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E865 results on K_{e3}

Julia A. Thompson for the E865 Collaboration

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A. Sher, Ph.D thesis, University of Pittsburgh (2002)
http://scipp.ucsc.edu/~sasha/th_ke3.ps
Alexander Sher et al., submitted to Phys. Rev. Lett.
hep-ex/0305042
Julia A. Thompson, Durham CKM Conference
hep-ex/0307053
Andrei Poblaguev, Bonn Chiral Dynamics Workshop

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

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

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

- In the Standard Model f_S=f_T=0

$$\begin{aligned} f_S/f_+(0) &= \ \ 0.004 \pm 0.005_{stat} \pm 0.005_{theor} \quad (\text{ISTRA+}, 2003) \\ f_T/f_+(0) &= -0.021 \pm 0.028_{stat} \pm 0.014_{theor} \quad (\text{ISTRA+}, 2003) \end{aligned}$$

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

- f_- is suppressed by small electron mass
  $$f_-(p_K - p_\pi)^\mu\ \bar{e}\gamma^\mu(1+\gamma^5)\nu = f_- m_e\ \bar{e}(1+\gamma^5)\nu$$

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

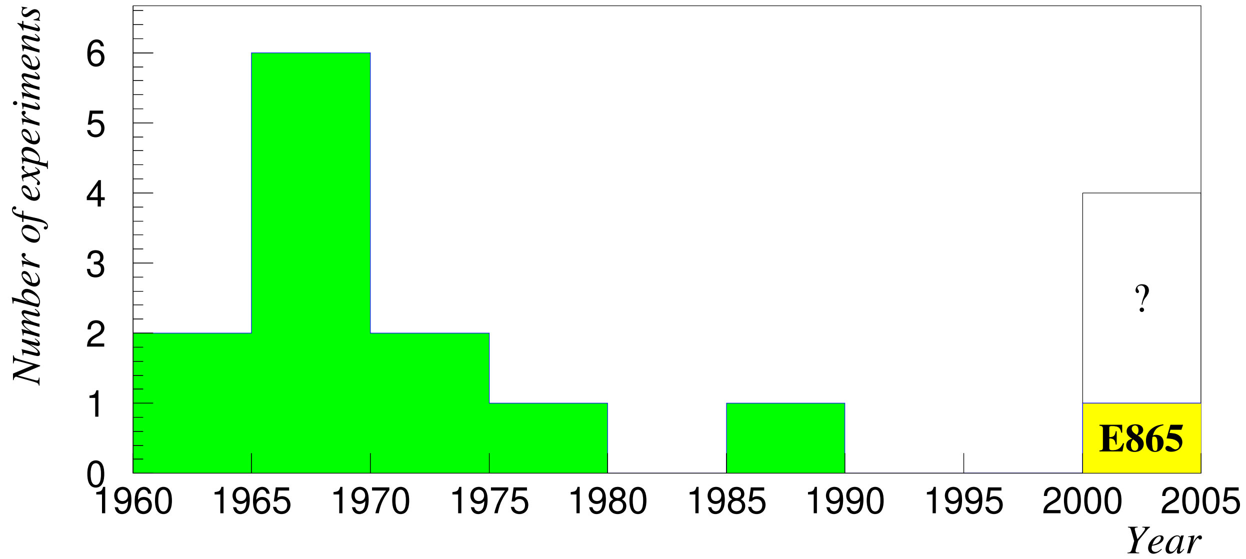
$$\begin{aligned} f_+(0) &= 1+\delta \quad (\delta \ll 1, \quad \text{Ademollo} - \text{Gatto theorem}) \\ \lambda_+ &= 0.0282 \pm 0.0027 \quad (\text{PDG2002 fit}) \end{aligned}$$

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

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, $|V_{us}|^{K^0_{e3}} \approx |V_{us}|^{K^+_{e3}}$)
- $|V_{ud}| = 0.9740 \pm 0.0005, \quad |V_{ud}|^2 = 0.9487 \pm 0.0010$

$\lvert V_{ud}\rvert$	$\sum \lvert V_{ui}\rvert^2$	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)
0.9713 ± 0.0013	0.9916 ± 0.0028	Neutron decay (G_A/G_V from PERKEO 2002)
0.9771 ± 0.0050	1.0029 ± 0.0100	Pion beta decay (PIBETA preliminary)

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

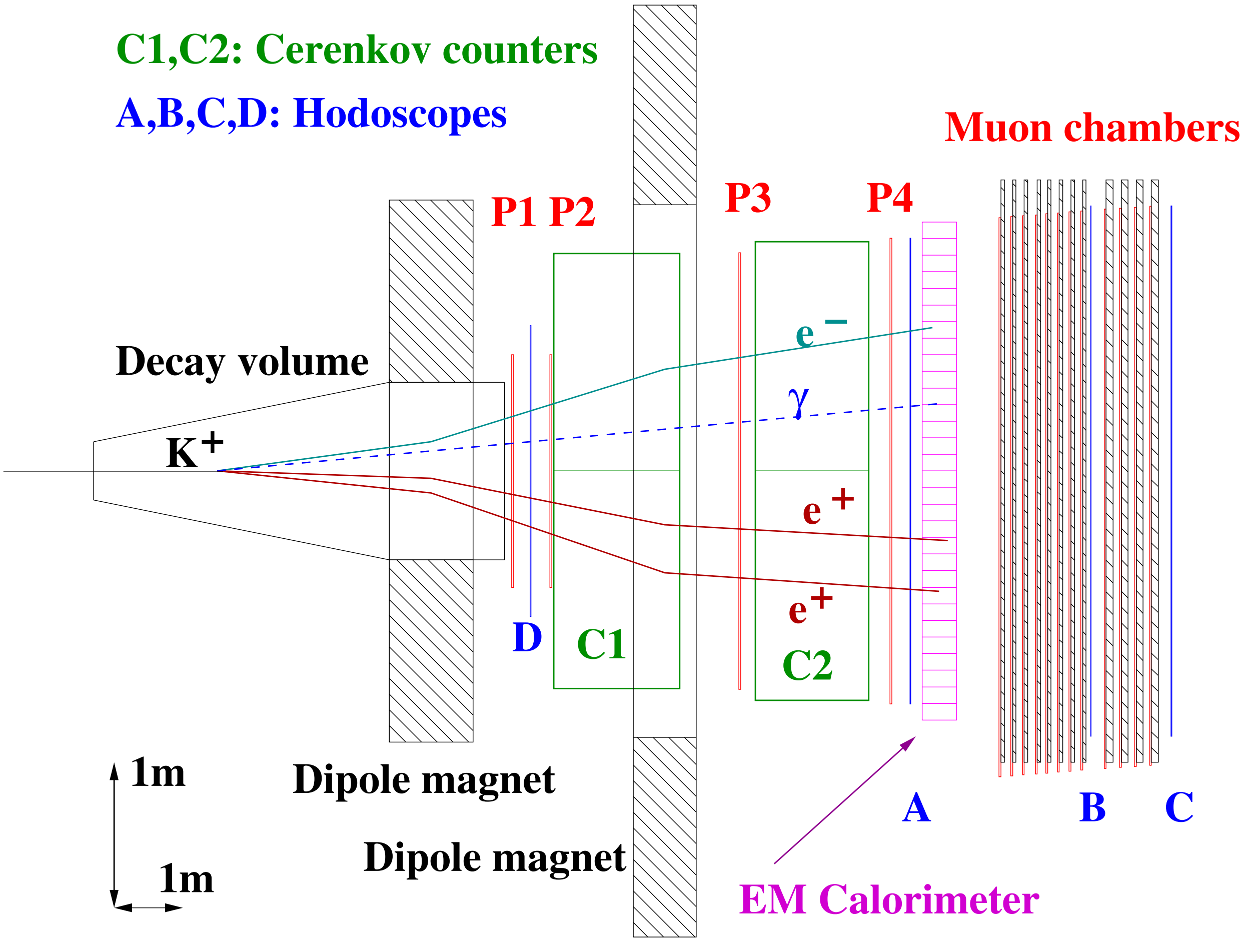
(2.3 standard deviations from unitarity)

In the last decade, a lot of efforts to “improve” the result for V_{ud} did not result in an improvement.

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.

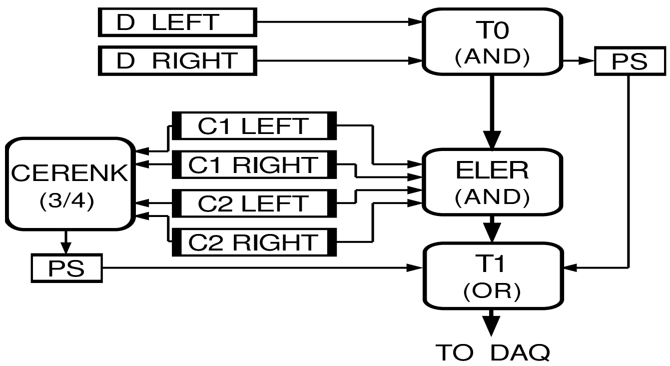
E865 at AGS



- 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}):**
  $K^+ \to \pi^+\pi^0_D \;+\; K^+ \to \mu^+\nu\pi^0_D \;+\; K^+ \to \pi^+\pi^0_D\pi^0$
- **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
  (This data was not included in the final result because of systematic errors)
- **Trigger 1998**:
  - **"e^+e^-"** (T0×ELER)
  - **"TAU"** (T0, prescaled)
  - **"CERENK"**
    (3 of 4, prescaled)



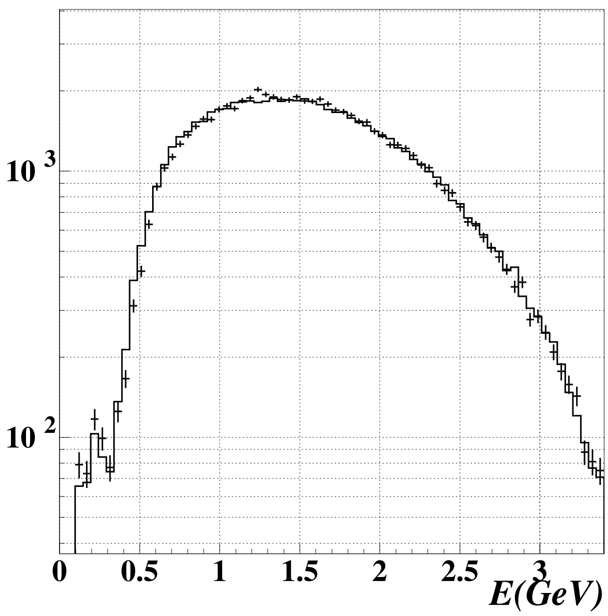
- **Run 1998:**
  - One week dedicated run
  - Reduced beam intensity (10^7 K^+ per 2.8 second AGS pulse)
  - About 50 million trigger collected

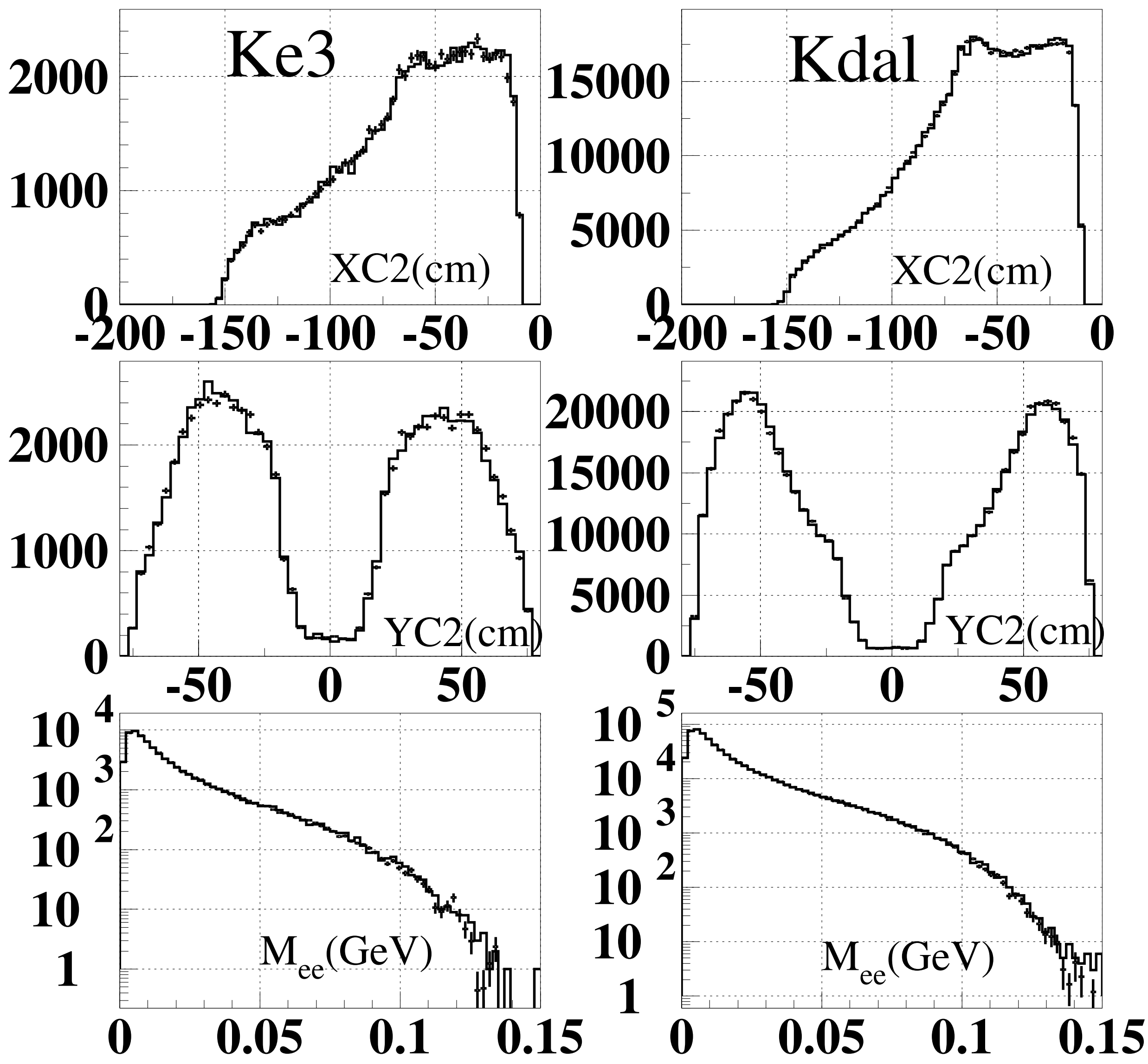
Event selection

- 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
  - $\pi^0 \to e^+e^-e^+e^-$ in K_{dal} decays
- **Events Overlapping**
  - K_{e3} sample **$(0.25 \pm 0.07)\%$**
  - K_{dal} sample **$(0.12 \pm 0.05)\%$**

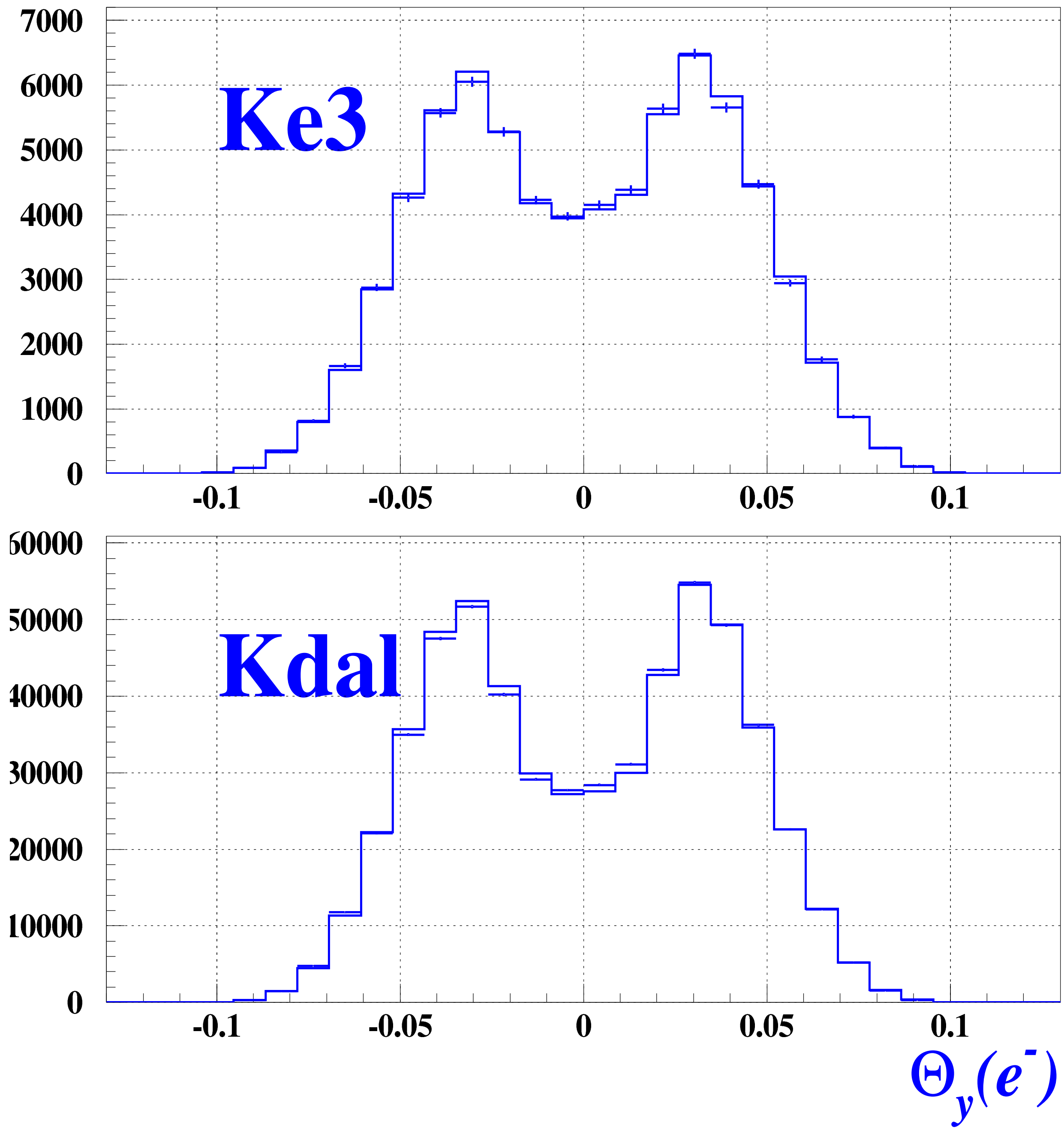



Ke3
Kdal
XC2(cm)
YC2(cm)
M_{ee}(GeV)
2000
1000
0
-200 -150 -100 -50 0
15000
10000
5000
-50 0 50
20000
10^4
10^3
10^2
10
1
10^5
0 0.05 0.1 0.15

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%**


7000
6000
5000
4000
3000
2000
1000
0
Ke3
-0.1
-0.05
0
0.05
0.1
60000
50000
40000
30000
20000
10000
0
Kdal
-0.1
-0.05
0
0.05
0.1
$\Theta_y(e^-)$

Consistency checks

- Compare sample with fully reconstructed π^0 (30% of all data) and sample where photon was not detected.
- $K^+ \to \pi^+\pi^+\pi^-$ branching ratio.

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

- 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 $\lambda_+^{PDG} = 0.0282 \pm 0.0027$

Results

$$\frac{Br(K_{e3(\gamma)})}{Br(K_{\pi 2} + K_{\mu 3} + K_{\pi 3})} = 0.1962 \pm 0.0008_{stat} \pm 0.0036_{syst}$$

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

Radiative corrections: -1.3%

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

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

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

$$|V_{us} f_+(0)| = 0.2239 \pm 0.0020_{rate} \pm 0.0007_{\lambda_+}$$

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

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

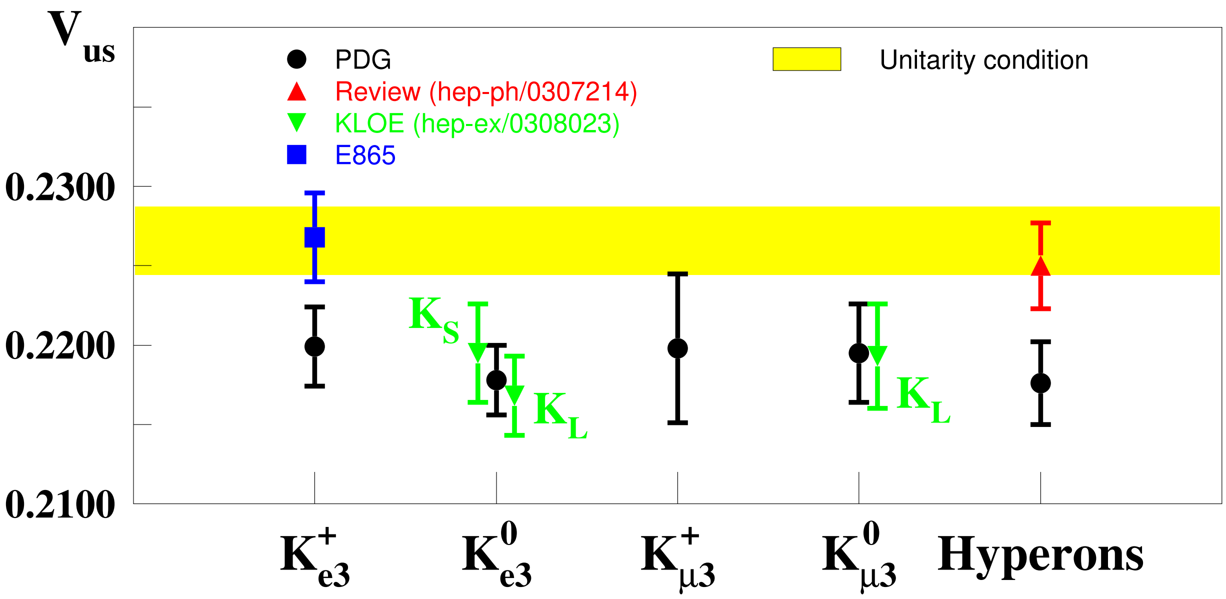
Comparison with previous K^+_{e3} decay rate experiments

	Experiment	Evts	Norm.	$\Gamma_{e3}/\Gamma_{\text{norm}}$ (%)	$Br(K^+_{e3})$ (%)	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	$\pi 2$	22.1±1.2	4.67±0.25±0.01	ee	Yes	0.03	$p_e < 200$
B	CESTER 66	1679	$\mu 2 + \pi 2$	5.89±0.21	4.98±0.18±0.01	—	Yes	0.	$p_e > 60$
	ESCHSTRUTH 68	5110	$\mu 2 + \pi 2$	6.16±0.22	5.21±0.19±0.01	—	Yes	0.	$p_e > 80$
	AUERBACH 67	470	$\mu 2$	7.91±0.54	5.02±0.34±0.01	—	Yes	0.	$130 < p_e < 190$
	BOTTERILL 68C	960	$\mu 2$	7.75±0.33	4.92±0.21±0.01	—	Yes	0.02	$p_e > 90$
C	GARLAND 68	561	$\mu 2$	6.9±0.6	4.38±0.38±0.01	—	—	0.	$p_e > 80$
	ZELLER 69	350	$\mu 2$	6.9±0.6	4.38±0.38±0.01	—	—	0.02	$p_e > 120$
	E865	70k	$\pi 2 + \mu 3 + \tau'$	19.62±0.37	5.13±0.09±0.04	ee	Yes	0.03	$p_e > 45$

$$
\begin{aligned}
Br(A) &= (4.83 \pm 0.07)\% \\
Br(B) &= (5.04 \pm 0.11)\% \quad \Rightarrow (5.00 \pm 0.11)\% \\
Br(C) &= (4.38 \pm 0.27)\% \quad \quad \updownarrow \text{ corrected for } \lambda_+ \\
Br(A+B) &= (4.89 \pm 0.06)\% \quad \Rightarrow (4.88 \pm 0.06)\% \\
Br(A+B+C) &= (4.87 \pm 0.06)\% \\
Br(E865) &= (5.13 \pm 0.10)\% \\
Br(Non\ K_{e3}) &= (4.82 \pm 0.15)\% \quad (K_{\mu 3}/K_{e3} + \text{other decays})
\end{aligned}
$$

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

V_{us}



V_{us}
0.2300
0.2200
0.2100
PDG
Review (hep-ph/0307214)
KLOE (hep-ex/0308023)
E865
Unitarity condition
K_S
K_L
K_L
K^+_{e3}
K^0_{e3}
$K^+_{\mu3}$
$K^0_{\mu3}$
Hyperons

Summary (BNL E865 K_{e3}^{+})

- 70,000 K_{e3}^{+} decays.
- Good PID.
- Extensive Cross-Checks.

$$Br(K_{e3(\gamma)}) = (5.13 \pm 0.02_{stat} \pm 0.09_{syst} \pm 0.04_{norm})\%$$
$$|V_{us}| = 0.2272 \pm 0.0020_{rate} \pm 0.0007_{\lambda_+} \pm 0.0018_{f_+(0)}$$

- $|V_{us}|$ agrees with V_{ud} and CKM Unitarity.
- $|V_{us}|$ agrees with recent renalysis of hyperon beta decays.

- Branching ratio higher by about 2.3 σ than previous K_{e3}^{+} decay rate experiments [PDG 2002: $(4.87 \pm 0.06)\%$].
- $|V_{us}|$ higher by several σ than $|V_{us}|$ from K_{e3}^{0} decay rate (with usual theoretical assumptions).
- $|V_{us}|$ higher than previous analysis of hyperon beta decays.