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

SLAC Experimental Seminar

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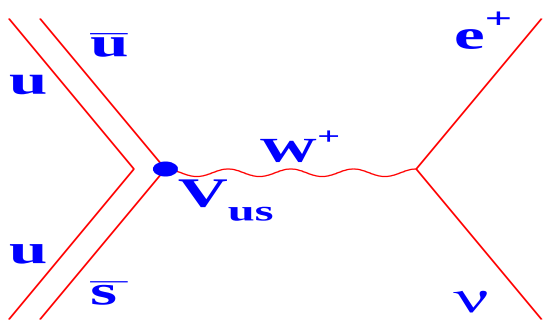
- Physics Motivation
- Detector and Trigger Description
- Detector Calibration and Event Selection
- Contamination of the selected Ke3 sample
- Systematic Errors
- Radiative Corrections
- Summary



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

$|V_{ud}| = 0.9740 \pm 0.0005$ - Nuclear Beta Decays

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

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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9969 \pm 0.0014$$

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

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

Ingredients for the V_{us} calculation:

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

BR(Ke3)

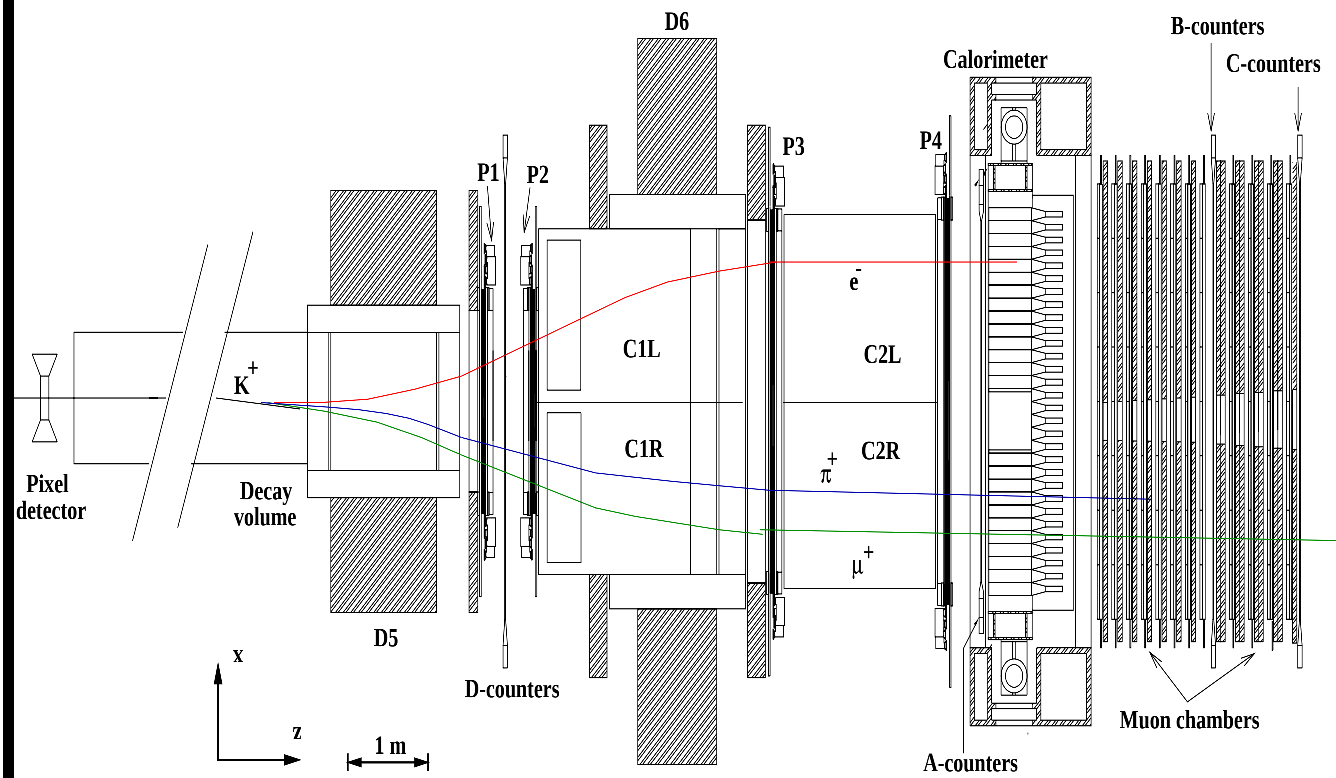
Prev. Measurement	Result	$,(Ke3)/,_{tot}$	N Ke3	Year
$,(Ke3)/,(\pi^+\pi^+\pi^-)$	0.850 ± 0.019	4.75 ± 0.1	4385	1971
$,(Ke3)/,_{tot}$	4.86 ± 0.1	4.86 ± 0.1	3516	1972
$,(Ke3)/,(\pi^+\pi^0)$	0.221 ± 0.012	4.67 ± 0.25	786	1973
$,(Ke3)/,(\pi^+\pi^+\pi^-)$	0.867 ± 0.027	4.85 ± 0.15	2768	1987

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

CKM Unitarity: $BR(Ke3)_{PDG} \times (1.060 \pm 0.027)$

E865: $BR(Ke3) = X(1 \pm 0.4\% \pm ???\% \pm 0.7\%)$ $\approx 65,000 events$

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

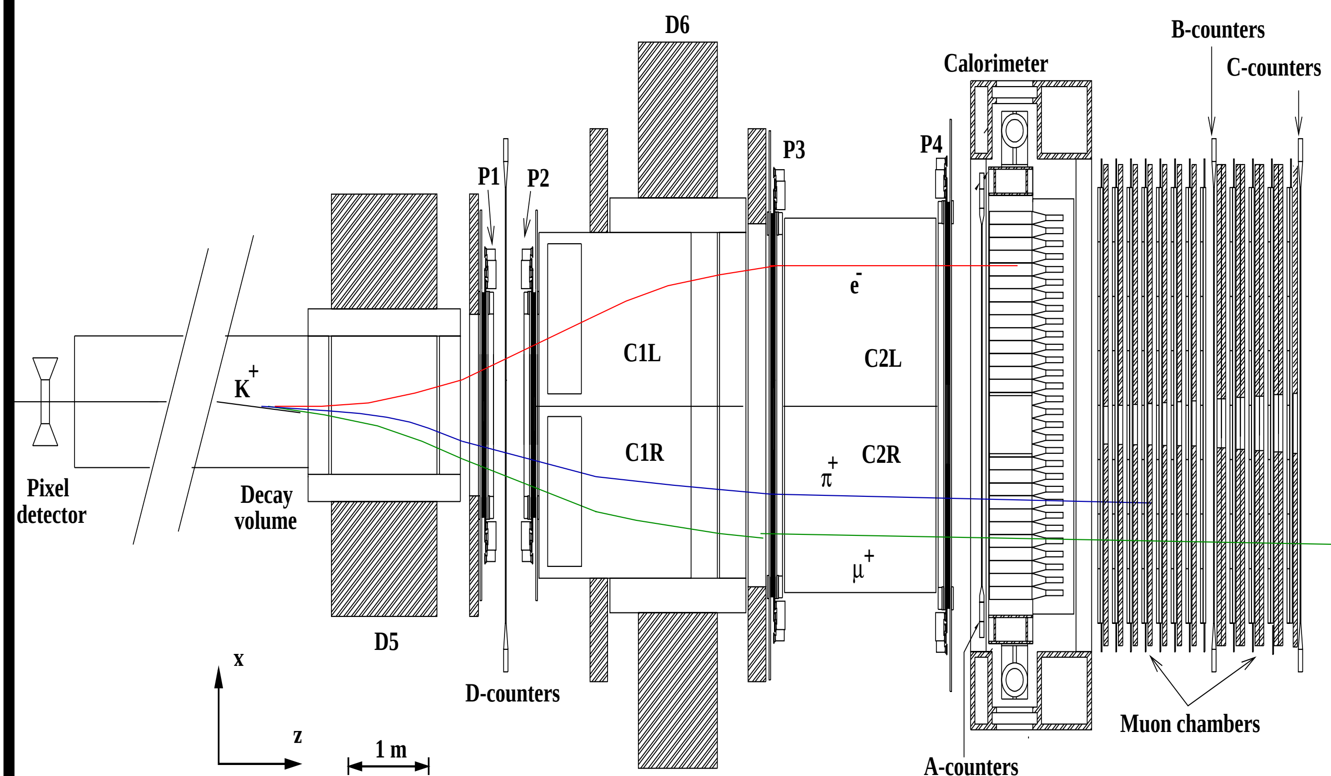
What can we measure?

Decay	B.R.
$K^+ \to \mu^+\nu(K\mu2)$	$(63.51 \pm 0.18)\%$
$K^+ \to \pi^+\pi^0(K\pi2)$	$(21.16 \pm 0.14)\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.59 \pm 0.05)\%$
$K^+ \to \pi^+\pi^0\pi^0(K\pi3)$	$(1.73 \pm 0.04)\%$
$K^+ \to \pi^0\mu^+\nu(K\mu3)$	$(3.18 \pm 0.08)\%$
$K^+ \to \pi^0 e^+\nu(Ke3)$	$(4.82 \pm 0.06)\%$
$\pi^0 \to e^+e^-\gamma$	$(1.198 \pm 0.032)\%$

- $\frac{BR(K^+ \to \pi^0 e^+ \nu)}{BR(Kdal)}$

- $BR(Kdal) = BR(K^+ \to \pi^+\pi^0)$
  $+ Acc^{K\mu2} \times BR(K^+ \to \pi^0\mu^+\nu)$
  $+ Acc^{K\pi3} \times BR(K^+ \to \pi^+\pi^0\pi^0)$
  $Acc^{K\mu2} \approx Acc^{K\pi3} \approx 1$

E865 Detector



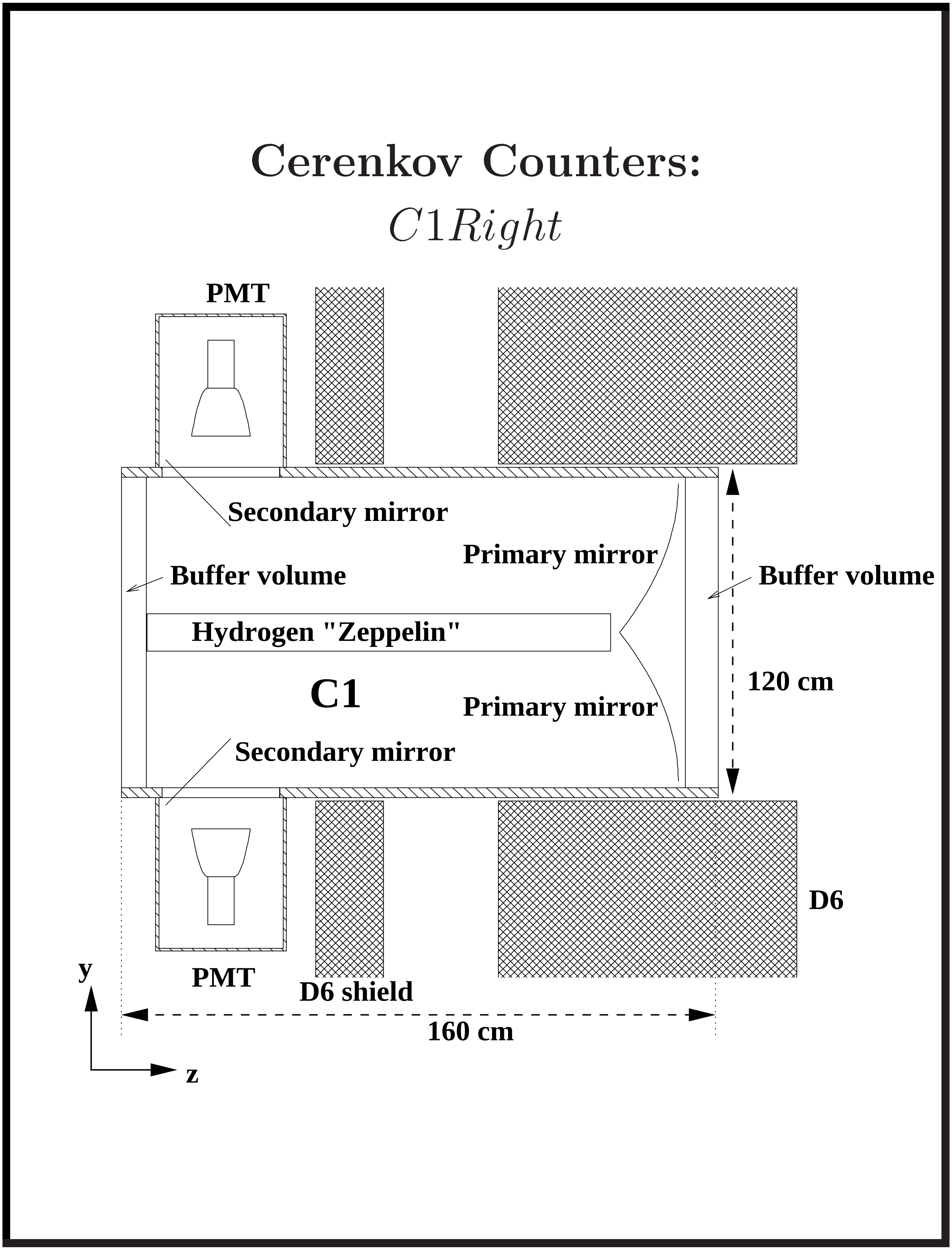
Tracking System:

- Four Proportional Wire Chambers (P1-P4)
- Dipole Magnet ($P_t = 255 MeV/c$)

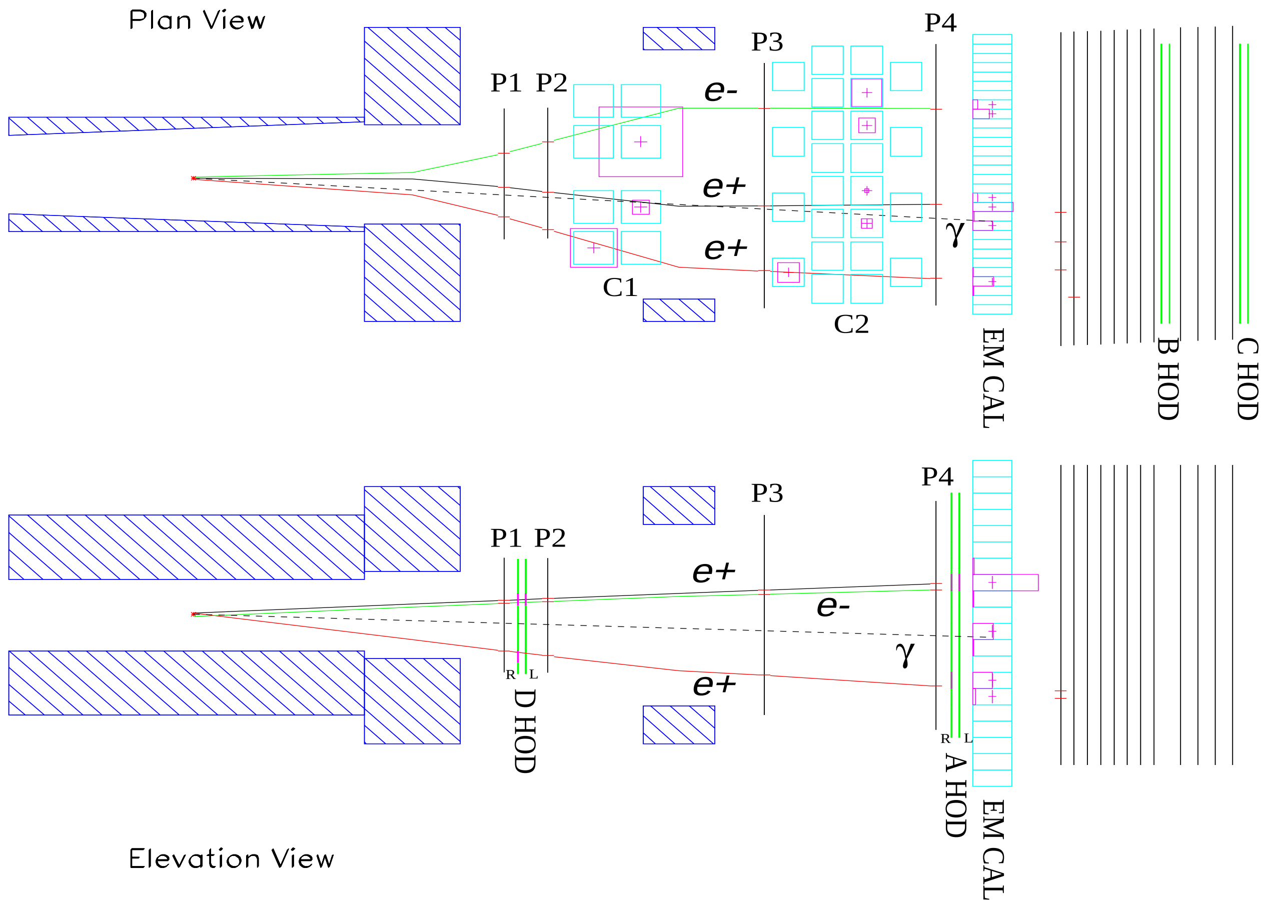
Particle Identification:

- Atmospheric pressure Cerenkov Counters (C1,C2)
- Shashlik design Electromagnetic calorimeter (EM CAL)
- Muon system

Trigger hodoscopes (A, B, C and D HOD)


Cerenkov Counters:
C1Right
PMT
Secondary mirror
Primary mirror
Buffer volume
Buffer volume
Hydrogen "Zeppelin"
C1
120 cm
Primary mirror
Secondary mirror
D6
PMT
D6 shield
y
160 cm
z

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

Data collection

- One week dedicated Ke3 run
- About 50 million triggers collected

First stage of analysis (PASS1)

- Three charged tracks with the common vertex
- Only Proportional Wire Chambers (PWCs) information was used

Detector Calibration from collected data

Cerenkov counters:

- Amplitude dependent time correction for each PMT
- One photoelectron gain and ADC pedestal for each PMT

D counter:

- Time correction dependent on the hit's coordinate along the scintillator slab

Calorimeter:

- Amplitude dependent time correction for each module
- Gain and pedestal for each module

Proportional Wire Chambers:

- Position and orientation of each chamber based on the collected data and measurements performed by the AGS survey team

Detector efficiencies

Detector efficiencies were determined from the collected data events.

1. Proportional Wire Chambers efficiencies were obtained from reconstructed tracks using built in redundancy (each PWC has four sensitive planes and only three out of four PWCs are required for track reconstruction).

2. D-counter efficiencies were determined as a function of X coordinate (along the scintillator slabs) from the $CERENK$ trigger.

3. Cerenkov counter efficiencies were obtained from the $CERENK$ trigger. The efficiency map was prepared in the four-dimensional phase-space (two coordinates and two angles) of the charged tracks.

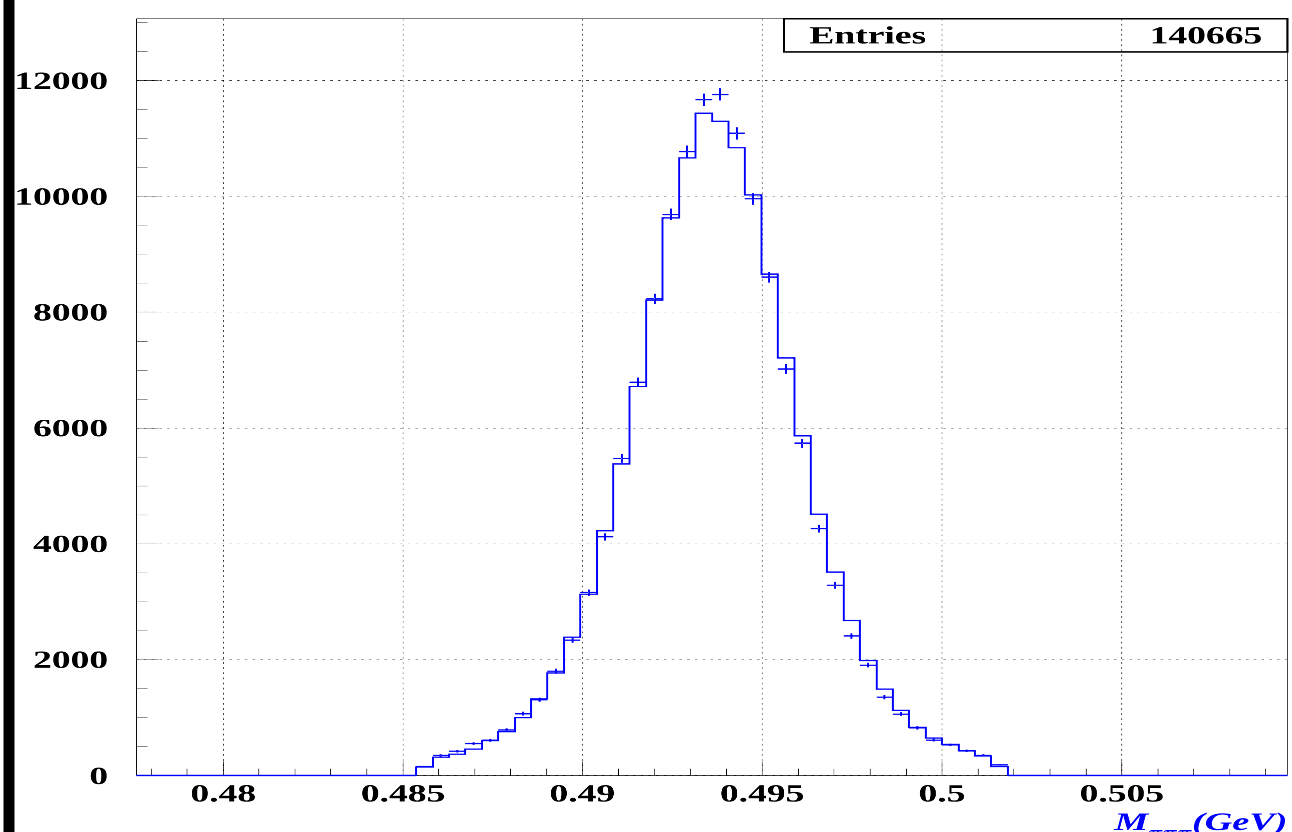
4. Calorimeter efficiencies were measured by observing the signals in the calorimeter modules that were hit by tracks reconstructed in the spectrometer.

Cut	Description	Selected samples	
		Kdal	Ke3
$Snorm$	Vertex quality cut.	YES	YES
$Zvtx$	Rejects upstream events	YES	YES
Aperture cut	Requires all three tracks to go through detector's sensitive regions	YES	YES
Cerenkov Ambiguity (CA)	Rejects events where any one Cerenkov photomultiplier could have detected Cerenkov photons from more than one track	YES	YES
e^+e^- PID	Requires in-time signals in both Cerenkov counters for the pair of negative and positive tracks that produces the smaller M_{ee} invariant mass	YES	YES
M_{ee}	Requires the invariant mass of the found e^+e^- pair to be small ($< 0.05 GeV$)	YES	YES
$(2/2)e^+$ PID	The second positive track is required to have in-time signals in both Cerenkov counters (C1 and C2)	NO	YES
$(2/3)e^+$ PID	The second positive track is required to satisfy at least two out of the following three conditions: in-time signal in C1; in-time signal in C2; energy deposition in the Calorimeter consistent with the track's momentum $(E/P) > 0.8$	NO	YES
π^+/μ^+ PID cut	Requirement for the second positive track to not have in-time signals in either Cerenkov counter	YES	NO

Monte Carlo Simulation

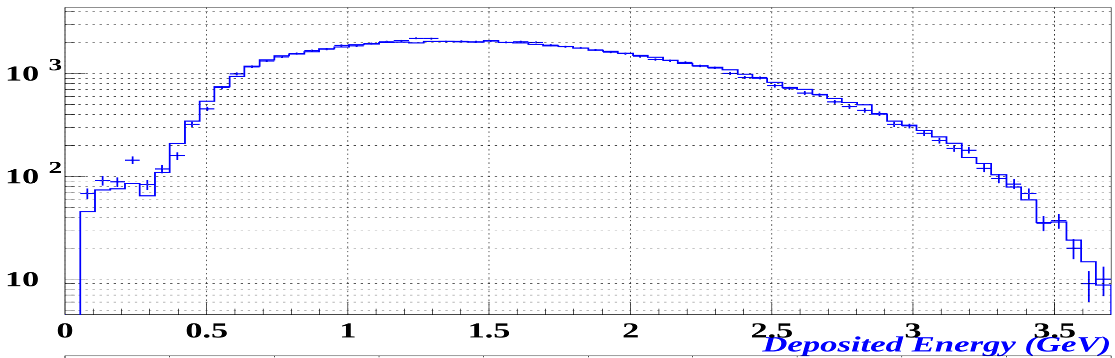
The Monte Carlo simulation was done for all pertinent decay modes.

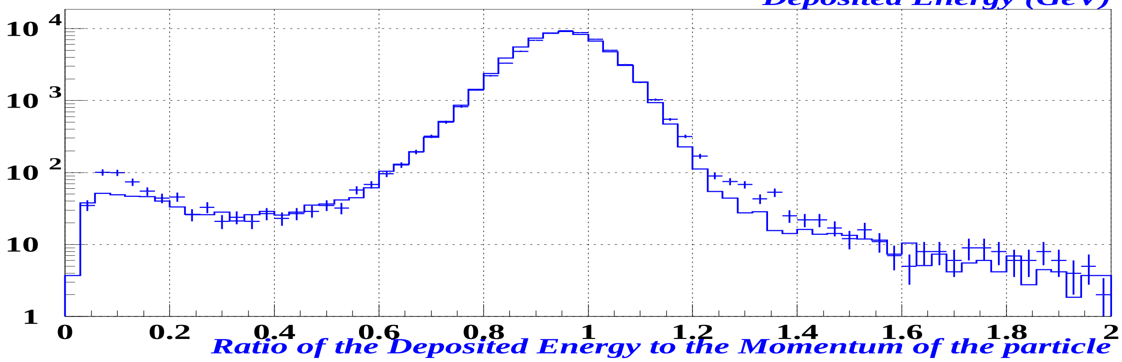
- The kaons from reconstructed data $K^+ \to \pi^+\pi^+\pi^-$ decays were used as a bank of initial kaons for the Monte Carlo.
- The phase-space dependent efficiency maps of the D counters, Cerenkov counters, and PWCs were applied to all Monte Carlo events.
- The simulated events were reconstructed and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

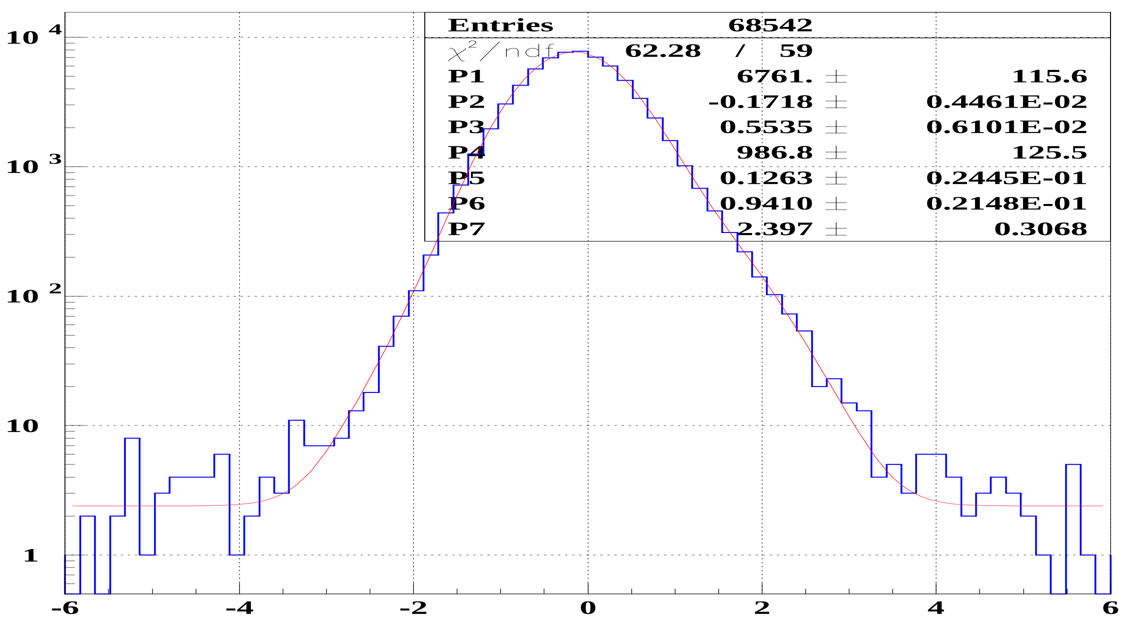


Decay Chain	Mechanism for the decay misidentification as Ke3	Fraction in the selected Ke3 sample (Monte Carlo estimate)
$K^+ \rightarrow \pi^+\pi^0$ $\pi^0 \rightarrow e^+e^-\gamma$	π^+ misidentified as e^+	$(0.05 \pm 0.01)\%$
$K^+ \rightarrow \pi^0\mu^+\nu$ $\pi^0 \rightarrow e^+e^-\gamma$	μ^+ misidentified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

Accidentals







- From the deposited energy distribution: $(0.39 \pm 0.06)\%$
- From the Cerenkov timing distribution: $(0.33 \pm 0.02)\%$

Systematic Errors

- Statistical error is 0.4% (about 65,000 selected Ke3 events without π^0 reconstruction)
- The systematic error is determined by the study of the stability of the result under variation of selection criteria, detector efficiencies applied to the Monte Carlo and subdivision of the selected samples (both signal and normalizer).

1. $Snorm$ and $Zvtx$ cuts
2. Detector Aperture
3. Cerenkov Ambiguity Cut (CAC)
4. PWC efficiencies
5. D counter efficiencies
6. Cerenkov efficiency
7. Full reconstruction of the π^0
8. Comparison of Data and Monte Carlo distributions

Cerenkov Ambiguity Cut(CAC)

- Rejects about 30% of the events with the π^0 in the final state
- Positions of the tracks at the Cerenkov mirror plane are used to make the cut

- Sharing of the Cerenkov light between adjacent mirror assemblies.
- Monte Carlo simulation accuracy of the pion response in the calorimeter.
- Accuracy of the final particles' simulation.

Final Particles simulation:

	without CAC	with CAC
MC/Data	1.000(0.002)	1.003

	Ke3(MC/D)	Dal(MC/D)	Dal/Ke3
CAC is in place	1.000(0.005)	1.000(0.002)	1.000(0.005)
No CAC applied	1.011(0.011)	0.997	0.986(0.011)

- Removal of CAC causes substantial increase in the double ratio error due to the correction caused by the necessary calorimeter inclusion in the particle identification.
- Will use CAC
- CAC error: 0.3%

PWC and D counter efficiencies

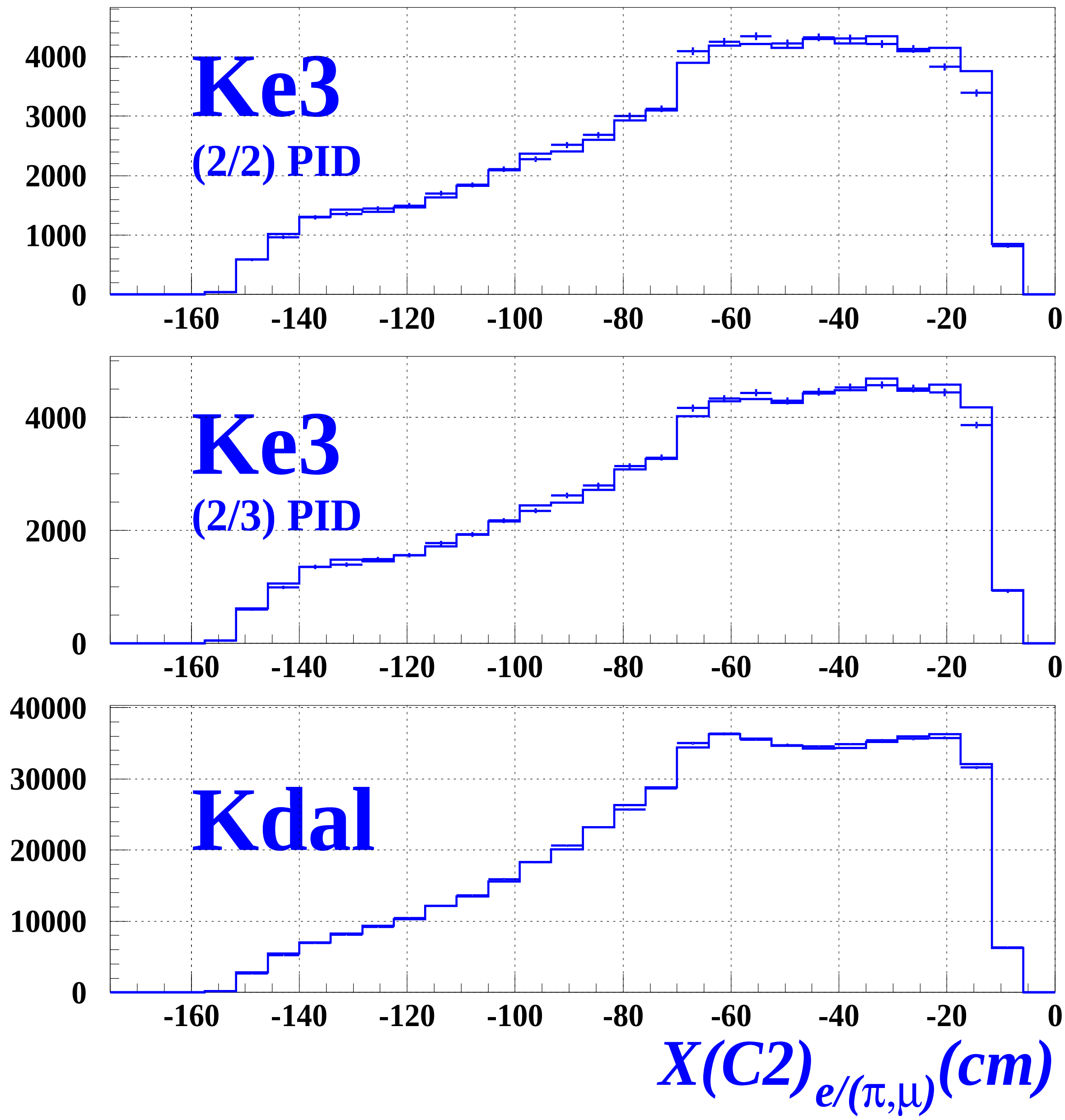
	Ke3(MC/D)	Dal(MC/D)	Dal/Ke3
Wire dependent map	1.000(0.005)	1.000(0.002)	1.000(0.005)
$(X; Y)$ dependent map	0.997	0.995	0.998
100% efficient PWCs	1.011	1.016	1.005

- PWC efficiency error: 0.2%

	Ke3(MC/D)	Dal(MC/D)	Dal/Ke3
Measured efficiency map	1.000(0.005)	1.000(0.002)	1.000(0.005)
100% efficient D counters	1.031	1.026	0.995

- D counter efficiency error: $0.5\% \times 0.30 = 0.15\%$

Cerenkov Efficiencies



Cerenkov Efficiencies

- Variation of the Cerenkov efficiency map binning and selection criteria for the efficiency measurement candidate events resulted in 0.5% variation in the Ke3/Kdal ratio, when using (2/2) e^+ PID.

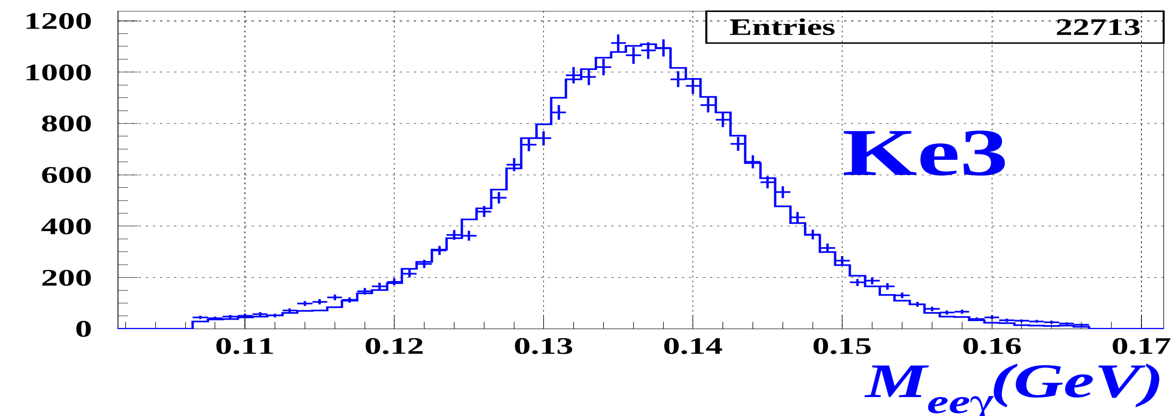
- Application of the alternative (2/3) e^+ PID causes 0.6% shift in the Ke3/Kdal ratio and improves agreement between data and Monte Carlo for the final particle distributions.

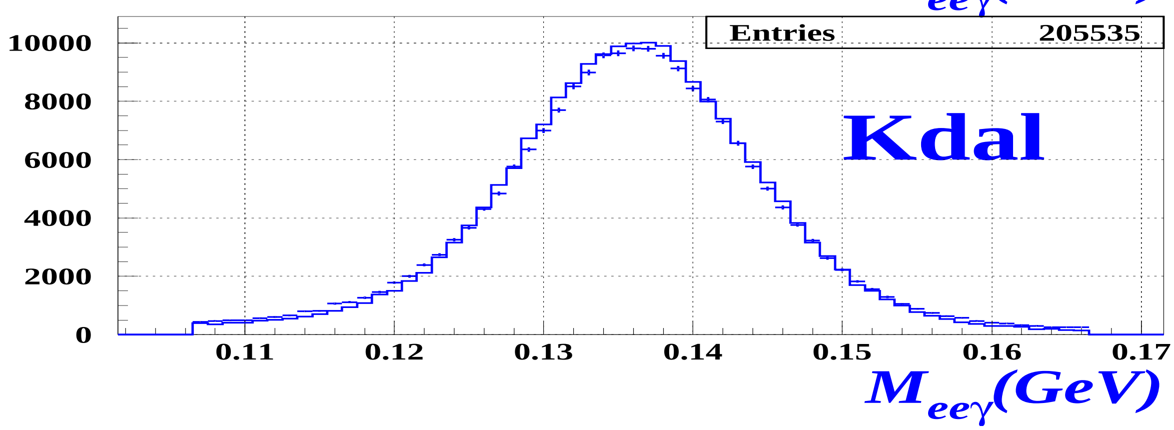
	Efficiency	Contamination by π/μ
(2/2) e^+ PID	0.9603(0.0005)	0.0011(0.0002)
(2/3) e^+ PID	0.9985(0.0001)	0.0032(0.0003)

- Will use (2/3) e^+ PID

- Cerenkov counters efficiency error: 0.3% (scaled from 0.5% to the case of (2/3) e^+ PID)

π^0 Reconstruction

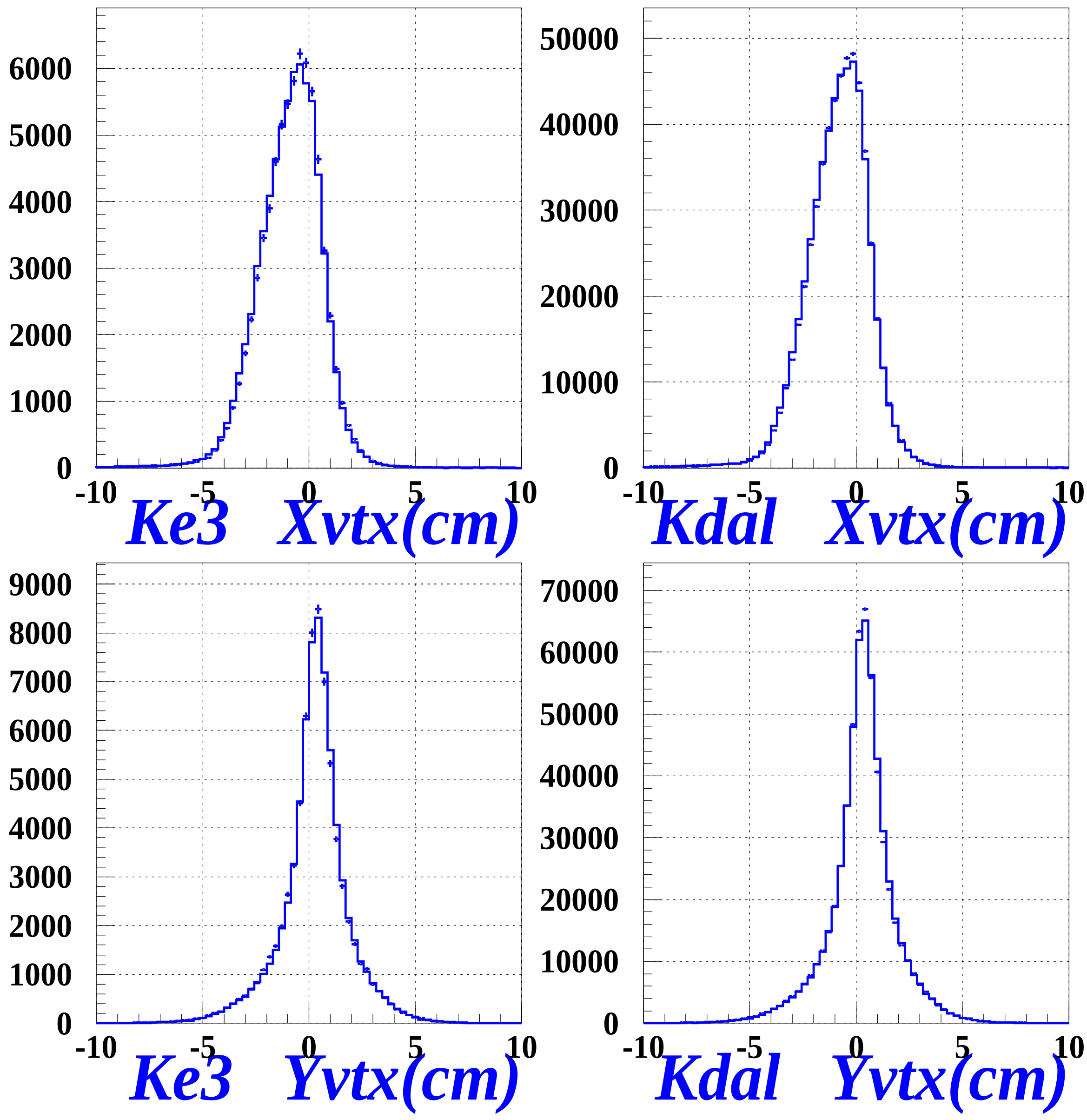




CUT	Ke3(MC/D)	Dal(MC/D)	Dal/Ke3
π^0	1.008(0.008)	1.011(0.004)	1.003(0.009)
NO π^0	0.996(0.006)	0.993(0.003)	0.997(0.007)

No statistically significant change in the final result

Data and Monte Carlo Comparison



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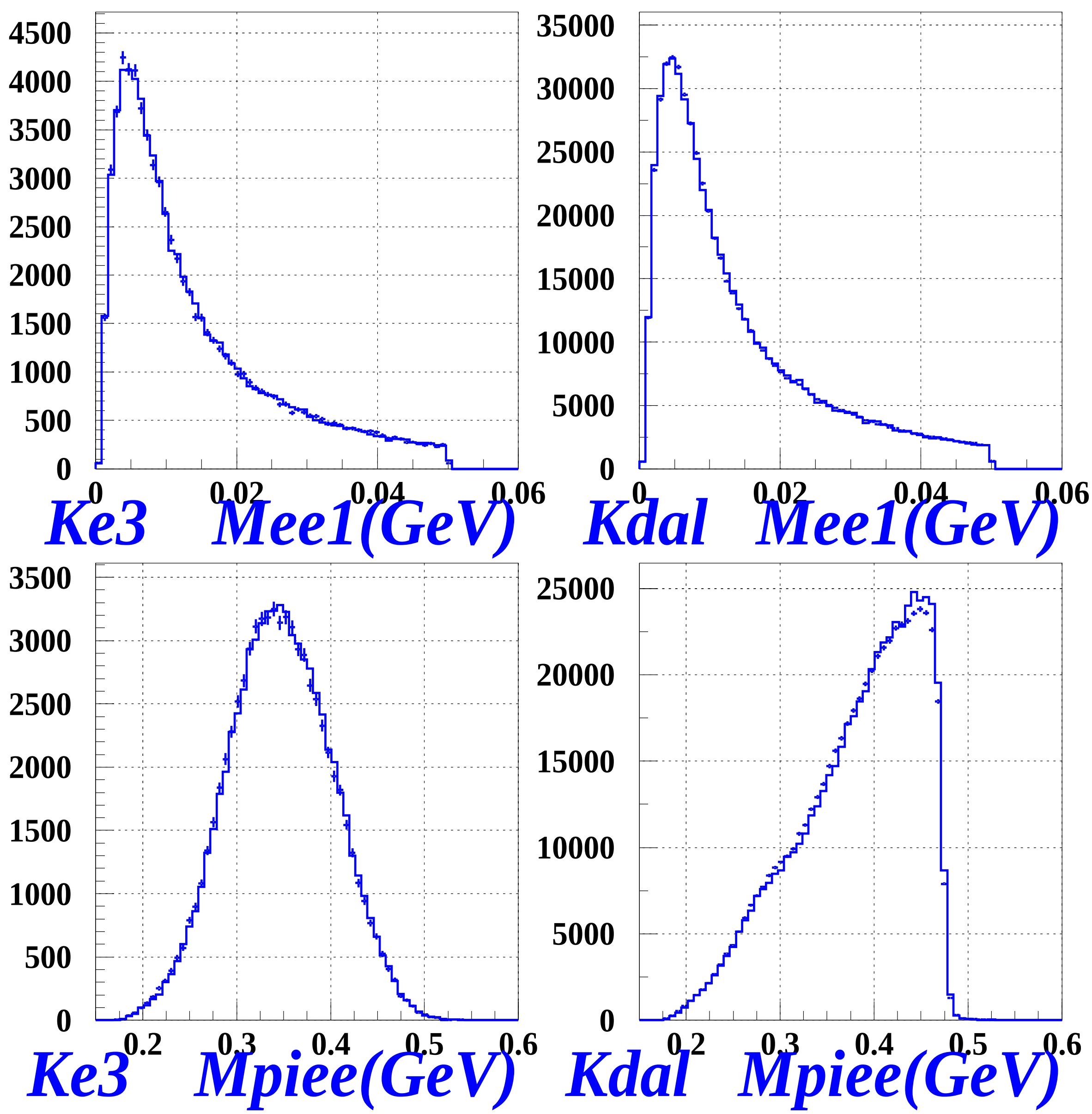

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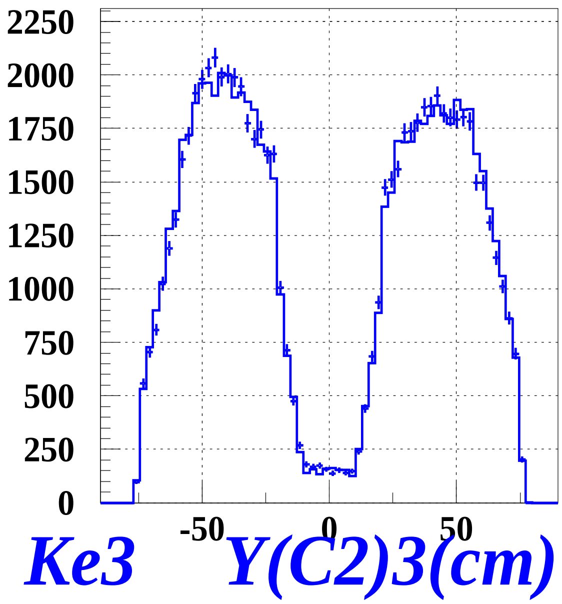
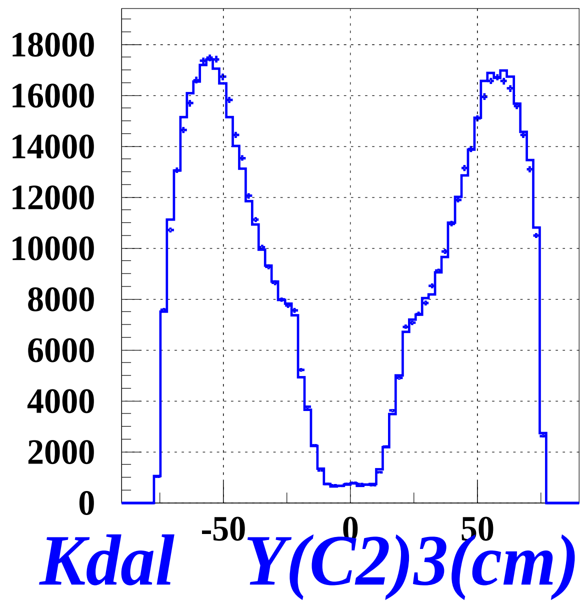
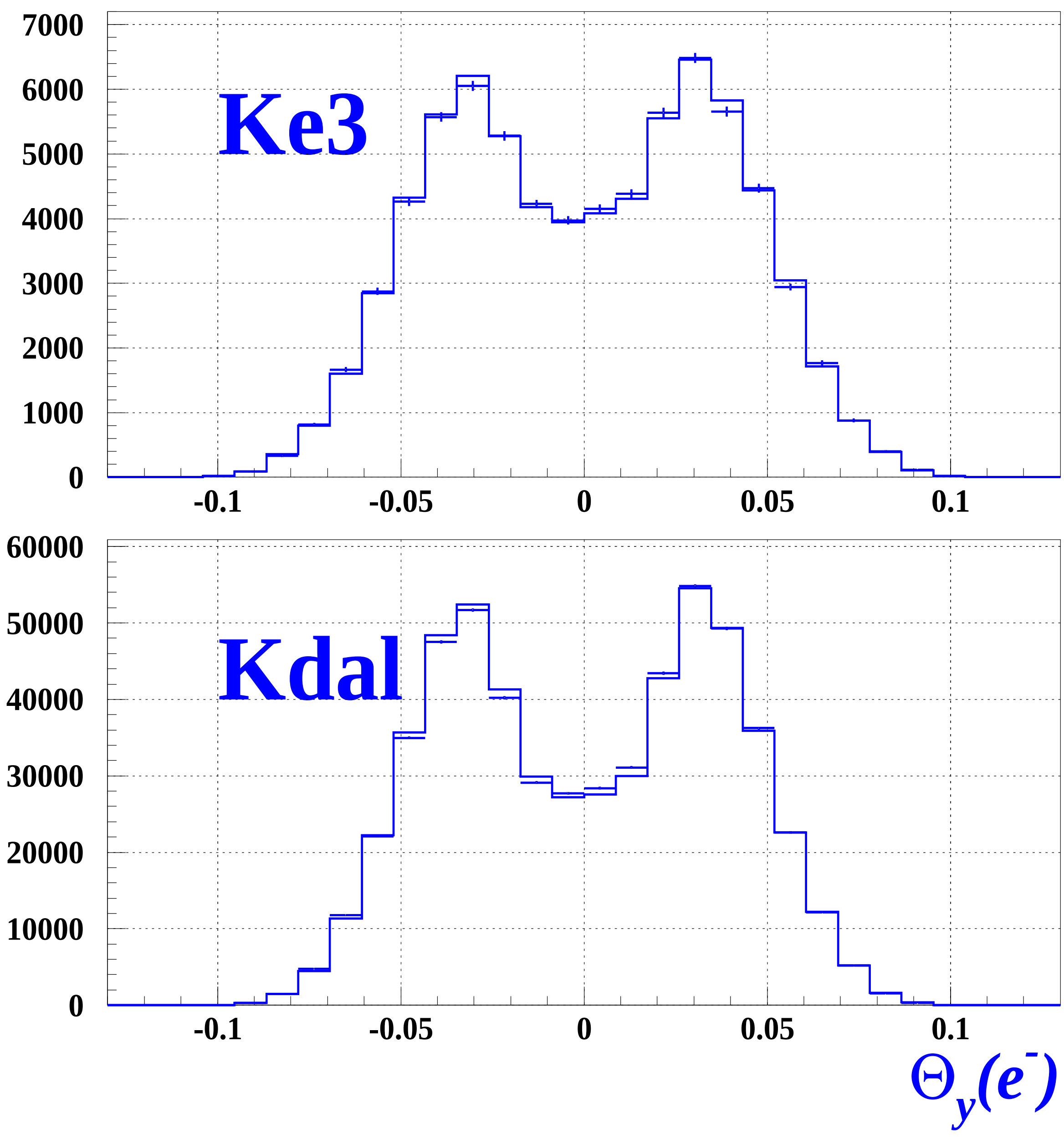




Up-Down Asymmetry



Up-Down Asymmetry

Causes:

- Asymmetric aperture of the downstream decay tank vacuum flange
- Asymmetric detector efficiencies
- Shifts in the coordinate system/magnetic field

Performed Checks:

- Put exact position and configuration of the flange in the Monte Carlo
- Detailed check of the Cerenkov efficiencies
- Detailed check of D counter and PWC efficiencies
- Updated calibration of PWC positions and orientations

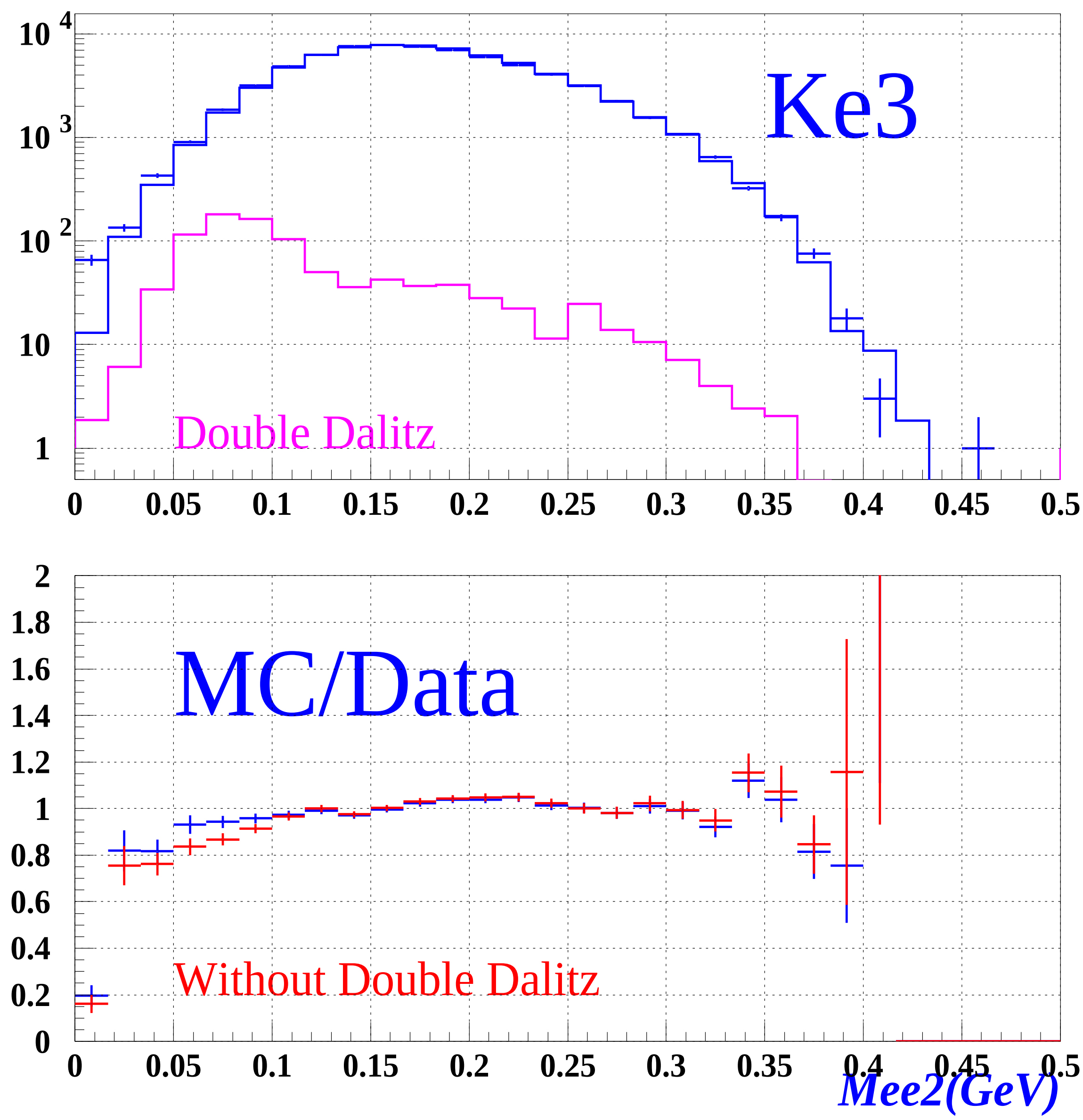
Use of the updated PWC positions reduced single ratio variations by a factor of three

Up-Down Asymmetry

	Ke3(MC/D)	Dal(MC/D)	Dal/Ke3
$\theta_y(e^-) < 0$ (2/3 PID)	1.000(0.007)	1.012(0.003)	1.012(0.008)
$\theta_y(e^-) > 0$ (2/3 PID)	1.000(0.007)	0.989(0.003)	0.989(0.008)
$\theta_y(e^-) < 0$ (2/2 PID)	1.003(0.007)	1.012(0.003)	1.009(0.008)
$\theta_y(e^-) > 0$ (2/2 PID)	0.997(0.007)	0.989(0.003)	0.992(0.008)

- Up-down asymmetry error: 1%
  The error is independent from the Cerenkov efficiency error.

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



Performed Checks:

- Contamination of the selected Ke3 sample caused by accidentals
- Inaccuracies of the tracks kinematics reconstruction in the spectrometer that are not reproduced in the Monte Carlo
- Effect of the inaccuracies of the detector inefficiencies simulation
- Effect of the radiative corrections and initial decay phase-space density simulation

No change in the Mee2 discrepancy

CUT	Ke3(MC/D)	Dal(MC/D)	Dal/Ke3
$Mee2 < 0.16GeV$	0.971(0.007)	0.974(0.004)	1.003(0.008)
$Mee2 > 0.16GeV$	1.020(0.006)	1.007(0.002)	0.987(0.006)
$\pi^0 + Mee2 < 0.16GeV$	0.988(0.013)	0.980(0.007)	0.992(0.015)
$\pi^0 + Mee2 > 0.16GeV$	1.008(0.010)	1.005(0.004)	0.997(0.011)
NO $\pi^0 + Mee2 < 0.16GeV$	0.963(0.010)	0.971(0.005)	1.008(0.011)
NO $\pi^0 + Mee2 > 0.16GeV$	1.027(0.008)	1.008(0.003)	0.981(0.009)

- Discrepancy is present both in signal and normalizer
- Discrepancy decreases with π^0 found: Physical Background ?

Preliminary conclusions:

- Do not make Mee2 cut
- Systematic error: 1%

Systematic Errors Summary

Source of systematic error	Estimated error
Snorm cut	0.6%
Zvtx 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%

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

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

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

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: $< 0.5\%$

Summary

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CKM Unitarity: $BR(Ke3)_{PDG} \times (1.060 \pm 0.027)$

E865: $BR(Ke3) = X(1 \pm 0.4\% \pm 1.6\% \pm 0.7\%)$ $\approx 65,000 events$