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

HQL2004

San Juan, June 1-5 2004

Alexander Sher
sasha@scipp.ucsc.edu

E865 Collaboration

R. Appel[6,3], G.S. Atoyan[4], B. Bassalleck[2], D.R. Bergman[6], N. Cheung[3], S. Dhawan[6], H. Do[6], J. Egger[5], S. Eilerts[2], H. Fischer[2], W. Herold[5], V.V. Issakov[4,6], H. Kaspar[5], D.E. Kraus[3], D.M. Lazarus[1], P. Lichard[3], J. Lowe[2], J. Lozano[6], H. Ma[1], W. Majid[6], S. Pislak[7,6], A.A. Poblaguev[4,6], P. Rehak[1], A. Sher[3], Al. Sher[7], J.A. Thompson[3], P. Truöl[7,6], and M.E. Zeller[6]

[1] *Brookhaven National Laboratory*

[2] *Department of Physics and Astronomy, University of New Mexico*

[3] *Department Of Physics and Astronomy, University of Pittsburgh*

[4] *Institute for Nuclear Research, Moscow*

[5] *Paul Scherrer Institute*

[6] *Physics Department, Yale University*

[7] *Physik-Istitut, Universität Zürich*

- Physics Motivation
- Detector and Trigger Description
- Detector Calibration; Event Selection; Monte Carlo simulation
- Contamination of the selected Ke3 sample
- Systematic Errors
- Consistency checks
- Result
- Summary

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

$$\mathcal{M}_{K\to e\nu\pi^0} = \frac{G_F V_{us}}{2}\Big\{ \left[f_+(t)(p_K+p_\pi)^\mu + f_-(t)(p_K-p_\pi)^\mu\right]\bar{e}\gamma^\mu(1+\gamma^5)\nu$$

$$+2M_K f_S\ \bar{e}(1+\gamma^5)\nu + \frac{2f_T}{M_K}p_K^\lambda p_\pi^\mu \bar{e}\sigma^{\lambda\mu}(1+\gamma^5)\nu\ \Big\}$$

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

- In the Standard Model $f_S = f_T = 0$

$$f_S/f_+(0) = \ .004 \pm .005_{stat} \pm .005_{th}\ \ (\mathrm{ISTRA}, 2003)$$

$$f_T/f_+(0) = -.021 \pm .028_{stat} \pm .014_{th}\ \ (\mathrm{ISTRA}, 2003)$$

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

- f_- is suppressed by small electron mass

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

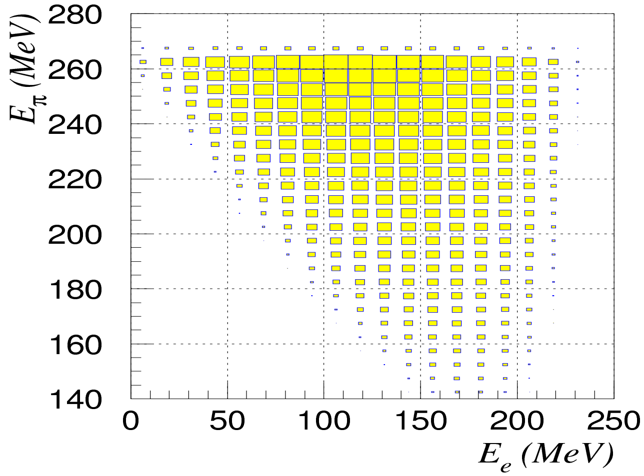
- $f_+(t) = f_+(0)[1+\lambda_+ t/m_{\pi^0}^2]$

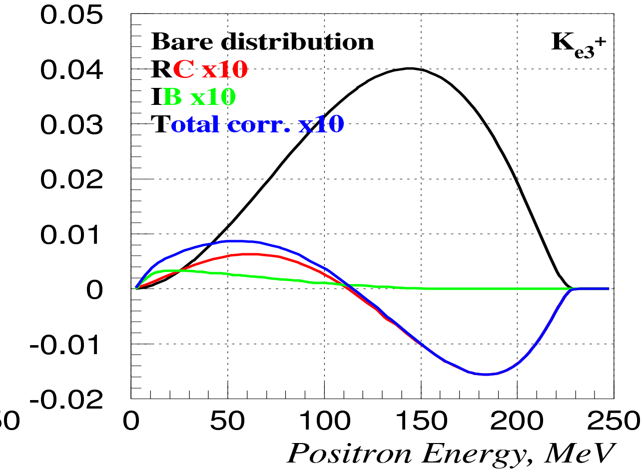
$$f_+(0) \quad = \quad 1+\delta \quad (\delta \ll 1,\ \mathrm{Ademollo-Gatto\ theorem})$$

$$\lambda_+ \quad = \quad 0.0282 \pm 0.0027 \quad (\mathrm{PDG2002\ fit})$$

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

Radiative corrections in the K_{e3}^{+} decay

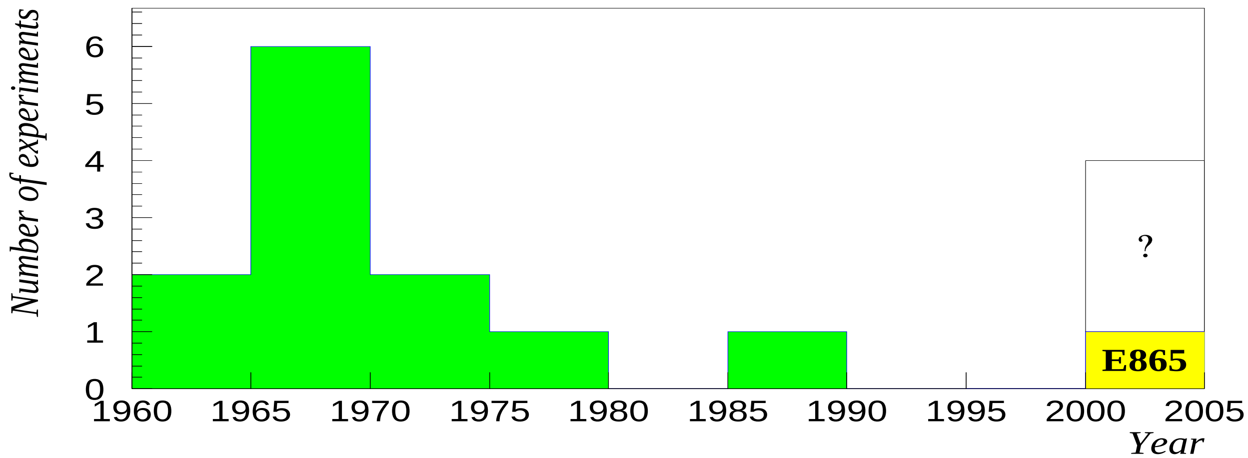




e^{+} energy cut	(MeV)	45	65	100	125	150
B.R. Corr.	(%)	0.5	1.0	2.0	3.0	4.0

- 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



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

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

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

Aren't the previous measurements sufficient?

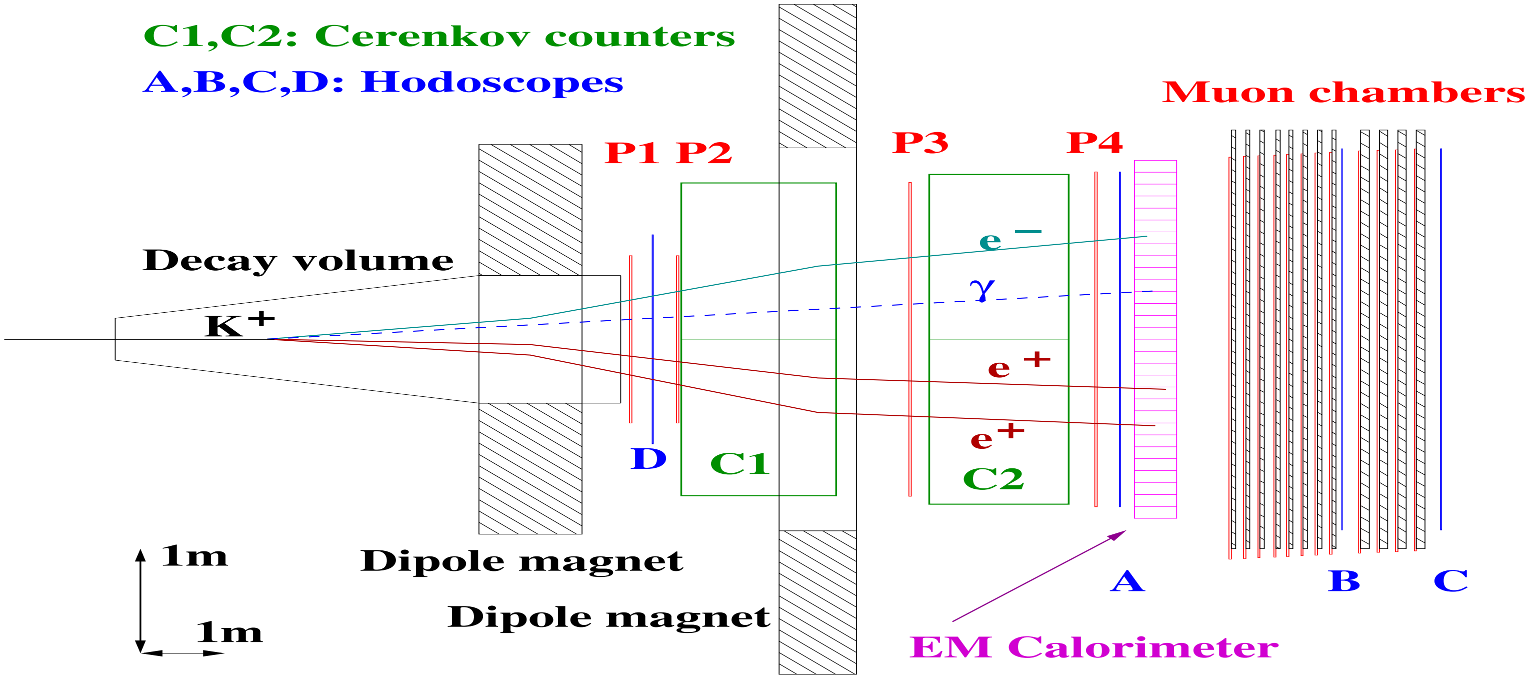
$$|V_{ud}|^2_{\text{nucl.}} + |V_{us}|^2 + |V_{ub}|^2 = 0.9968 \pm 0.0014$$

(2.3 standard deviations from unitarity)

In the last decade, "improvements" in $\boldsymbol{V_{ud}}$ did not improve CKM unitarity. **What if $\boldsymbol{V_{us}}$ 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 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

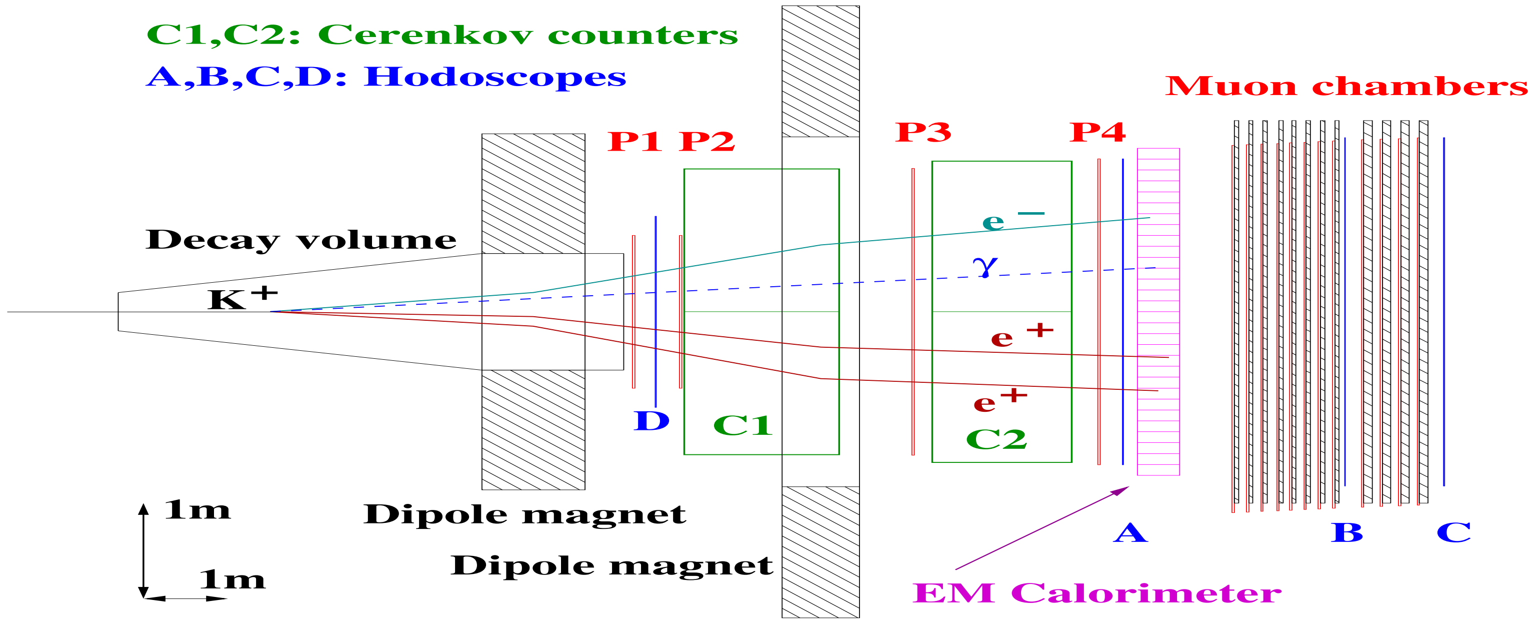
Decay	B.R.
$K^+ \to \pi^+\pi^0 (K\pi2)$	$(21.16 \pm 0.14)\%$
$K^+ \to \pi^+\pi^+\pi^-$	$(5.59 \pm 0.05)\%$
$K^+ \to \pi^+\pi^0\pi^0 (K\pi3)$	$(1.73 \pm 0.04)\%$
$K^+ \to \pi^0\mu^+\nu (K\mu3)$	$(3.18 \pm 0.08)\%$
$K^+ \to \pi^0 e^+\nu (Ke3)$	$(4.82 \pm 0.06)\%$
$\pi^0 \to e^+e^-\gamma$	$(1.198 \pm 0.032)\%$

- $\frac{BR(K^+ \to \pi^0 e^+ \nu)}{Kdal} = \frac{N_{Ke3}/Acc^{Ke3}}{N_{Kdal}/Acc^{K\pi2}}$

- $Kdal = BR(K^+ \to \pi^+\pi^0)$
  $+ (Acc^{K\mu3}/Acc^{K\pi2}) \times BR(K^+ \to \pi^0\mu^+\nu)$
  $+ (Acc^{K\pi3}/Acc^{K\pi2}) \times BR(K^+ \to \pi^+\pi^0\pi^0)$

$Acc^{Ke3} \approx Acc^{K\pi2} \approx Acc^{K\mu3} \approx Acc^{K\pi3}$

E865 Detector



Tracking System:

•Four Proportional Wire Chambers (P1-P4)

•Dipole Magnet ($P_t = 255 MeV/c$)

Particle Identification:

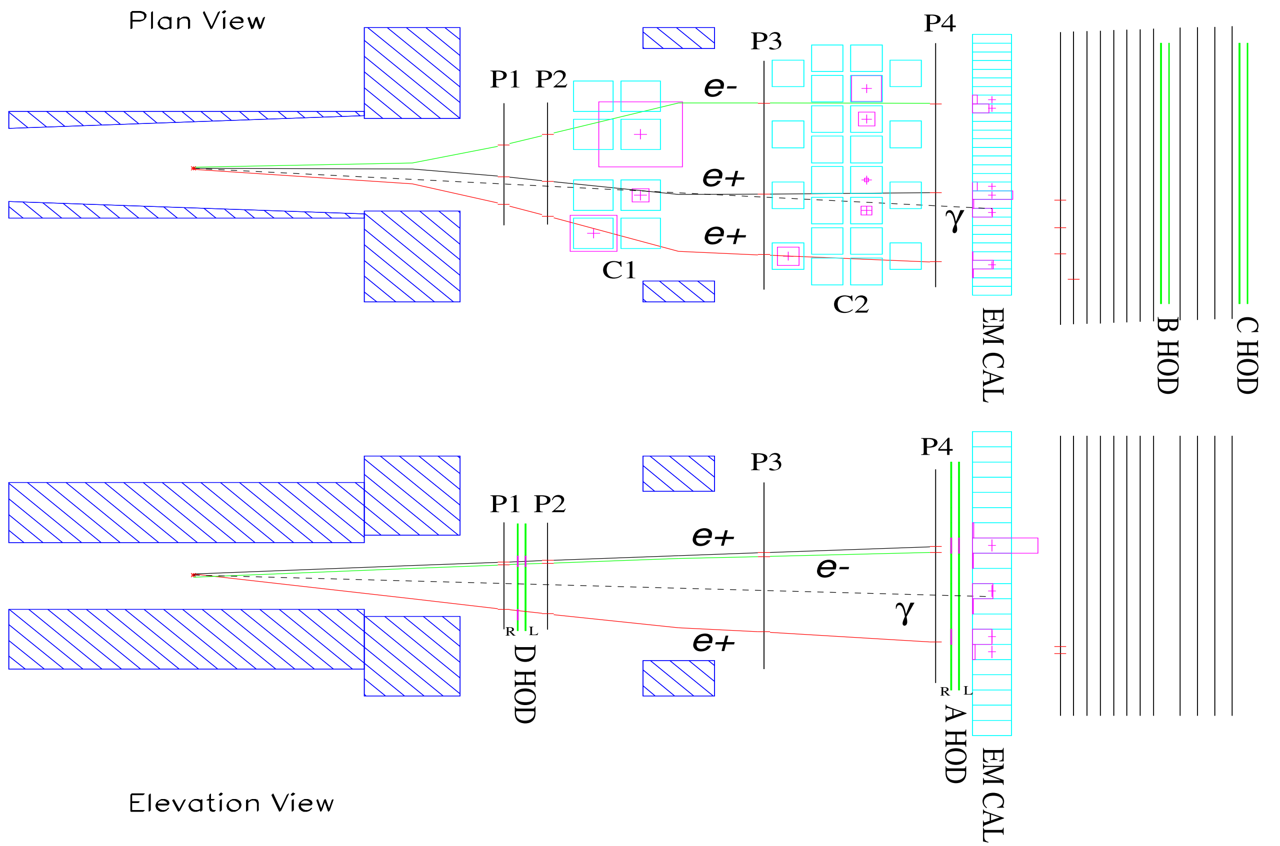
•Atmospheric pressure Cerenkov Counters (C1,C2)

•Shashlik design Electromagnetic calorimeter (EM CAL)

•Muon system

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

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 in the end of 1998
- 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.

Event Selection

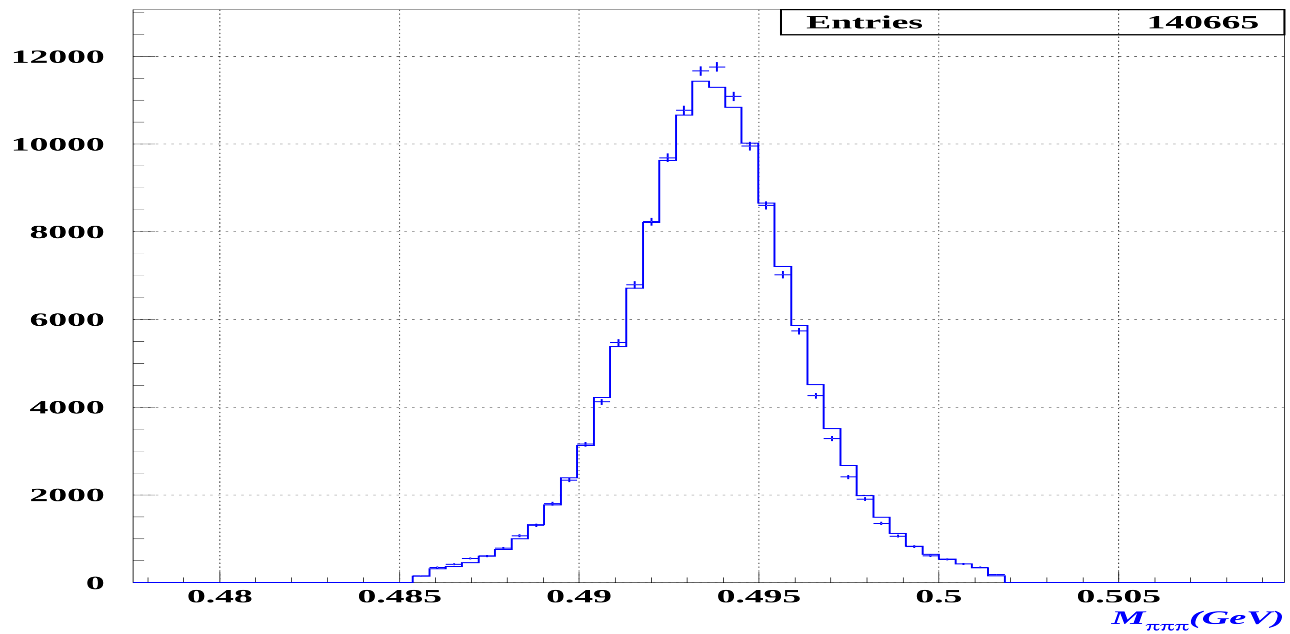
Cut	Description	Selected samples	
		Kdal	Ke3
$Snorm$	Vertex quality cut.	YES	YES
$Zvtx$	Rejects upstream events	YES	YES
Aperture cut	Requires all three tracks to go through detector's sensitive regions	YES	YES
Cerenkov Ambiguity (CA)	Rejects events where any one Cerenkov photomultiplier could have detected 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 ($< 0.05GeV$)	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
.not.(2/2) π^+/μ^+ PID	Requirement for the second positive track to NOT satisfy the $(2/2)e^+$ PID	YES	NO

Flow-chart of the data reduction by applied selection criteria

Selection criteria	Number of events
Collected $ELER$ triggers	37,676,459
Three tracks with the common vertex	2,851,581
Vertex, aperture, and Cerenkov Ambiguity cuts	710,486
$M_{ee} < 0.05 GeV$	643,720
Low mass e^+e^- pair identification	625,727
(2/3)e^+ PID of the second positive track (Ke3 selection)	71,204

Monte Carlo Simulation

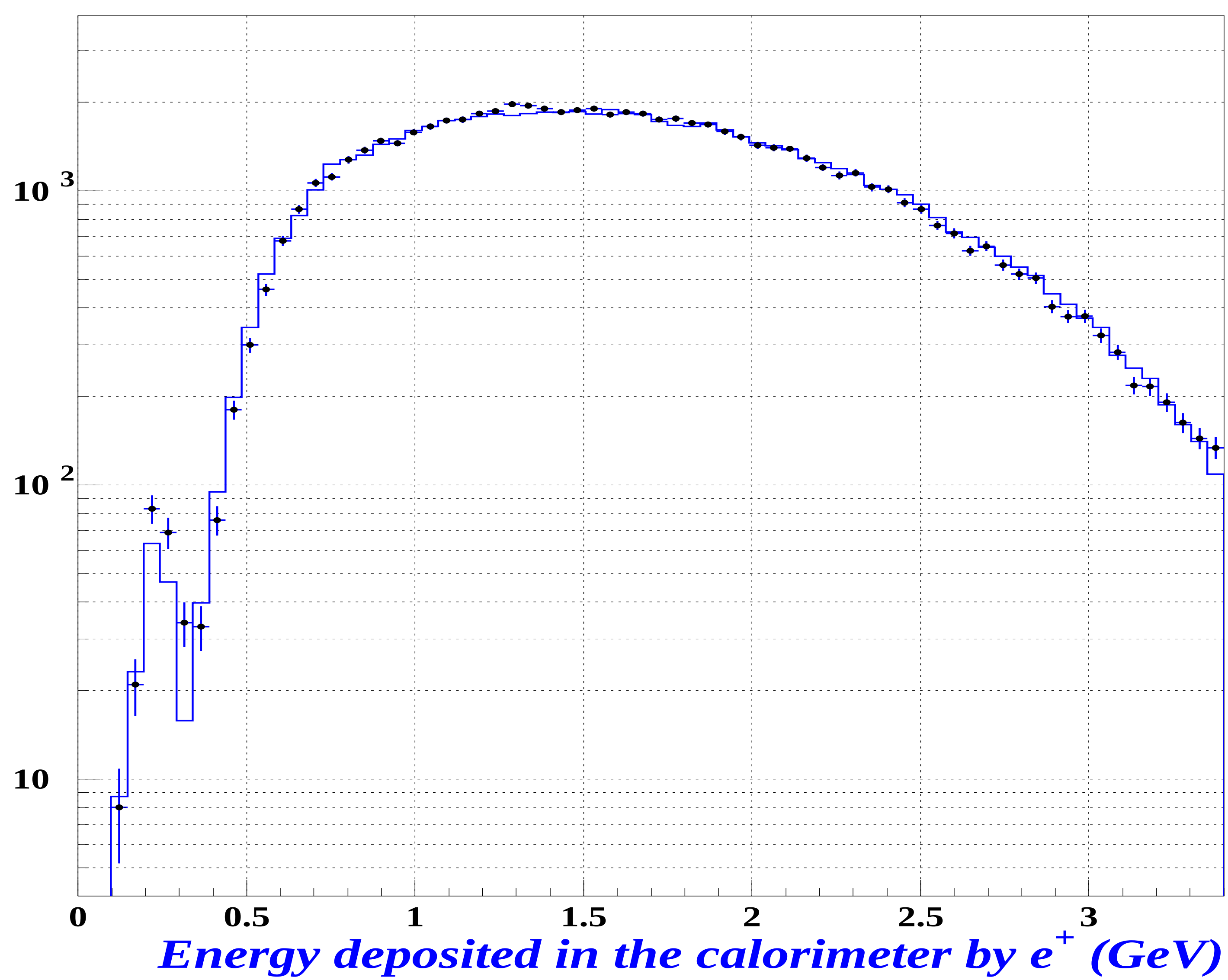
- The kaons from reconstructed data $K^+ \to \pi^+\pi^+\pi^-$ decays were used as a bank of initial kaons for the Monte Carlo.
- The phase-space dependent efficiency maps of the D counters, Cerenkov counters, and PWCs were applied to all Monte Carlo events.
- Accidental hits obtained from the data were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



Monte Carlo estimate of the selected Ke3 sample contamination

Decay Chain	Mechanism for the decay misidentification as Ke3	Contamination with (2/2) e^+ PID or (2/3) e^+ PID
$K^+ \to \pi^+\pi^0;\ \pi^0 \to e^+e^-\gamma$	π^+ identified as e^+	$(0.25 \pm 0.03 \pm 0.1)\%$ $(0.76 \pm 0.05 \pm 0.2)\%$
$K^+ \to \pi^0\mu^+\nu;\ \pi^0 \to e^+e^-\gamma$	μ^+ identified as e^+	$(0.10 \pm 0.01 \pm 0.04)\%$ $(0.11 \pm 0.01 \pm 0.03)\%$
$K^+ \to \pi^+\pi^0\pi^0$ with one $\pi^0 \to e^+e^-\gamma$	π^+ identified as e^+	$(0.13 \pm 0.02 \pm 0.05)\%$ $(0.32 \pm 0.03 \pm 0.09)\%$
$K^+ \to \pi^+\pi^0\pi^0$ with two $\pi^0 \to e^+e^-\gamma$	π^+ identified as e^+ or the three tracks are $e^+e^+e^-$	$(0.13 \pm 0.01)\%$ $(0.13 \pm 0.01)\%$
$K^+ \to \pi^+\pi^0;\ \pi^0 \to e^+e^-e^+e^-$	π^+ identified as e^+ or the three tracks are $e^+e^+e^-$	$(0.51 \pm 0.03)\%$ $(0.51 \pm 0.03)\%$
$K^+ \to \pi^0\mu^+\nu;\ \pi^0 \to e^+e^-e^+e^-$	μ^+ identified as e^+ or the three tracks are $e^+e^+e^-$	$(0.065 \pm 0.005)\%$ $(0.066 \pm 0.005)\%$
$K^+ \to \pi^+\pi^0\pi^0;\ \pi^0 \to e^+e^-e^+e^-$	π^+ identified as e^+ or the three tracks are $e^+e^+e^-$	$(0.036 \pm 0.004)\%$ $(0.043 \pm 0.004)\%$
$K^+ \to \pi^0e^+\nu;\ \pi^0 \to e^+e^-e^+e^-$	the three tracks are $e^+e^+e^-$	$(0.55 \pm 0.02)\%$ $(0.55 \pm 0.02)\%$
Total:		$(1.77 \pm 0.05 \pm 0.19)\%$ $(2.49 \pm 0.05 \pm 0.32)\%$

Contamination due to accidental tracks: $(0.1 - 0.2)\%$

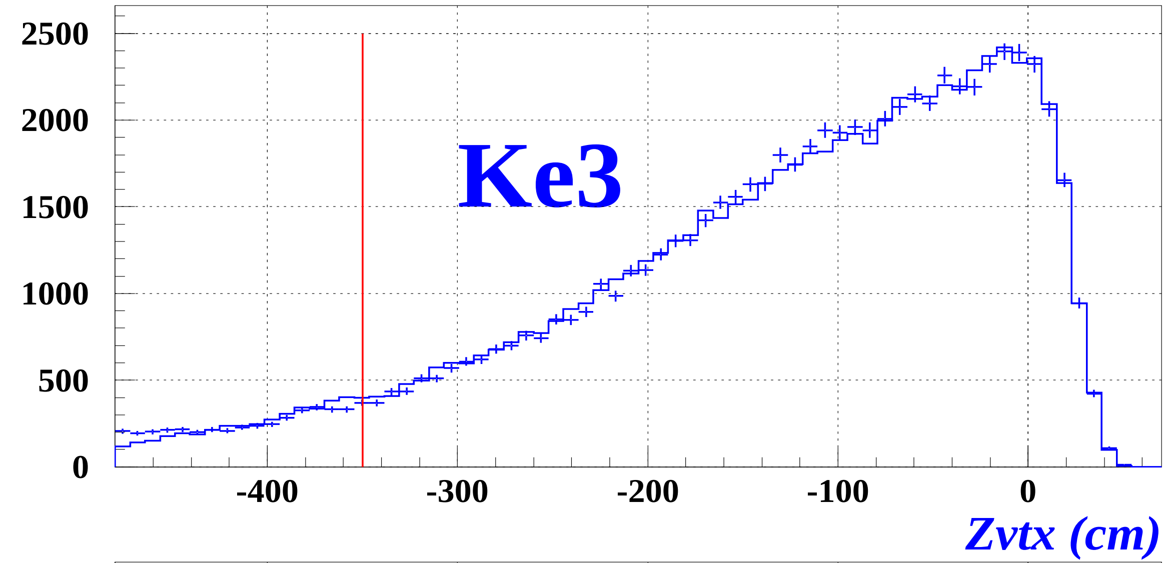


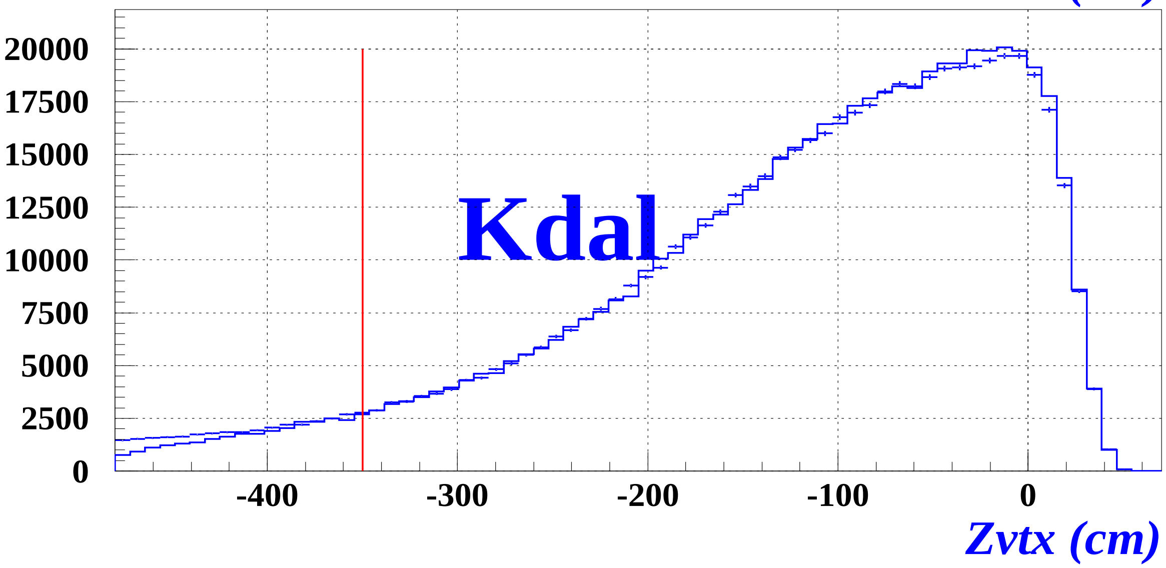
Minimum ionization loss in the calorimeter is ≈250MeV

Systematic Errors

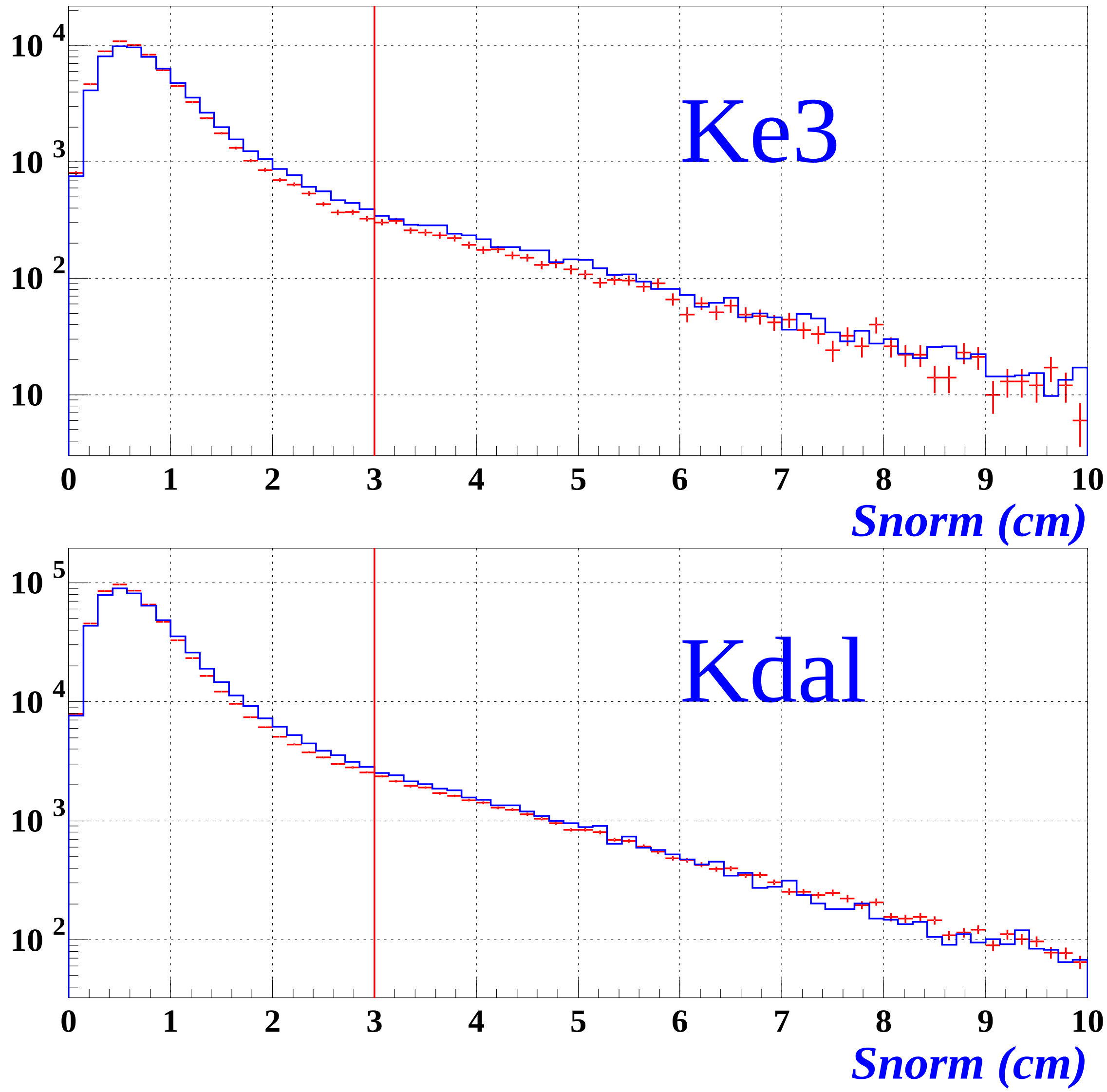
- Statistical error is 0.4% (about 70,000 selected Ke3 events without π^0 reconstruction)
- Systematic error :
  - Sources :
    * Detector efficiencies
    * Detector acceptance
    * Physical backgrounds
    * Reconstruction of tracks in the spectrometer
    * Decay phase space density simulation
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

Data and Monte Carlo Comparison

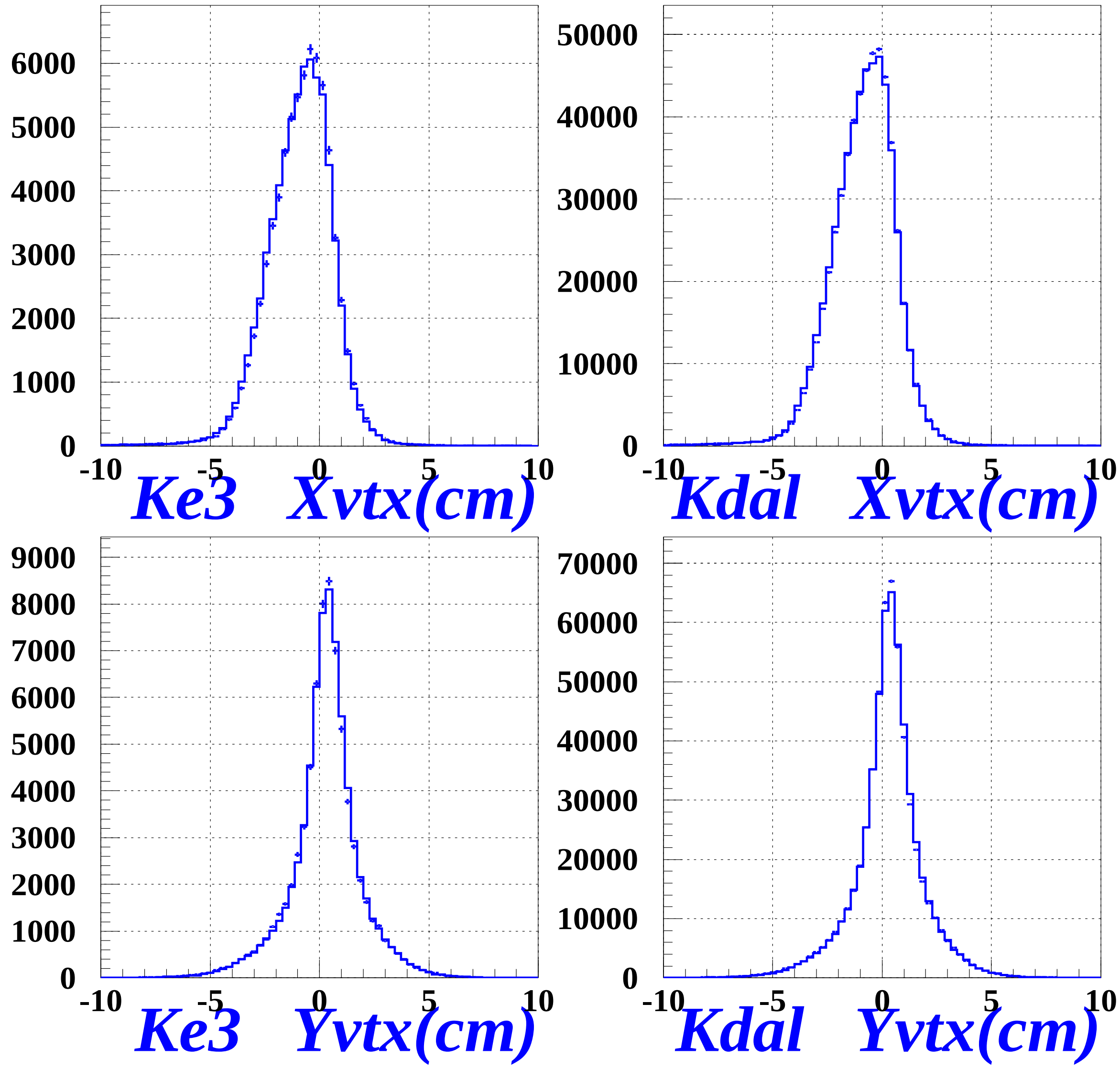




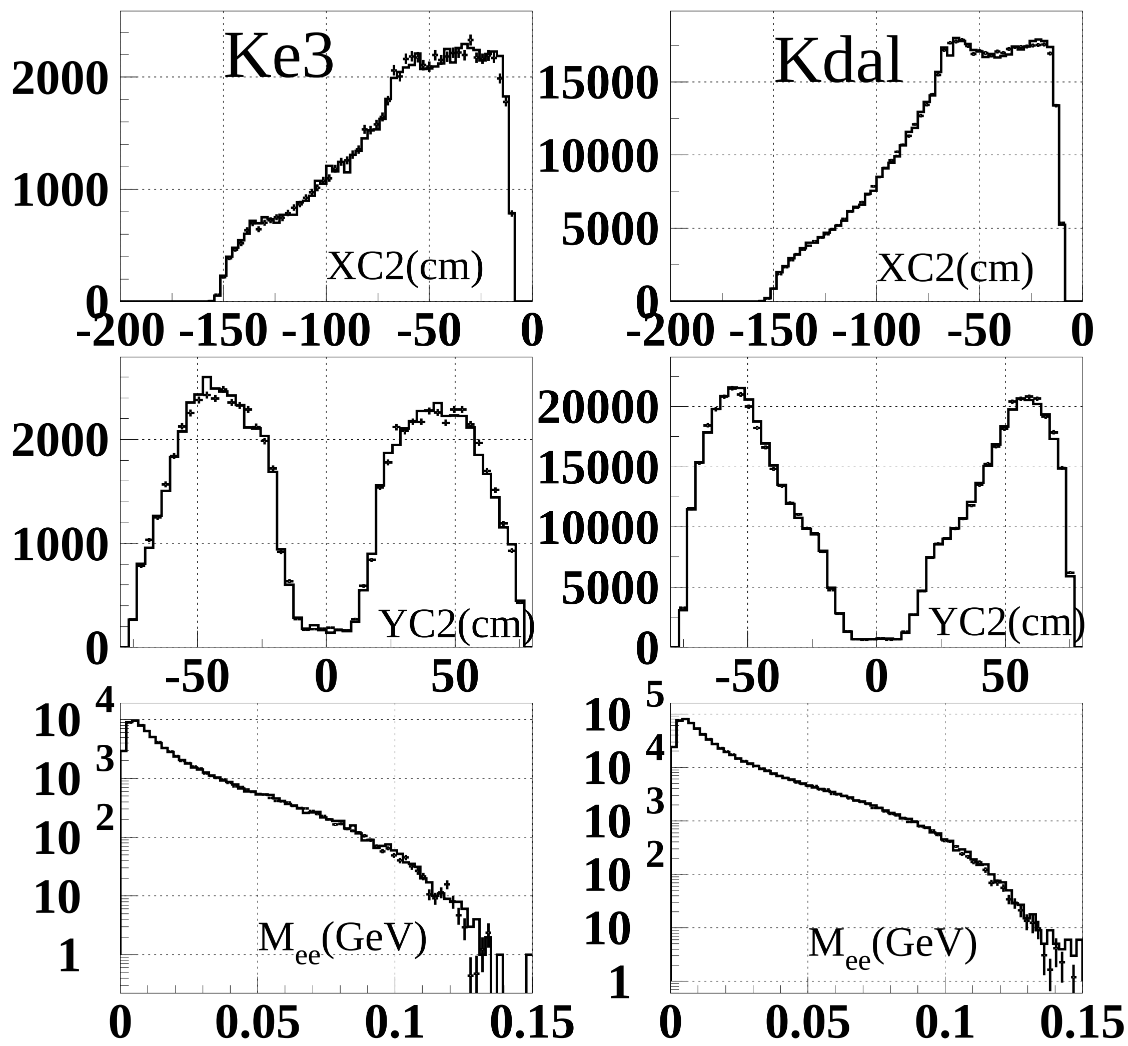
Data and Monte Carlo Comparison



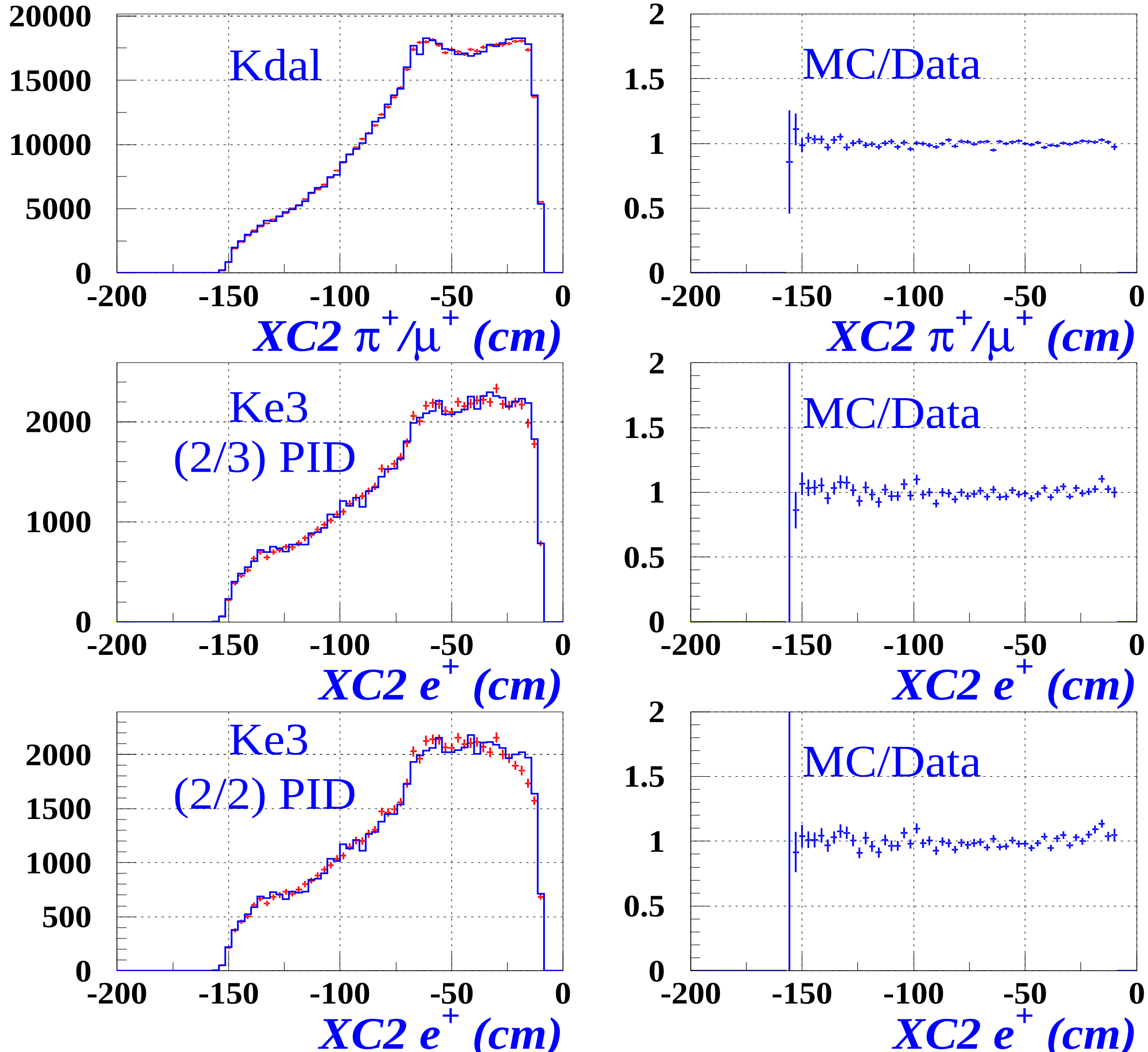
Data and Monte Carlo Comparison



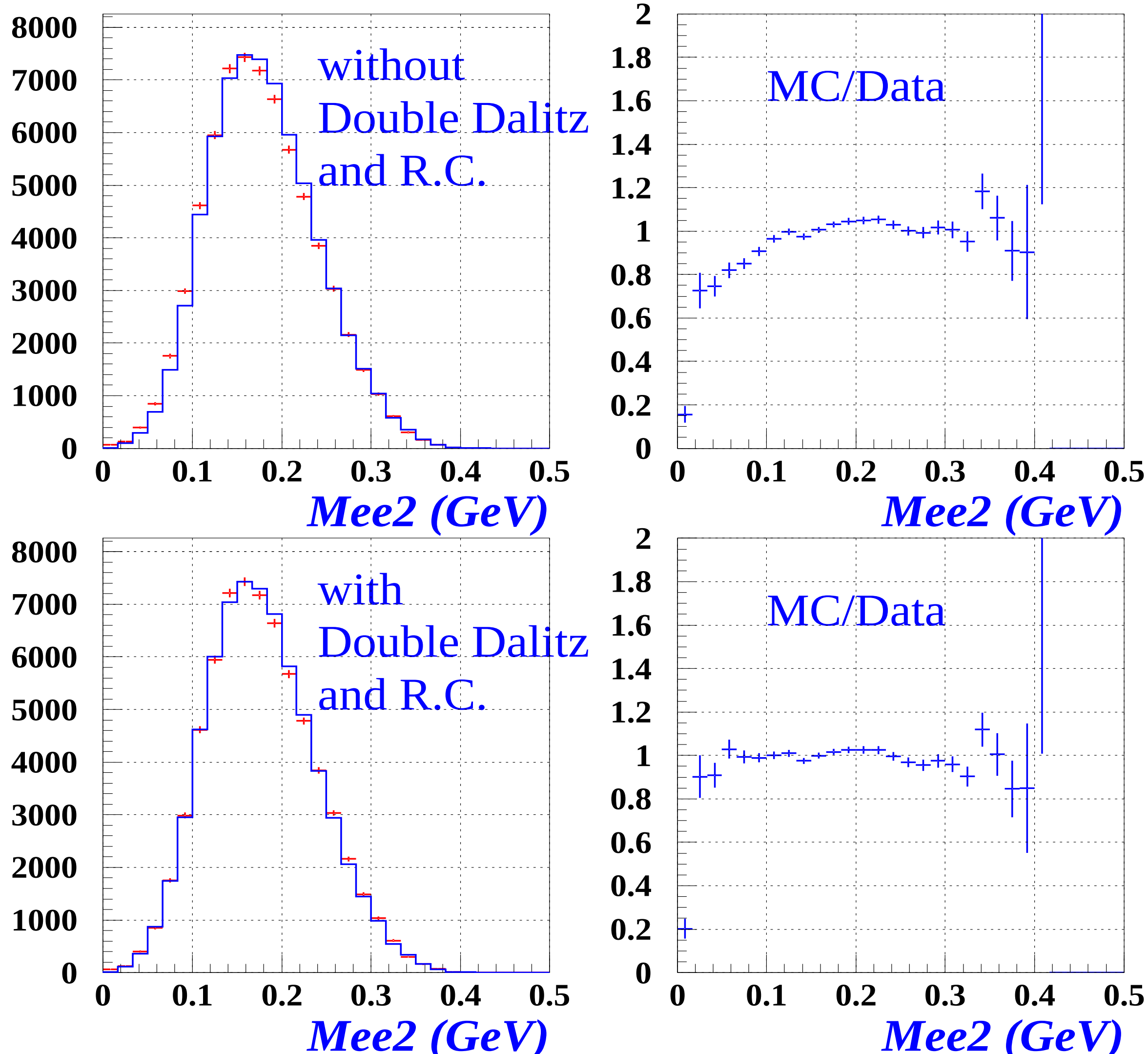
Data and Monte Carlo Comparison



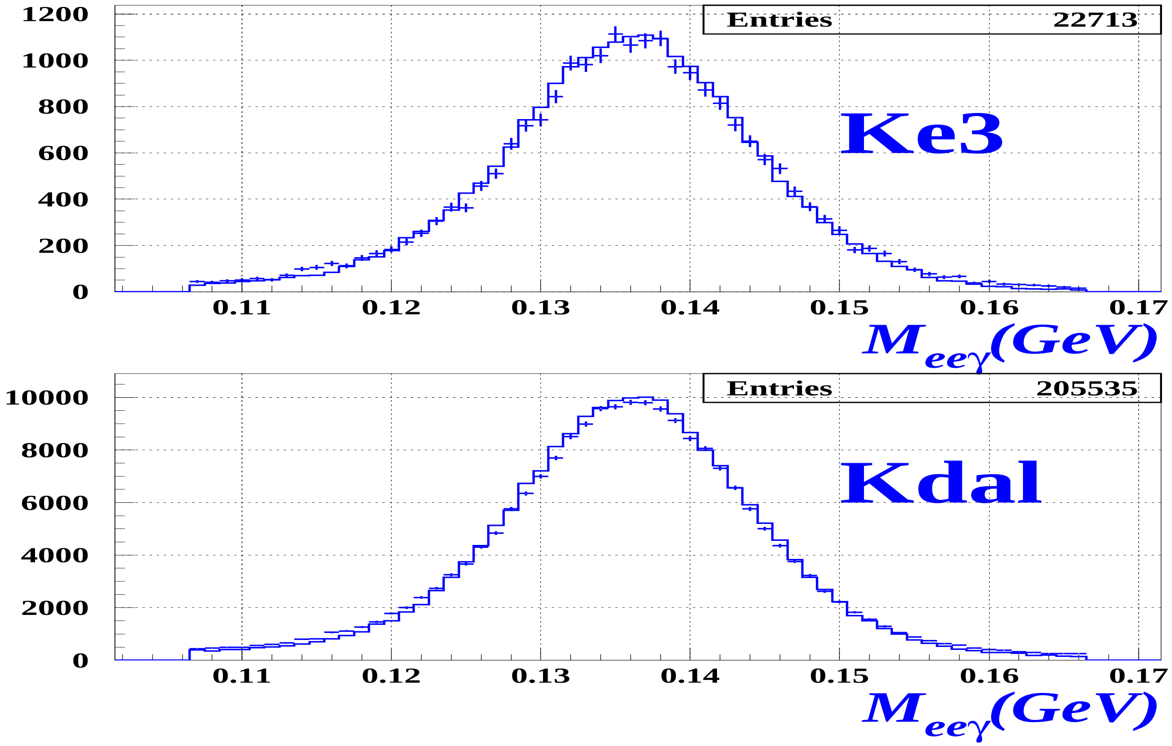
X coordinate of the second positive track (not e^+ from π^0 decay) at the mirror plane of C2



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



π^0 Reconstruction



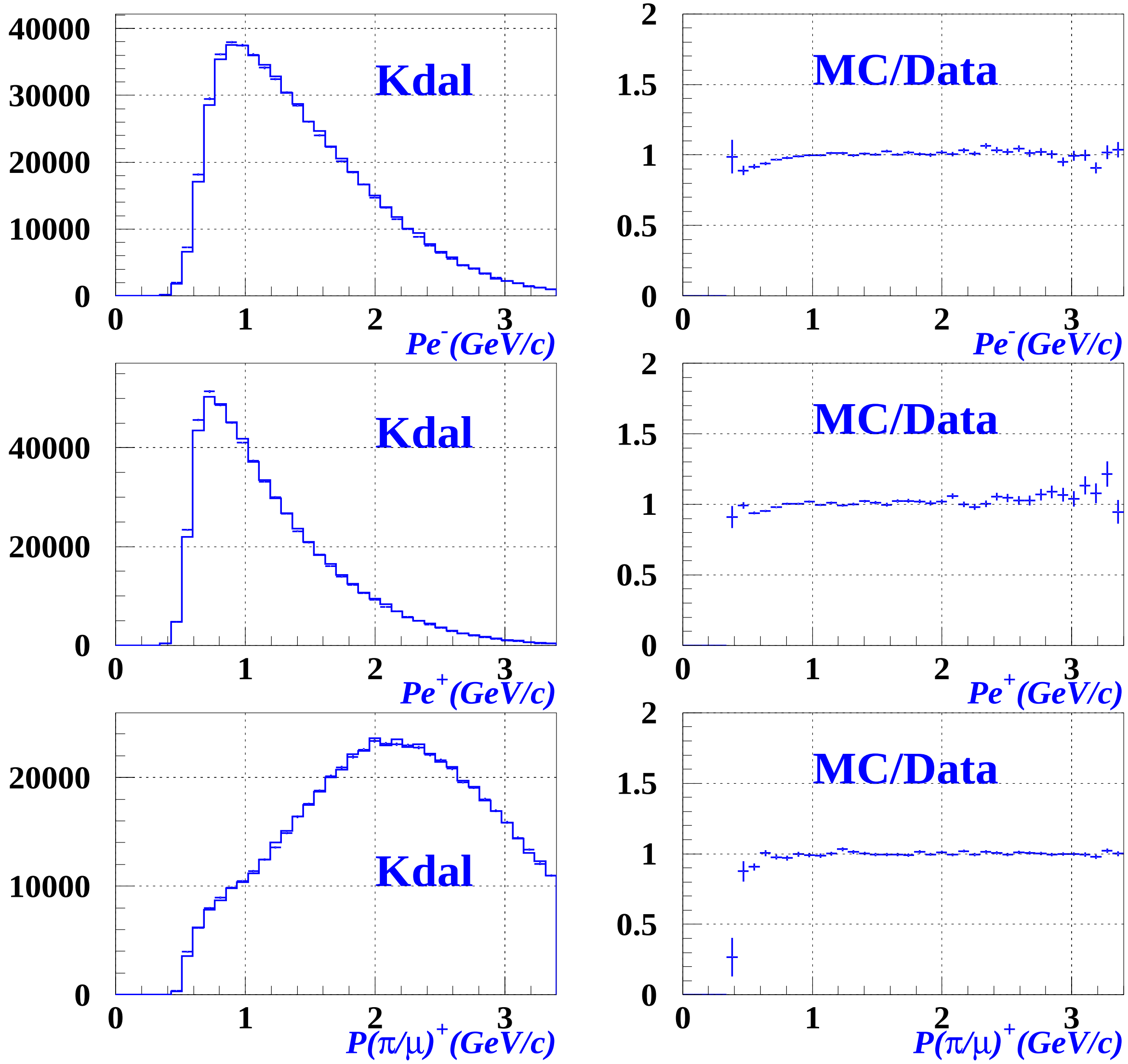
CUT	Ke3(MC/D)	Kdal(MC/D)	Kdal/Ke3
π^0	1.008(0.008)	1.011(0.004)	1.003(0.009)
NO π^0	0.996(0.006)	0.993(0.003)	0.997(0.007)

No statistically significant change in the final result

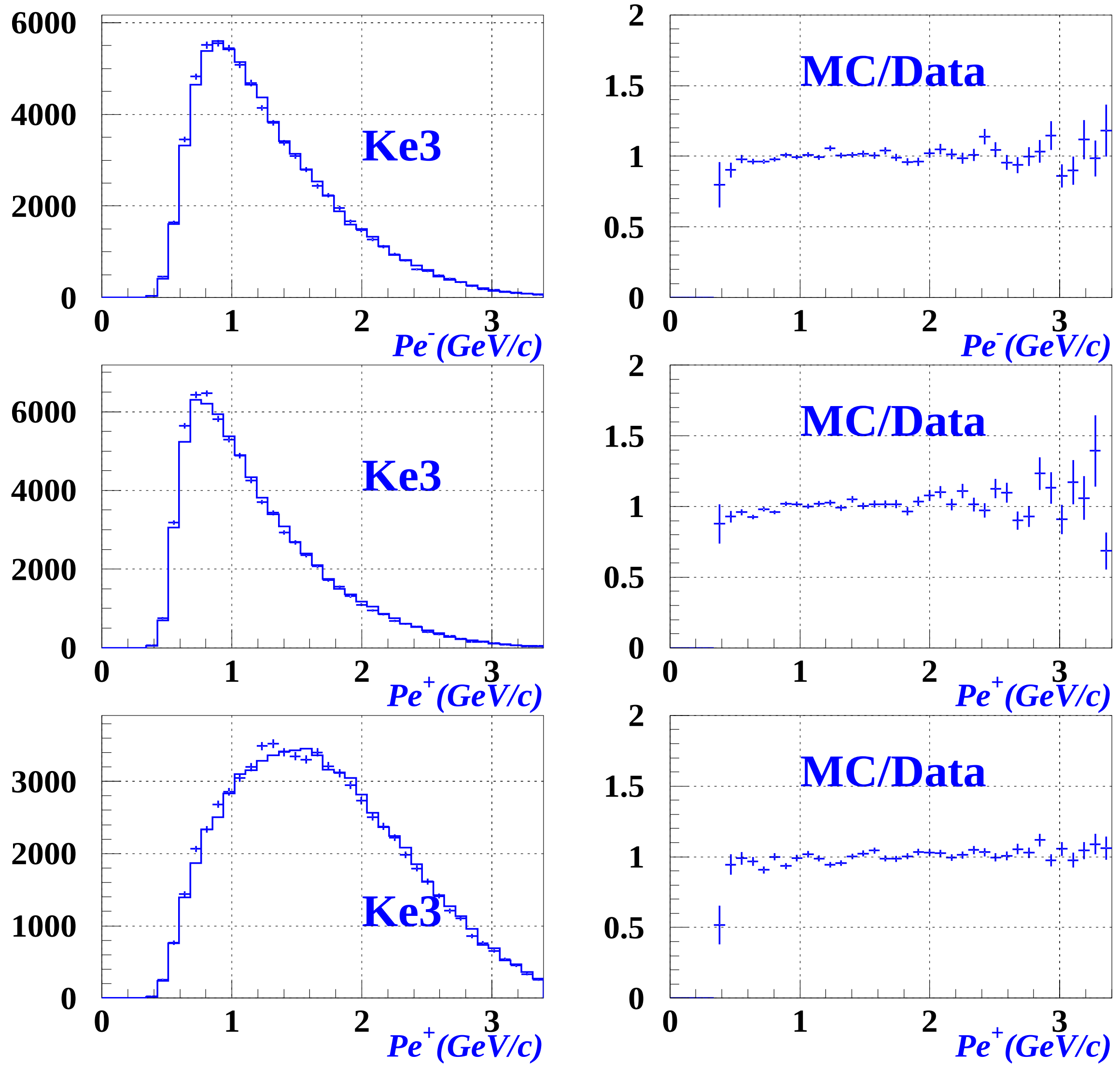
Systematic Errors Summary

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

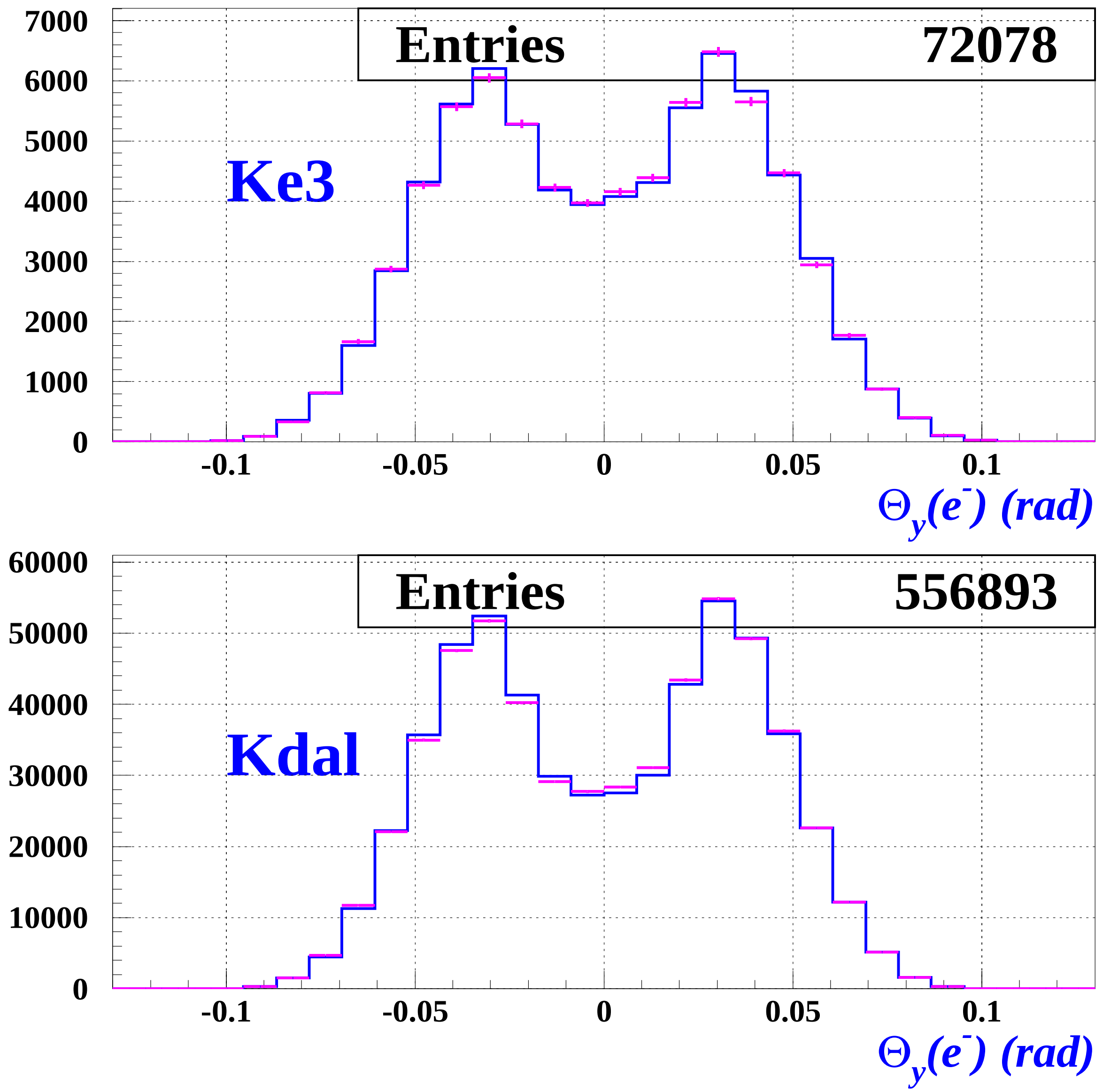
Momentum distribution discrepancy



Momentum distribution discrepancy



Vertical distribution discrepancy



1997 Ke3 Data

Calorimeter, A-hodoscope, and D-hodoscope were required for any trigger.
Ke3 sample: $\approx 1.5\times$ the 1998 data.

- No direct calorimeter, A-hodoscope, and D-hodoscope efficiency measurement
- No ELER trigger efficiency measurement
- The error is dominated by a systematic uncertainty: benefit of adding more data is small

The 1998 data was used for the final result; the 1997 data was used for the consistancy check.

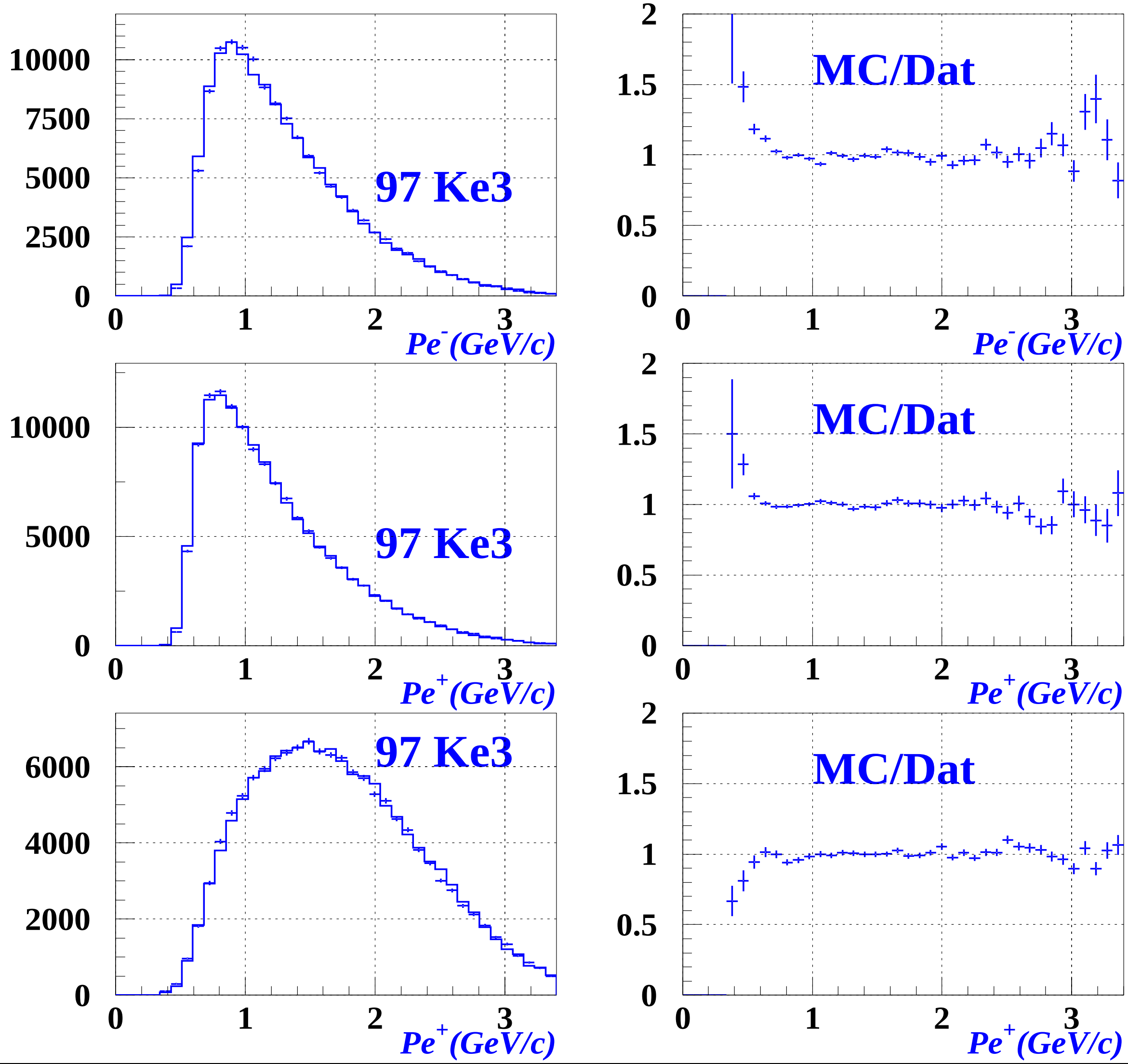
Consistency Checks

- $\frac{BR(K^+ \to \pi^+ \pi^+ \pi^-)}{Kdal} = (1.01 \pm 0.02) \times R_{PDG}$
  Larger systematic uncertainies than for the $\frac{BR(K^+ \to \pi^0 e^+ \nu)}{Kdal}$.

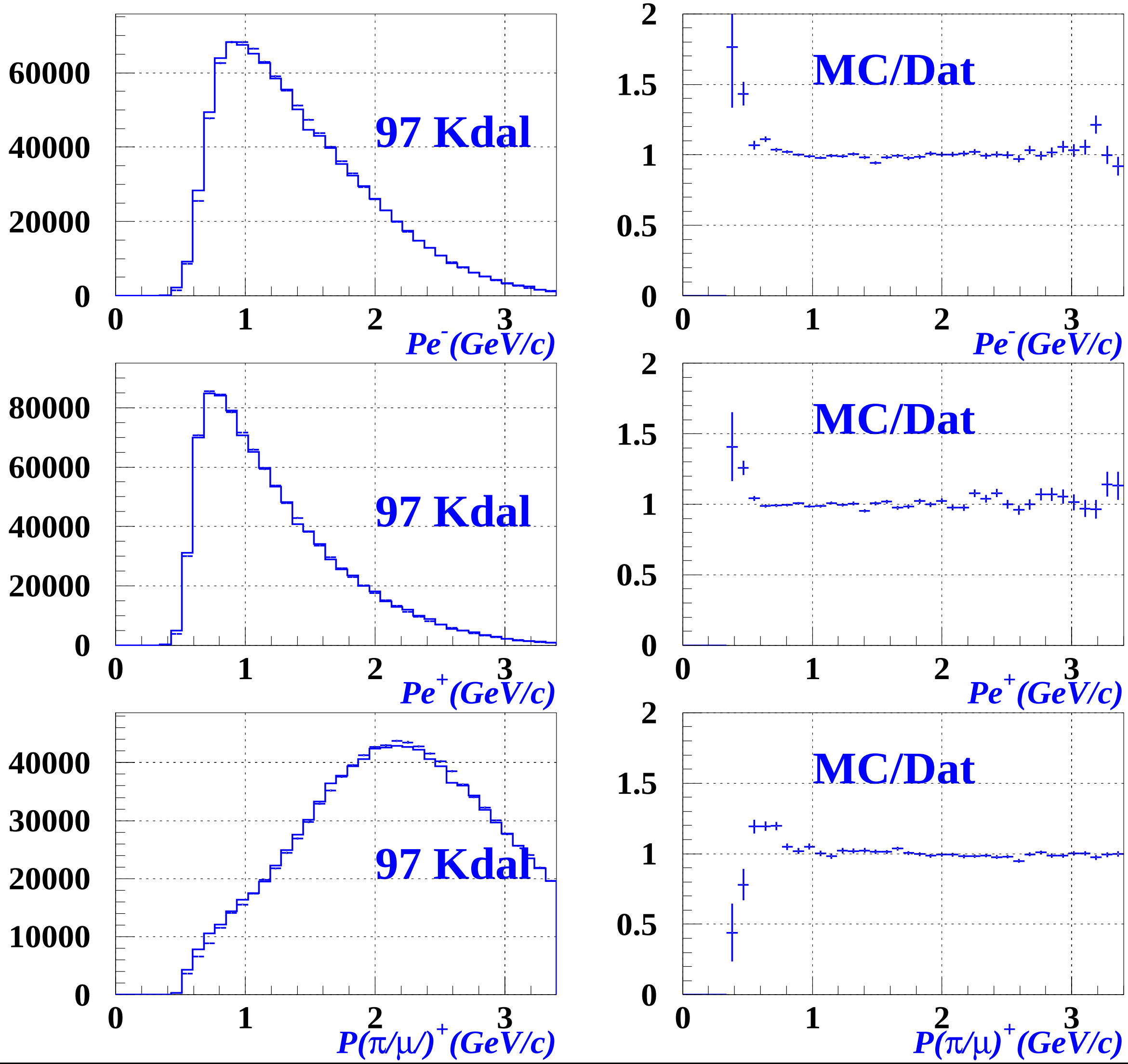
- 1997 Ke3 data: Result differs by $(0.6 \pm 0.7)\%$
  Different on-line trigger; different detector efficiencies, and calibrations.

- Form-factor slope fit:
  $\lambda_+ = 0.0324 \pm 0.0044$ $\chi^2 = 28.39/25 df$ (1998 Data)
  $\lambda_+ = 0.0290 \pm 0.0044$ $\chi^2 = 26.67/25 df$ (1997 Data)
  $\lambda_+ = 0.0278 \pm 0.0019$ (PDG)

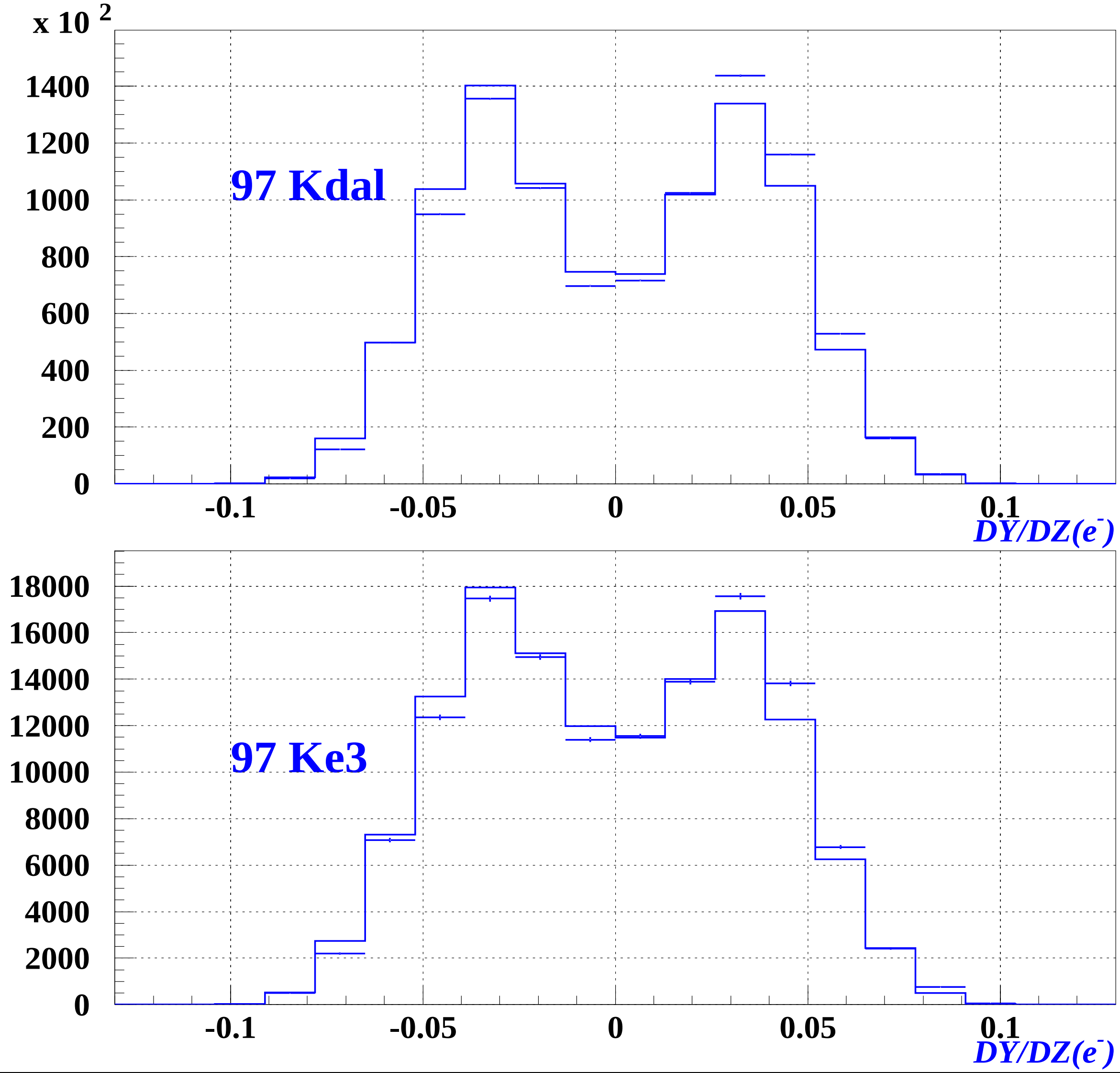
Momentum distribution discrepancy in the 1997 Data



Momentum distribution discrepancy in the 1997 Data



Vertical angle distribution discrepancy in the 1997 Data



Results

- $\frac{BR(K^+ \rightarrow \pi^0 e^+ \nu(\gamma))}{KDAL} = \quad 0.2002 \pm 0.0008_{stat} \pm 0.0036_{sys}$
- $KDAL = BR(K^+ \rightarrow \pi^+ \pi^0)$
  $+ BR(K^+ \rightarrow \pi^0 \mu^+ \nu) + BR(K^+ \rightarrow \pi^+ \pi^0 \pi^0)$
- Using the PDG values for the Branching Ratios in the denominator we infer:
  $BR(K^+ \rightarrow \pi^0 e^+ \nu(\gamma)) = (5.13 \pm 0.02_{stat} \pm 0.09_{sys} \pm 0.04_{norm})\%$
- Total radiative correction: -1.3%(virtual+IB) + 0.5% (IB outside of the Dalitz plot) = -0.8%
  $BR(K^+ \rightarrow \pi^0 e^+ \nu) = (5.17 \pm 0.02_{stat} \pm 0.09_{sys} \pm 0.04_{norm})\%$

PDG: $BR(K^+ \rightarrow \pi^0 e^+ \nu) = (4.87 \pm 0.06)\%$

V_{us}

Using:

- $S_{EW}(M_\rho, M_Z) = 1.0232$
(W.J. Marciano, A. Sirlin, Phys. Rev. Lett. **71**, 3629 (1993))

- $f_+(0) = 0.9874 \pm 0.0084$
(V. Cirigliano *et al.*, Eur. Phys. J. C **23**, 121 (2002))

we obtain:

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

Summary

E865 results:

$BR(K^+ \to \pi^0 e^+ \nu(\gamma)) = (5.13 \pm 0.02_{stat} \pm 0.09_{sys} \pm 0.04_{norm})\%$

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

$|V_{ud}|^2_{nucl.} + |V_{us}|^2_{E865} + |V_{ub}|^2 = 0.9999 \pm 0.0016$

Problems:

- Disagreement with previous K^+_{e3} decay rate measurements by ≈2.3 standard deviations.
- $|V_{us}|_{E865}$ is in disagreement with the previous value from the K^0_{e3} decay. But agrees with the preliminary KLOE results.