$K^+ \to \pi^0 e^+ \nu$ (Ke3) Branching Ratio Measurement in the E865 Experiment at Brookhaven National Laboratory AGS

DPF2002

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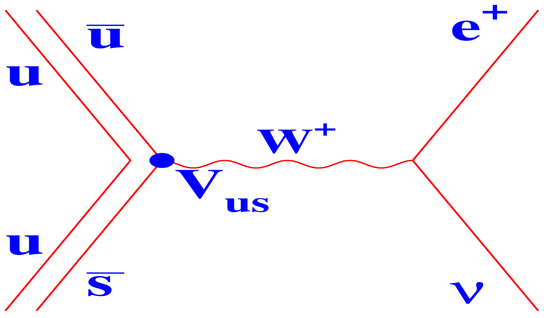

$$d\Gamma(K \to \pi e\nu) \propto |V_{US}|^2 \times |f_+(0)|^2 \times [1 + \lambda_+ \left(\frac{q^2}{M_\pi^2}\right)]^2 dq^2$$

$|V_{ud}| = 0.9740 \pm 0.0005$ - Nuclear Beta Decays (from $0^+ \to 0^+$ transitions; error from Hardy and Towner)

$|V_{us}| = 0.2196 \pm 0.0023$ - Solely from Ke3

$|V_{ub}| = 0.0036 \pm 0.0010$ - B meson semileptonic decays

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \delta;$$

$$\sigma_{|V_{ij}|^2} = (9.7; \quad 10.1; \quad 0.036) \times 10^{-4}$$

$$\delta = (3.1 \pm 1.4) \times 10^{-3}$$

$$\sigma_{|V_{US}|} = |V_{US}| \left[\pm 0.5 \frac{\sigma_\Gamma}{\Gamma} \pm 0.047 \frac{\sigma_{\lambda_+}}{\lambda_+} \pm \frac{\sigma_{f_+(0)}}{f_+(0)}\right]$$

- λ_+: experiment
- $f_+(0)$: theory
- Radiative corrections: theory
- Ke3 decay rate: experiment

Unitarity Sum

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

$\|V_{ud}\|$ value	Obtained from	δ
0.9740 ± 0.0005	Superallowed Nuclear Beta Decays (1)	$(3.1 \pm 1.4) \times 10^{-3}$
0.9740 ± 0.0010	Superallowed Nuclear Beta Decays (2)	$(3.1 \pm 2.2) \times 10^{-3}$
0.9728 ± 0.0012	Neutron Decays Average (3)	$(5.4 \pm 2.5) \times 10^{-3}$
0.9735 ± 0.0012	Neutron and Beta Decays Average (4)	$(4.1 \pm 2.5) \times 10^{-3}$
0.9713 ± 0.0013	New Neutron Decays Result (5)	$(8.3 \pm 2.7) \times 10^{-3}$

(1) J.C. Hardy and I.S. Towner, talk at WEIN98 (Santa Fe, June 14-21, 1998)
(2) PDG estimate (error is increased due to uncertainty in the charge-symmetry-violation correction)
(3) PDG average over Neutron Decay experiments
(4) PDG average over Nuclear and Neutron Decay results
(5) H. Abele *et al.*, Phys. Rev. Lett. **88** (2002)

$BR(Ke3)_{CKM}$ inferred from $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

$\mathrm{BR(Ke3)}_{PDG} = (4.82 \pm 0.06)\%$

$|V_{ud}|$ value	Obtained from	$\frac{BR(Ke3)_{CKM}}{BR(Ke3)_{PDG}}$
0.9740 ± 0.0005	Superallowed Nuclear Beta Decays (1)	(1.053 ± 0.027)
0.9740 ± 0.0010	Superallowed Nuclear Beta Decays (2)	(1.053 ± 0.044)
0.9728 ± 0.0012	Neutron Decays Average (3)	(1.101 ± 0.052)
0.9735 ± 0.0012	Neutron and Beta Decays Average (4)	(1.073 ± 0.052)
0.9713 ± 0.0013	New Neutron Decays Result (5)	(1.161 ± 0.056)

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BR(Ke3)

Prev. Measurement	Result	$\Gamma(Ke3)/\Gamma_{tot}$	N Ke3	Year
$\Gamma(Ke3)/\Gamma(\pi^+\pi^+\pi^-)$	0.850 ± 0.019	4.75 ± 0.1	4385	1971
$\Gamma(Ke3)/\Gamma_{tot}$	4.86 ± 0.1	4.86 ± 0.1	3516	1972
$\Gamma(Ke3)/\Gamma(\pi^+\pi^0)$	0.221 ± 0.012	4.67 ± 0.25	786	1973
$\Gamma(Ke3)/\Gamma(\pi^+\pi^+\pi^-)$	0.867 ± 0.027	4.85 ± 0.15	2768	1987

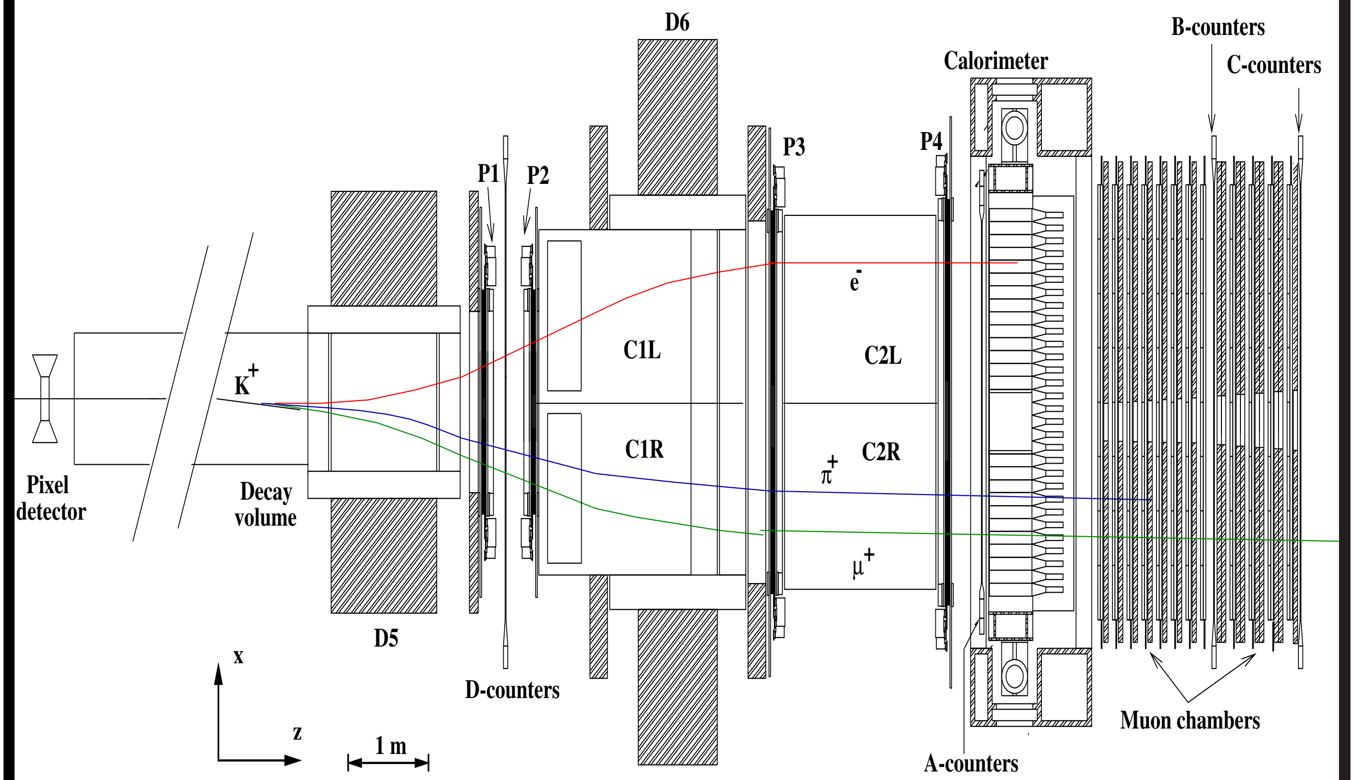
PDG fit: $BR(Ke3)_{PDG} = (4.82 \pm 0.06)\%$

CKM Unitarity: $BR(Ke3)_{PDG} \times (1.053 \pm 0.027)$

($|V_{ud}|$ from $0^+ \to 0^+$; Hardy and Towner)

E865: $BR(Ke3) = X(1 \pm 0.004 \pm ??? \pm 0.007)$ $\approx 70,000 events$

E865 Experiment



- Beam: 6GeV/c; 10^7 K^+; 2×10^8 π^+; 1.7×10^8 protons per 2.8 second AGS pulse.

- Designed to search for the decay $K^+ \to \pi^+ \mu^+ e^-$ (LFV) at the level of 10^{-11}

- No Kaon flux measurement

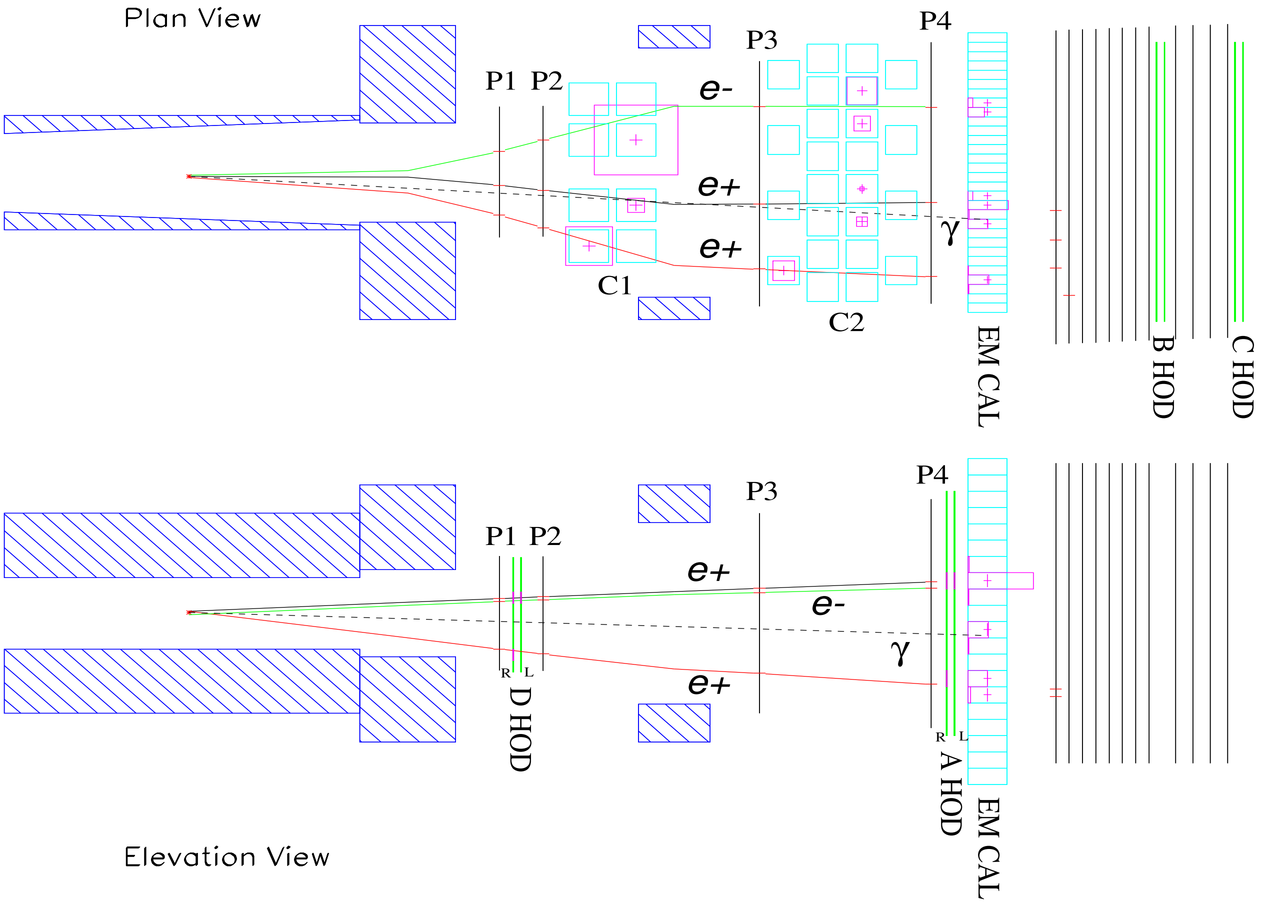
Kaon decays collected for Ke3 measurement

Decay	B.R.
$K^+ \to \pi^+\pi^0 (K\pi 2)$	$(21.16 \pm 0.14)\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.59 \pm 0.05)\%$
$K^+ \to \pi^+\pi^0\pi^0 (K\pi 3)$	$(1.73 \pm 0.04)\%$
$K^+ \to \pi^0\mu^+\nu (K\mu 3)$	$(3.18 \pm 0.08)\%$
$K^+ \to \pi^0 e^+\nu (Ke3)$	$(4.82 \pm 0.06)\%$
$\pi^0 \to e^+e^-\gamma$	$(1.198 \pm 0.032)\%$

- $$\frac{BR(K^+ \to \pi^0 e^+ \nu)}{Kdal} = \frac{N_{Ke3}/Acc^{Ke3}}{N_{Kdal}/Acc^{K\pi 2}}$$
- $$\begin{aligned} Kdal &= BR(K^+ \to \pi^+\pi^0) \\ &+ (Acc^{K\mu 3}/Acc^{K\pi 2}) \times BR(K^+ \to \pi^0\mu^+\nu) \\ &+ (Acc^{K\pi 3}/Acc^{K\pi 2}) \times BR(K^+ \to \pi^+\pi^0\pi^0) \end{aligned}$$

$Acc^{Ke3} \approx Acc^{K\pi 2} \approx Acc^{K\mu 3} \approx Acc^{K\pi 3}$

E865 Ke3 Trigger



First Level Trigger (T0):

•$(D\ HOD_{LEFT}) \times (D\ HOD_{RIGHT})$

Ke3 Trigger (ELER):

• $T0 \times C1_{RIGHT} \times C1_{LEFT} \times C2_{RIGHT} \times C2_{LEFT}$

Cerenkov Efficiency Trigger (CERENK):

•Three out of four Cerenkov Counters

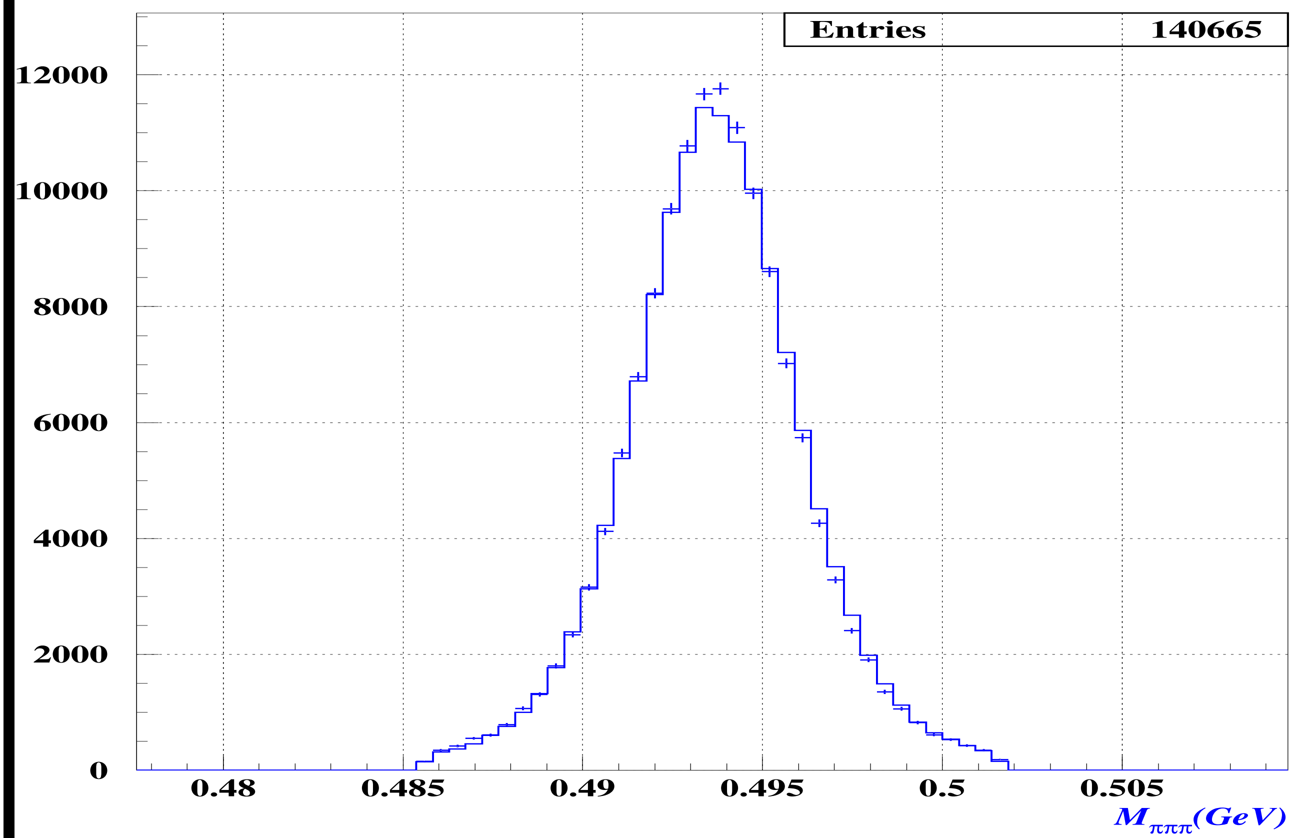
Prescaled T0 Trigger (T0PS):

•T0 prescaled by 10,000

Monte Carlo Simulation

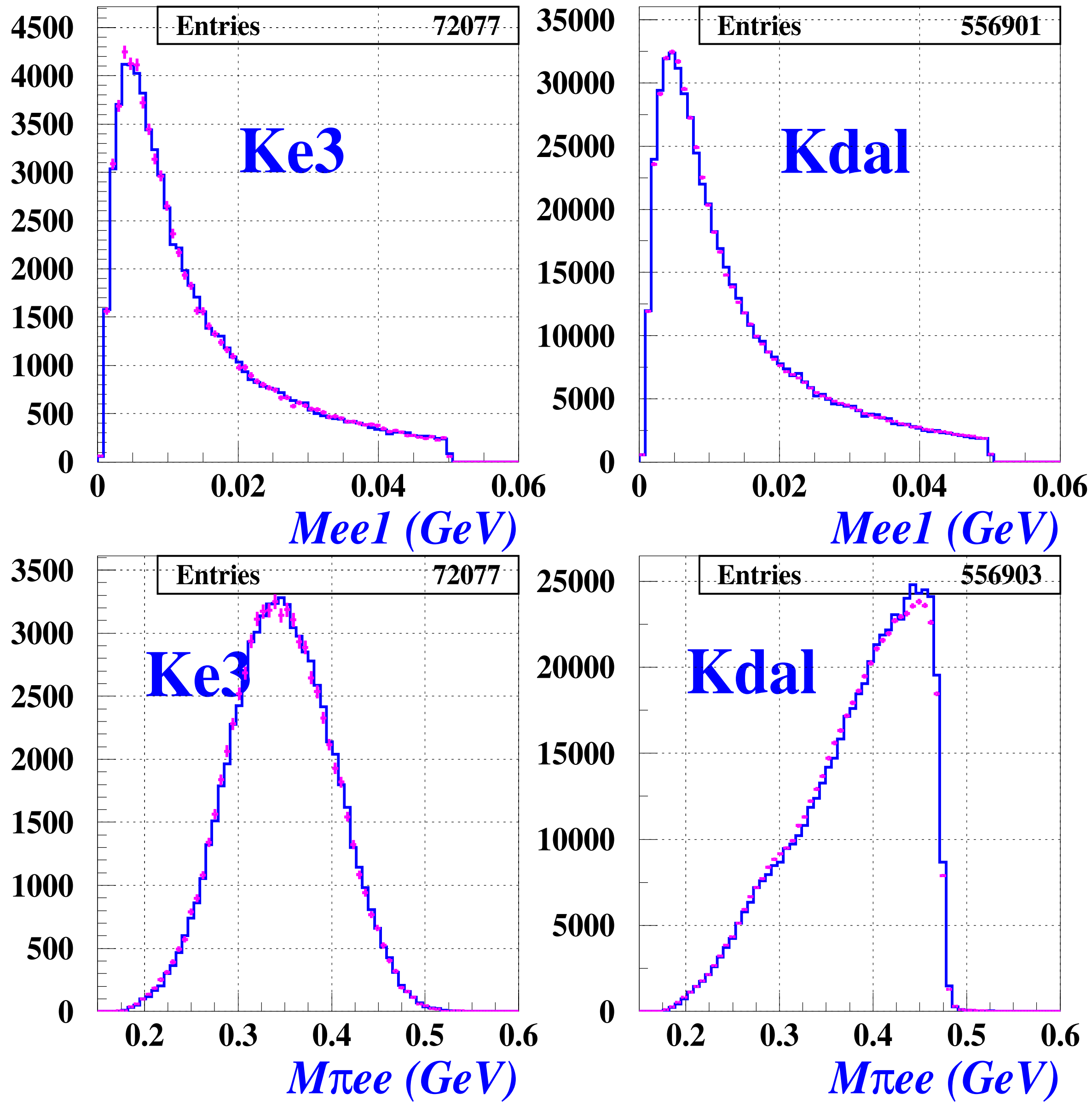
The Monte Carlo simulation was done for all pertinent decay modes.

- The kaons from reconstructed data $K^+ \to \pi^+\pi^+\pi^-$ decays were used as a bank of initial kaons for the Monte Carlo.
- The phase-space dependent efficiency maps of the D counters, Cerenkov counters, and PWCs were applied to all Monte Carlo events.
- The simulated events were reconstructed and selected by the same code as the data events.



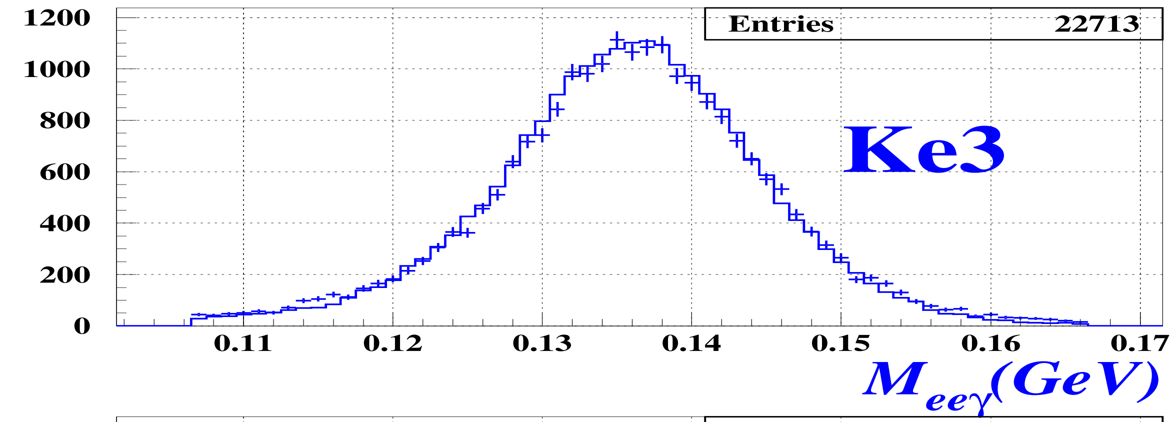
Decay Chain	Mechanism for the decay misidentification as Ke3	Fraction in the selected Ke3 sample (Monte Carlo estimate)
$K^+ \to \pi^+\pi^0$; $\pi^0 \to e^+e^-\gamma$	π^+ misidentified as e^+	$(0.05 \pm 0.01)\%$
$K^+ \to \pi^0\mu^+\nu$; $\pi^0 \to e^+e^-\gamma$	μ^+ misidentified as e^+	$(0.024 \pm 0.004)\%$
$K^+ \to \pi^+\pi^0\pi^0$ with one $\pi^0 \to e^+e^-\gamma$	π^+ misidentified as e^+	$(0.04 \pm 0.01)\%$
$K^+ \to \pi^+\pi^0\pi^0$ with two $\pi^0 \to e^+e^-\gamma$	π^+ misidentified as e^+ or the three reconstructed tracks are $e^+e^+e^-$	$(0.064 \pm 0.008)\%$
$K^+ \to \pi^+\pi^0$; $\pi^0 \to e^+e^-e^+e^-$	π^+ misidentified as e^+ or the three reconstructed tracks are $e^+e^+e^-$	$(0.52 \pm 0.03)\%$
$K^+ \to \pi^+\pi^0\pi^0$; $\pi^0 \to e^+e^-e^+e^-$	π^+ misidentified as e^+ or the three reconstructed tracks are $e^+e^+e^-$	$(0.06 \pm 0.01)\%$
$K^+ \to \pi^0\mu^+\nu$; $\pi^0 \to e^+e^-e^+e^-$	μ^+ misidentified as e^+ or the three reconstructed tracks are $e^+e^+e^-$	$(0.04 \pm 0.01)\%$
$K^+ \to \pi^0e^+\nu$; $\pi^0 \to e^+e^-e^+e^-$	the three reconstructed tracks are $e^+e^+e^-$	$(0.55 \pm 0.02)\%$
Total:		$(1.35 \pm 0.04)\%$

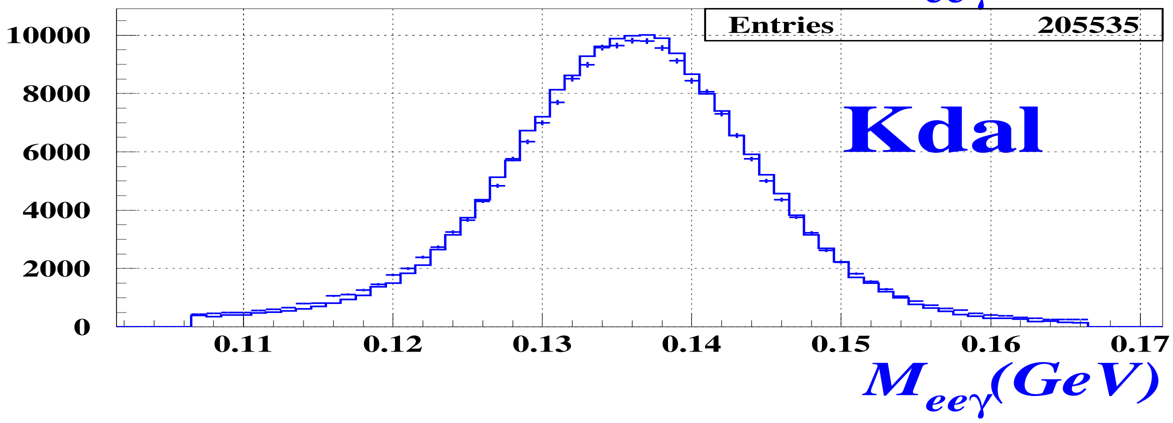
Contamination due to accidental tracks: $(0.33 \pm 0.02)\%$
(from data timing distributions)



Entries 72077
Ke3
Mee1 (GeV)
Entries 556901
Kdal
Mee1 (GeV)
Entries 72077
Ke3
Mπee (GeV)
Entries 556903
Kdal
Mπee (GeV)

π^0 Reconstruction





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)

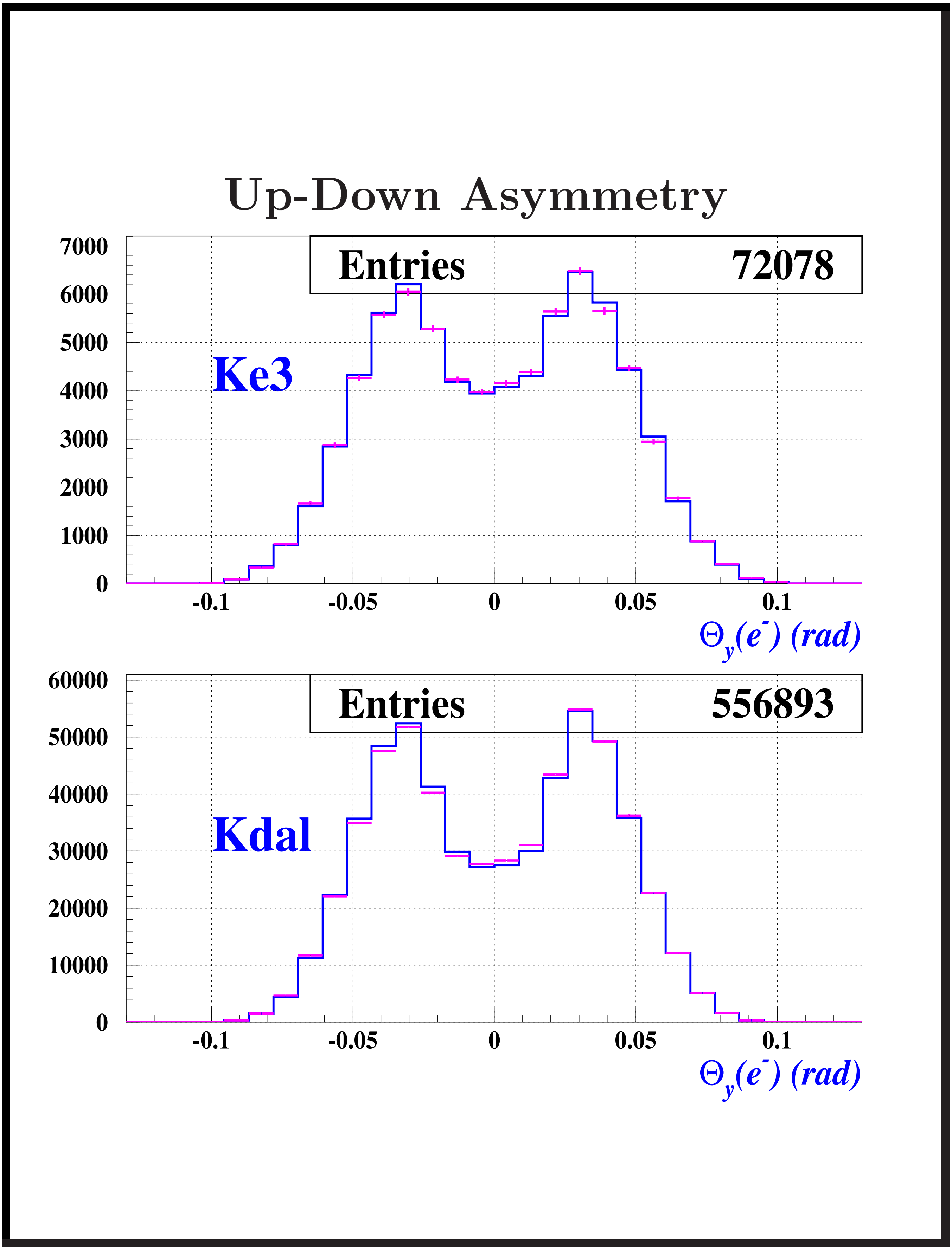
No statistically significant change in the final result

Systematic Errors

- Statistical error is 0.4% (about 70,000 selected Ke3 events without π^0 reconstruction)
- Systematic error :
  - Sources :
    * Detector efficiencies
    * Detector acceptance
    * Physical backgrounds
    * Reconstruction of tracks in the spectrometer
    * Decay phase space density simulation
  - Study by observing result variation in the presence of :
    * Alternative methods of detector efficiencies measurement and application
    * Variations of selection criteria
    * Full reconstruction of the π^0
    * Variations of the event reconstruction method
    * Variations in the spectrometer magnetic field
    * Variations in the simulation of the Ke3 phase space density
    * Comparison of Data and Monte Carlo distributions
    * Data subdivisions

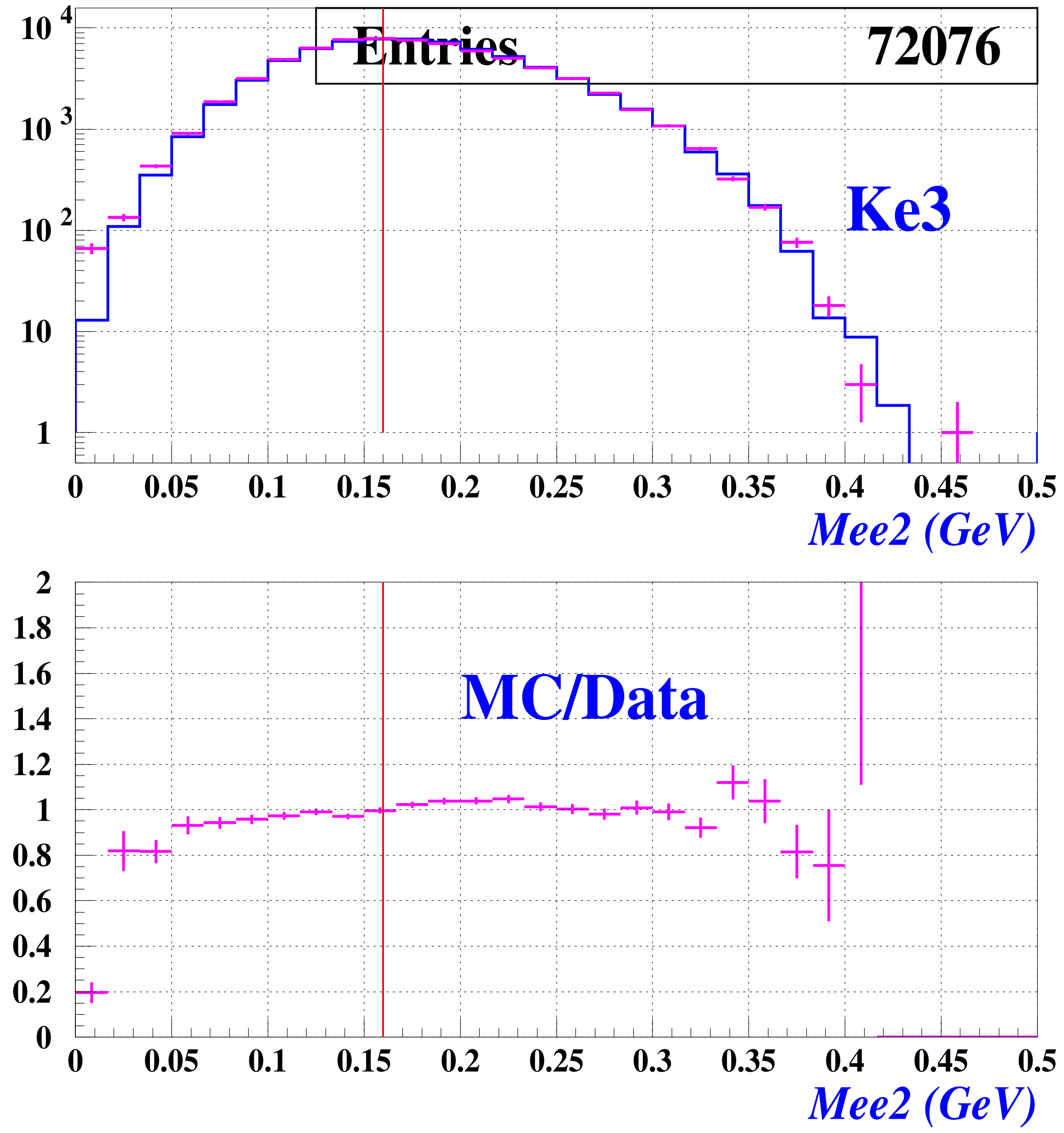
Systematic Errors Summary

Source of systematic error	Estimated error
Vertex quality cut	0.6%
Vertex position cut	0.06%
Detector Aperture	0.1%
Cerenkov Ambiguity Cut	0.3%
PWC efficiencies	0.2%
D counter efficiencies	0.15%
Cerenkov efficiencies	0.3%
Up-down asymmetry	1.0%
Mee2 distribution	1.0%
Uncorrelated sum	1.6%



Up-Down Asymmetry
Entries 72078
Ke3
7000
6000
5000
4000
3000
2000
1000
0
-0.1
-0.05
0
0.05
0.1
$\Theta_y(e^-)$ (rad)
Entries 556893
Kdal
60000
50000
40000
30000
20000
10000
0
-0.1
-0.05
0
0.05
0.1
$\Theta_y(e^-)$ (rad)

Invariant mass of e^- and the second positive track (not e^+ from π^0 decay)



$BR(K^+ \to \pi^+\pi^+\pi^-)/Kdal$

$\pi^0 \to e^+e^-\gamma$ branching ratio:

- Experimental result:
  $BR(\pi^0 \to e^+e^-\gamma) = (1.198 \pm 0.032)\%$
- Theoretical prediction (QED):
  $BR(\pi^0 \to e^+e^-\gamma) = (1.184 \pm 0.002)\%$

Ingredients:

- $T0PS$ trigger prescale factor:
  $PRESCALE = 0.001108 \pm 0.00002$
- ELER trigger efficiency:
  $EFF_{eler} = (968/984) = 0.983 \pm 0.004$

Result:

- $\frac{BR(K^+ \to \pi^+\pi^+\pi^-)}{Kdal} = (1.01 \pm 0.02) \times R_{PDG}$

where R_{PDG} is the PDG value.

Radiative Corrections

!!WORK IN PROGRESS!!

- E.S. Ginsberg: 1970
- T. Becherrawy: 1970
- V. Cirigliano et al: 2001

Expect:

- Effect: few percent
- Related Error: $< 0.5\%$

Preliminary Result

- $$\frac{BR(K^+ \to \pi^0 e^+ \nu)}{Kdal} = \frac{N_{Ke3}/Acc^{Ke3}}{N_{Kdal}/Acc^{K\pi 2}}$$

- $Kdal = BR(K^+ \to \pi^+ \pi^0)$
  $+ (Acc^{K\mu 3}/Acc^{K\pi 2}) \times BR(K^+ \to \pi^0 \mu^+ \nu)$
  $+ (Acc^{K\pi 3}/Acc^{K\pi 2}) \times BR(K^+ \to \pi^+ \pi^0 \pi^0)$

E865 PRELIMINARY RESULT
without Radiative Corrections

- $$\frac{BR(K^+ \to \pi^0 e^+ \nu)}{Kdal} = \quad 0.1949 \times (1 \pm 0.004 \pm 0.016)$$

- $Kdal = BR(K^+ \to \pi^+ \pi^0)$
  $+ 1.014 \times BR(K^+ \to \pi^0 \mu^+ \nu)$
  $+ 1.116 \times BR(K^+ \to \pi^+ \pi^0 \pi^0)$

- Using PDG values for Branching Ratios in the denominator we infer:
  $BR(K^+ \to \pi^0 e^+ \nu) = (5.13 \pm 0.02 \pm 0.08 \pm 0.04)\%$

Comparison to Previous Results

Prev. Measurement	Result	$\Gamma(Ke3)/\Gamma_{tot}$	N Ke3	Year
$\Gamma(Ke3)/\Gamma(\pi^+\pi^+\pi^-)$	0.850 ± 0.019	4.75 ± 0.1	4385	1971
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$BR(Ke3) = (5.13 \pm 0.02 \pm 0.08 \pm 0.04)\% \quad \approx 70,000 events$

$BR(Ke3)_{CKM}$ inferred from $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

$\mathrm{BR(Ke3)}_{PDG} = (4.82 \pm 0.06)\%$

$\lvert V_{ud}\rvert$ value	Obtained from	$\frac{BR(Ke3)_{CKM}}{BR(Ke3)_{PDG}}$
0.9740 ± 0.0005	Superallowed Nuclear Beta Decays (1)	(1.053 ± 0.027)
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PRELIMINARY E865 RESULT without radiative corrections

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