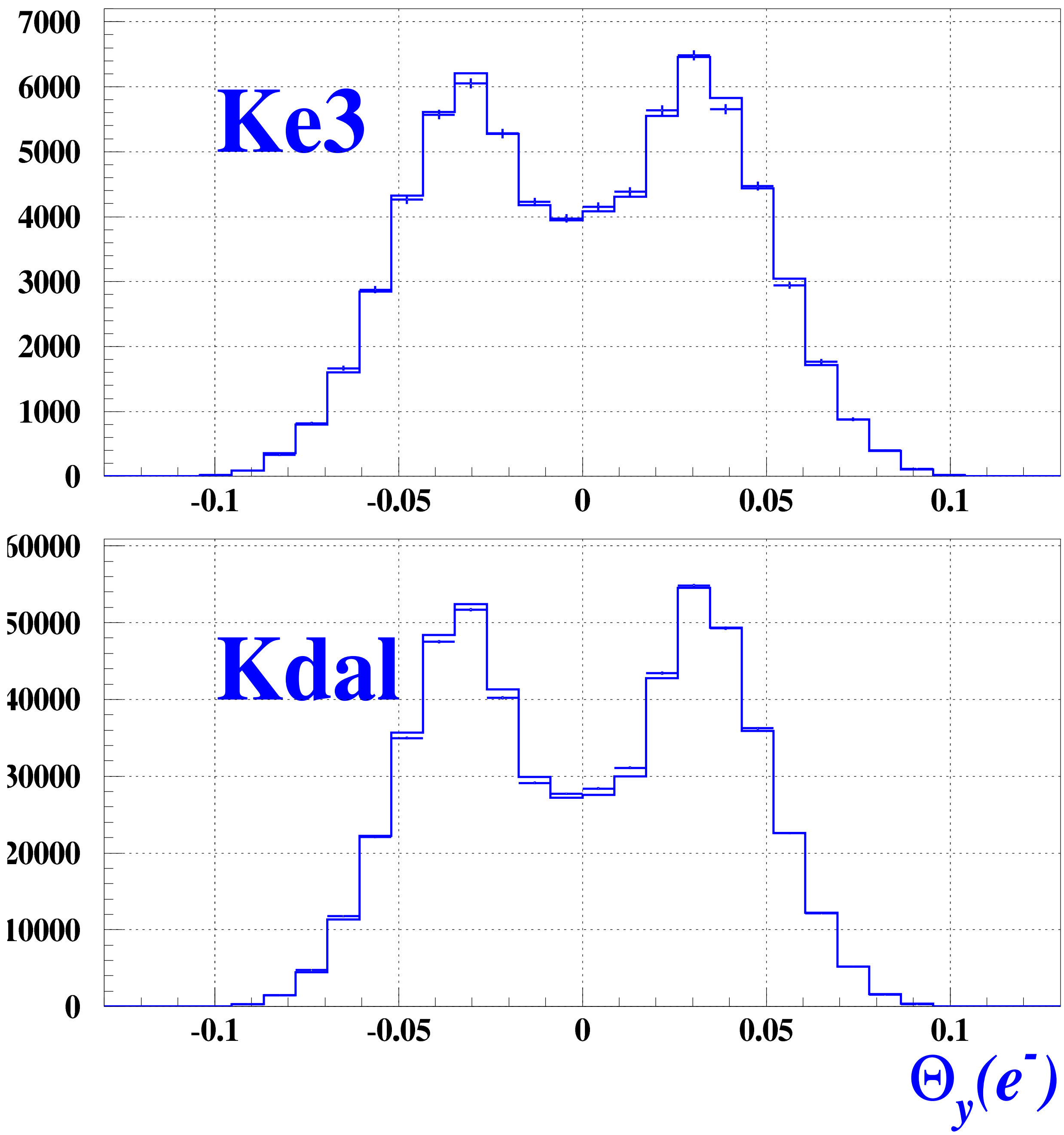


For Ke3 and Kdal candidates, X and Y at C2, and the mass of the e^+e^- from the π^0 Dalitz decay. Histograms are simulation, and points with errors are data.

Errors

- **Statistical error ($\approx$ 0.4%)**
  (about 70,000 selected K_{e3} events without π^0 reconstruction)
- **Systematic error ($\approx$ 1.8%, total)**

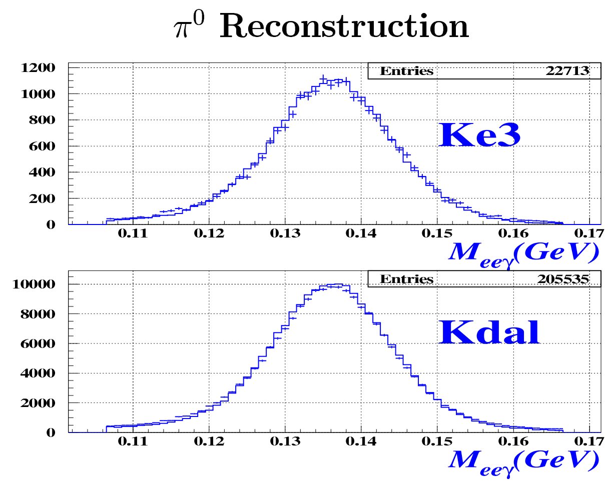
Source of systematic error	**Error estimate**
Magnetic field uncertainty	0.3%
Vertex finding and quality cut	0.6%
Vertex position cut	0.4%
Čerenkov Ambiguity Cut	0.3%
M_{ee} cut	0.2%
Detector Aperture	0.2%
$(\pi/\mu)^+$ identification	0.04%
MWPC efficiencies	0.2%
D counter efficiencies	0.15%
Čerenkov efficiencies	0.3%
Contamination of the selected samples	0.3%
Removal of extra tracks	0.2%
Vertical spatial/angle distributions discrepancy	0.8%
e^+/e^- momentum distributions discrepancy	1.3%
ELER trigger efficiency	0.1%
Uncertainty in the K_{e3}^+ form factor slope	0.1%
Total error	**1.8%**



Vertical spatial/angle distributions discrepancy. Histogams are simulation, and points with errors are data

Consistency checks

- **Compare sample with fully reconstructed π^0 (30% of all data) and sample where photon was not detected.**



CUT	Ke3(MC/D)	Dal(MC/D)	Dal/Ke3
π^0	1.008(0.008)	1.011(0.004)	1.003(0.009)
NO π^0	0.996(0.006)	0.993(0.003)	0.997(0.007)

- **$K^+ \rightarrow \pi^+\pi^+\pi^-$ branching ratio.**

$$Br(K \rightarrow 3\pi)/Br(K_{dal}) = (1.01 \pm 0.02) \times R_{\text{PDG}}$$

- **1997 data versus 1998 data**
  (consistency within one standard deviation)

- **Experimental estimation of the form factor slope λ_+:**
  - 1997: $\lambda_+ = 0.0324 \pm 0.0044_{stat}$
  - 1998: $\lambda_+ = 0.0290 \pm 0.0044_{stat}$

  Results are consistent with PDG value $\lambda_+^{PDG} = 0.0282 \pm 0.0027$

E865 Results

$$\frac{Br(K_{e3(\gamma)})}{Br(K_{\pi 2}+K_{\mu 3}+K_{\pi 3})} = 0.1962 \pm 0.0008_{stat} \pm 0.0035_{syst}$$

$$\Downarrow$$

$$Br(K_{e3(\gamma)}) = (5.13 \pm 0.02_{stat} \pm 0.09_{syst} \pm 0.04_{norm})\%$$

$$\Downarrow$$

Radiative corrections: -1.3%

Inner bremstrahlung corrections (out of Dalitz plot): $+0.5\%$

$$Br_{\text{bare}}(K_{e3(\gamma)}) = (5.17 \pm 0.02_{stat} \pm 0.09_{syst} \pm 0.04_{norm})\%$$

$$\Downarrow$$

Short distance enhancement factor $S_{EW}(M_\rho, M_Z) = 1.0232$

$$|V_{us} f_+(0)| = 0.2243 \pm 0.0022_{rate} \pm 0.0007_{\lambda_+}$$

$$\Downarrow$$

Theory: $f_+(0) = 0.9874 \pm 0.0084$

$$|V_{us}| = 0.2272 \pm 0.0023_{rate} \pm 0.0007_{\lambda_+} \pm 0.0018_{f_+(0)}$$

Comparison with previous K^+_{e3} decay rate experiments

	Experiment	Evts	Norm.	$\Gamma_{e3}/\Gamma_{\rm norm}$ (%)	$Br(K^+_{e3})$ (%)	π^0	RC	λ_+	p_e range (MeV)
A	SHAKLEE 64	429	*total*	4.7±0.3	4.70±0.30	$\gamma\gamma$	—	−0.02	total
	CHIANG 72	3516	*total*	4.86±0.10	4.86±0.10	$\gamma\gamma$	—	0.03	total
	BORREANI 64	230	τ	90±6	5.02±0.33±0.03	—	—	0.	total
	BRAUN 75	2827	τ	85.6±4.0	4.77±0.22±0.03	$\gamma\gamma$	—	0.03	total
	BARMIN 87	2768	τ	86.7±2.7	4.83±0.15±0.03	$\gamma\gamma$	—	?	total
	LUCAS 73	786	$\pi2$	22.1±1.2	4.67±0.25±0.01	ee	Yes	0.03	$p_e < 200$
B	CESTER 66	1679	$\mu2+\pi2$	5.89±0.21	4.98±0.18±0.01	—	Yes	0.	$p_e > 60$
	ESCHSTRUTH 68	5110	$\mu2+\pi2$	6.16±0.22	5.21±0.19±0.01	—	Yes	0.	$p_e > 80$
	AUERBACH 67	470	$\mu2$	7.91±0.54	5.02±0.34±0.01	—	Yes	0.	$130 < p_e < 190$
	BOTTERILL 68C	960	$\mu2$	7.75±0.33	4.92±0.21±0.01	—	Yes	0.02	$p_e > 90$
C	GARLAND 68	561	$\mu2$	6.9±0.6	4.38±0.38±0.01	—	—	0.	$p_e > 80$
	ZELLER 69	350	$\mu2$	6.9±0.6	4.38±0.38±0.01	—	—	0.02	$p_e > 120$
	E865	70k	$\pi2+\mu3+\tau'$	19.62±0.37	5.13±0.09±0.04	ee	Yes	0.03	$p_e > 45$

$$
\begin{aligned}
Br(A) &= (4.83 \pm 0.07)\% \\
Br(B) &= (5.04 \pm 0.11)\% && \Rightarrow (5.00 \pm 0.11)\% \\
Br(C) &= (4.38 \pm 0.27)\% && \updownarrow \text{ corrected for } \lambda_+ \\
Br(A+B) &= (4.89 \pm 0.06)\% && \Rightarrow (4.88 \pm 0.06)\% \\
Br(A+B+C) &= (4.87 \pm 0.06)\% && \text{(PDG fit)} \\
Br(non\ K_{e3}) &= (4.82 \pm 0.15)\% && \text{(PDG fit without } K_{e3} \text{ entries)} \\
Br(E865) &= (5.13 \pm 0.10)\%
\end{aligned}
$$

$$
\begin{aligned}
Br(E865) &= Br(B) && (0.9\sigma) \\
Br(E865) &\neq Br(A) && (2.5\sigma) \\
Br(E865) &\neq Br(A+B) && (2.2\sigma) \\
Br(A) &\ ?\ Br(B) && (1.5\sigma)
\end{aligned}
$$

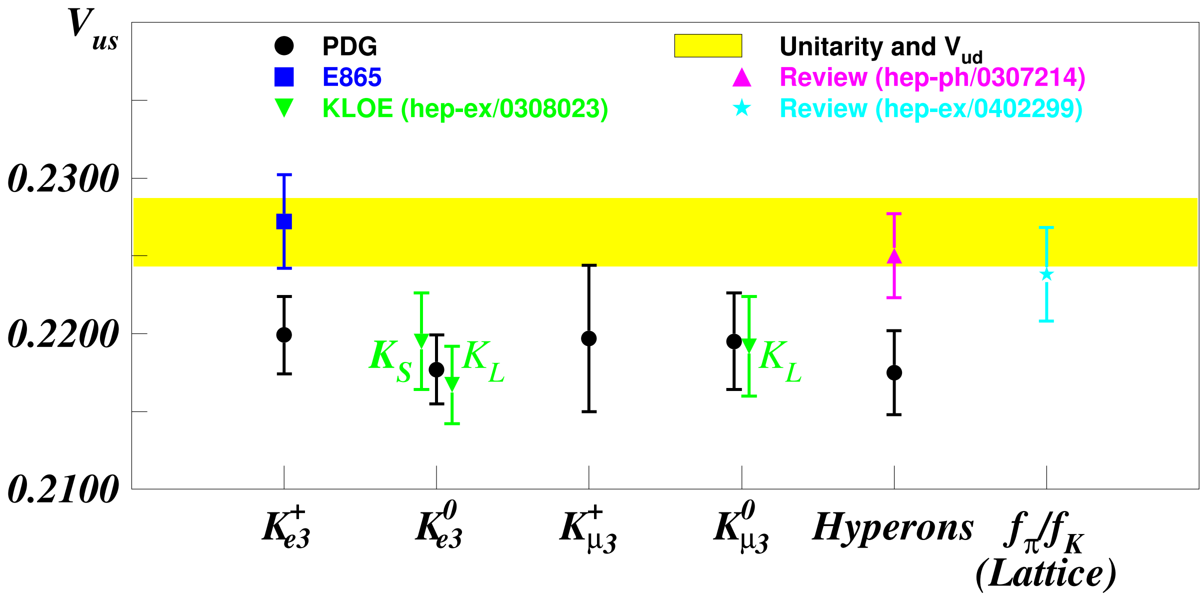
No explanation of the discrepancy was found

V_{us}

$f_+^{K^+\pi^0}(0) = 0.0984 \pm 0.0084,\ f_+^{K^+\pi^0}(0)/f_+^{K^0\pi^-}(0) = 1.022$

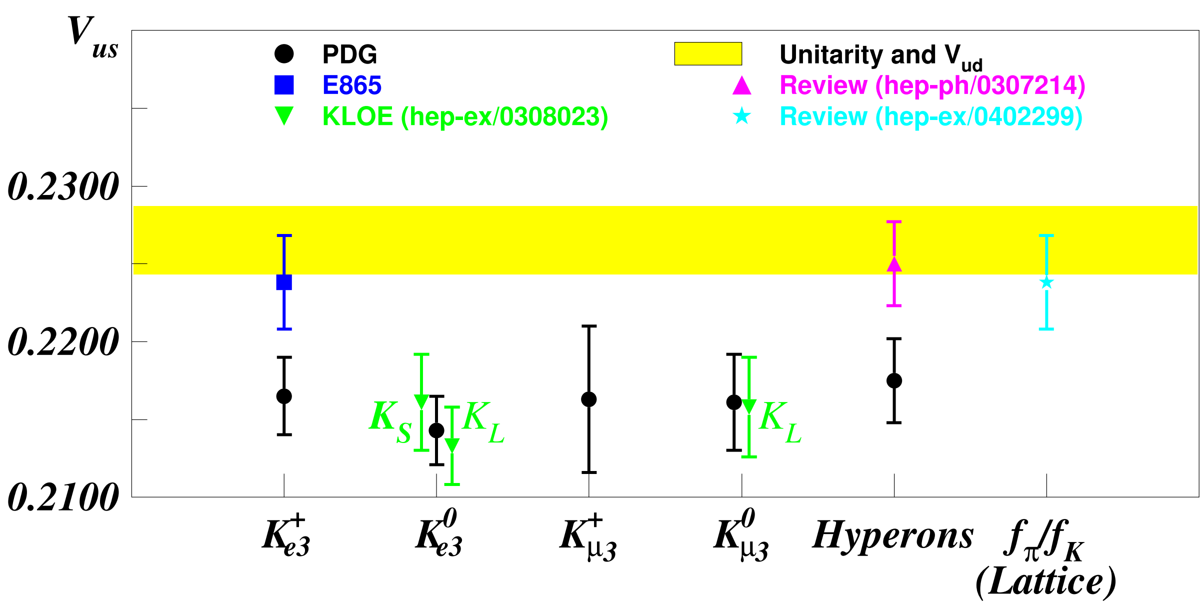
H. Leutwyler, M. Roos, Z. Phys. C. **25**, 91 (1984)

V. Cirigliano et al., Eur. Phys. C **23**, 121 (2002)



$f_+^{K^+\pi^0}(0) = 1.002 \pm 0.010,\ f_+^{K^0\pi^-}(0) = 0.981 \pm 0.010,$

V. Cirigliano, H. Neufeld, H. Pichl, hep-ph/0401173



Summary

E865 results:

$$Br(K_{e3(\gamma)}) = (5.13 \pm 0.02_{stat} \pm 0.09_{syst} \pm 0.04_{norm})\%$$

$$|V_{us}| = 0.2272 \pm 0.0020_{rate} \pm 0.0007_{\lambda_+} \pm 0.0018_{f_+(0)}$$

Virtue:

$$|V_{ud}|^2_{\text{nucl.}} + |V_{us}|^2_{\text{E865}} + |V_{ub}|^2 = 1.0003 \pm 0.0016$$

Problems:

- **Disagreement with previous K^+_{e3} decay rate experiments by about 2.3 standard deviations.**
- **$|V_{us}|$ is in disagreement with the value from the K^0_{e3} decay rate if extracted under conventional theoretical assumptions about symmetry breaking.**