A New Measurement of $|V_{us}|$ from KTeV

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- Introduction to $|V_{us}|$
- Measurements of K_L Branching Fractions
- Measurements of K_L Semileptonic Form Factors
- Results and conclusions

The KTeV Collaboration:
Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, UCLA, UCSD, Virginia, Wisconsin

Unitarity Tests of CKM Matrix

Uncertainty on $\Sigma_j V_{ij}^2$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

0.2%

2.7%

30 %

For first row, PDG quotes 2.2 σ deviation from unitarity:

$$1-\left(|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2\right)=0.0043\pm0.0019 \quad \text{(PDG 2002)}$$

PDG $|V_{ux}|$ Evaluations

$|V_{ud}| = 0.9734 \pm 0.0008$ from $0^+ \rightarrow 0+$ nuclear β decays, neutron decay

$|V_{ub}| = (3.6 \pm 0.7) \times 10^{-3}$ from semileptonic B decay

$|V_{us}| = 0.2196 \pm 0.0023$ from K^+, K^0 decays to $\pi e \nu$ ($\pi \mu \nu$ not used by PDG because of large uncertainties in form factor measurements).

Recent K^+ measurement from BNL E865 consistent with unitarity.

⇒ Interesting to revisit K_L measurements (PDG fit values based on averages of many old experiments with large errors)

Determination of $|V_{us}|$ in Semileptonic K_L Decays

KTeV measures
$B(K_L \to \pi e \nu)$ and
$B(K_L \to \pi \mu \nu)$

KTeV measures
form factors needed
to calculate phase
space integrals

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell)\left|V_{us}\right|^2 f_+^2(0) I_K^\ell$$

Rad. Corrections
(theory)

Form factor
at t=0
(theory)

KTeV Measurements

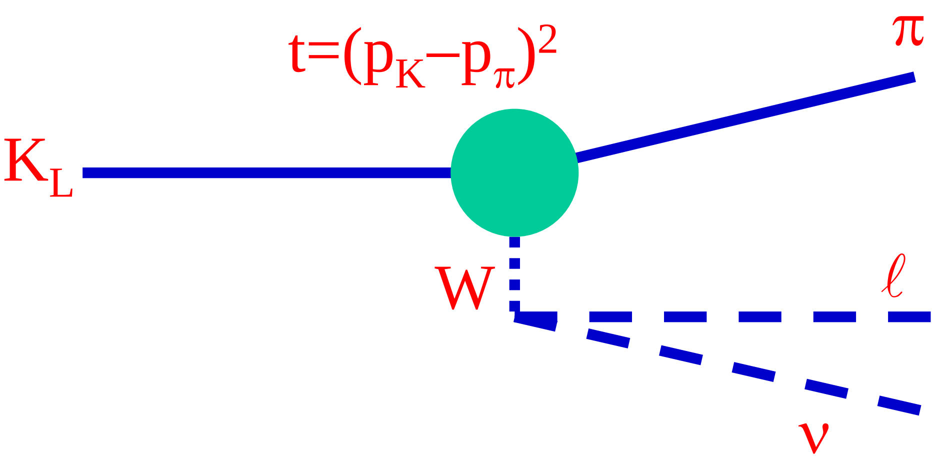
- To determine semileptonic partial widths, KTeV measures branching fractions for the 6 largest decay modes:

$$K_L \to \pi^{\pm} e^{\mp} \nu,\ K_L \to \pi^{\pm} \mu^{\mp} \nu,\ K_L \to \pi^{+}\pi^{-}\pi^{0},\ K_L \to \pi^{0}\pi^{0}\pi^{0},$$

$$K_L \to \pi^{+}\pi^{-},\ K_L \to \pi^{0}\pi^{0}$$

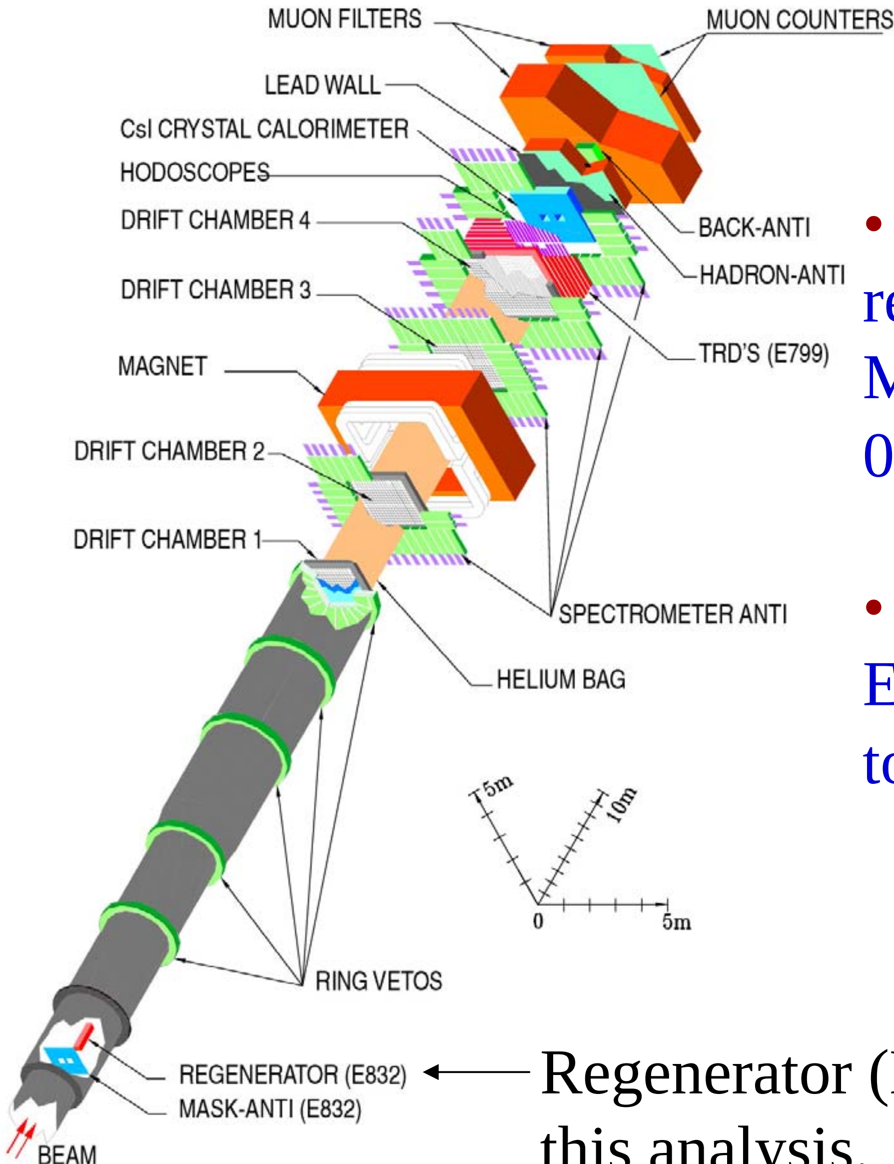
The K_L lifetime (τ_L) is used to convert branching fractions into partial widths

- Form factors describe the t distribution of decay:



We measure the two independent form factors for semileptonic decay, and determine the phase space integrals I_K.

KTeV Detector



- Charged particle momentum resolution < 1% for p>8 GeV/c; Momentum scale known to 0.01% from $K \rightarrow \pi^+\pi^-$.

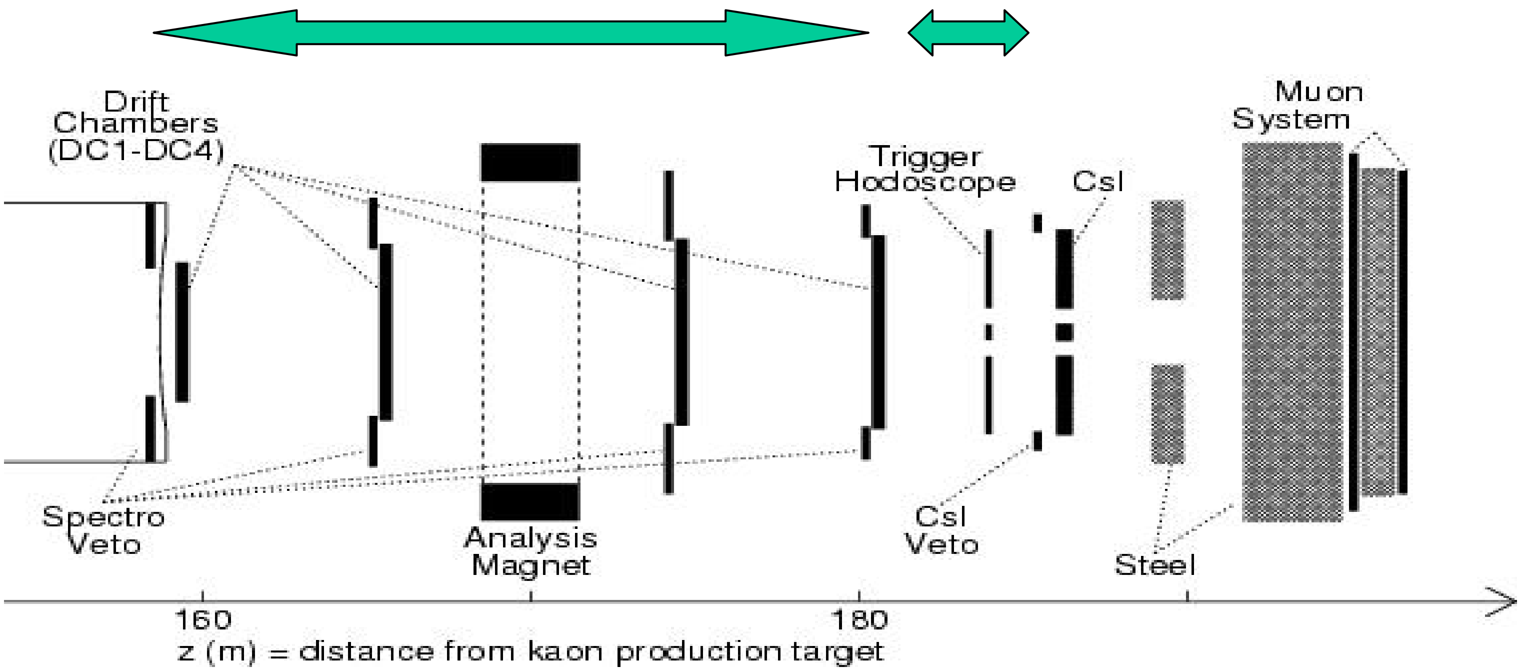
- CsI energy resolution < 1% for E_γ > 3 GeV; energy scale known to 0.1% from $K \rightarrow \pi e \nu$.

← Regenerator (K_S) beam not used in this analysis.

Material upstream of CsI Calorimeter

Spectrometer:
1.2% rad len
0.7% π int len

3.1% rad len
1.4% π int len



Material estimate checked with $K \to \pi e \nu$ with external brem. and $K_L \to \pi^0 \pi^0 \pi^0$ with γ conversion.

To determine the semileptonic widths, we measure the following 5 ratios:

$$\Gamma_{K\mu3}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{\pm}\mu^{\mp}\nu)/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

$$\Gamma_{+-0}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{+}\pi^{-}\pi^{0})/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

$$\Gamma_{000}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{0}\pi^{0}\pi^{0})/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

$$\Gamma_{+-}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{+}\pi^{-})/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

$$\Gamma_{00}/\Gamma_{000} = \Gamma(K_L \to \pi^{0}\pi^{0})/\Gamma(K_L \to \pi^{0}\pi^{0}\pi^{0})$$

These six decay modes account for 99.93% of K_L decays, so ratios may be combined to determine branching fractions.

E.g.,

$$B_{Ke3} = \frac{0.9993}{1 + \frac{\Gamma_{K\mu3}}{\Gamma_{Ke3}} + \frac{\Gamma_{000}}{\Gamma_{Ke3}} + \frac{\Gamma_{+-0}}{\Gamma_{Ke3}} + \frac{\Gamma_{+-}}{\Gamma_{Ke3}} + \frac{\Gamma_{00}}{\Gamma_{Ke3}}}$$

Features of Branching Fraction Analysis

•Each ratio measured in statistically independent data sample collected with a single trigger (samples sizes are 10^5 to 10^6 per decay mode)

•Each ratio measured in two data samples:
"high intensity" (same data used for ε'/ε analysis)
"low intensity" (no regenerator and $\times 10$ lower intensity)
Result for each ratio based on sample with lower total uncertainty

•Monte Carlo simulation is used to correct for acceptance difference between pair of modes

•Simulation includes inner bremsstrahlung contributions for all decay modes with charged particles, so branching fractions include radiated photons.

Charged Decay Modes

$$K_L \to \pi^{\pm} e^{\mp} \nu,\ K_L \to \pi^{\pm} \mu^{\mp} \nu,\ K_L \to \pi^{+} \pi^{-} \pi^{0},\ K_L \to \pi^{+} \pi^{-}$$

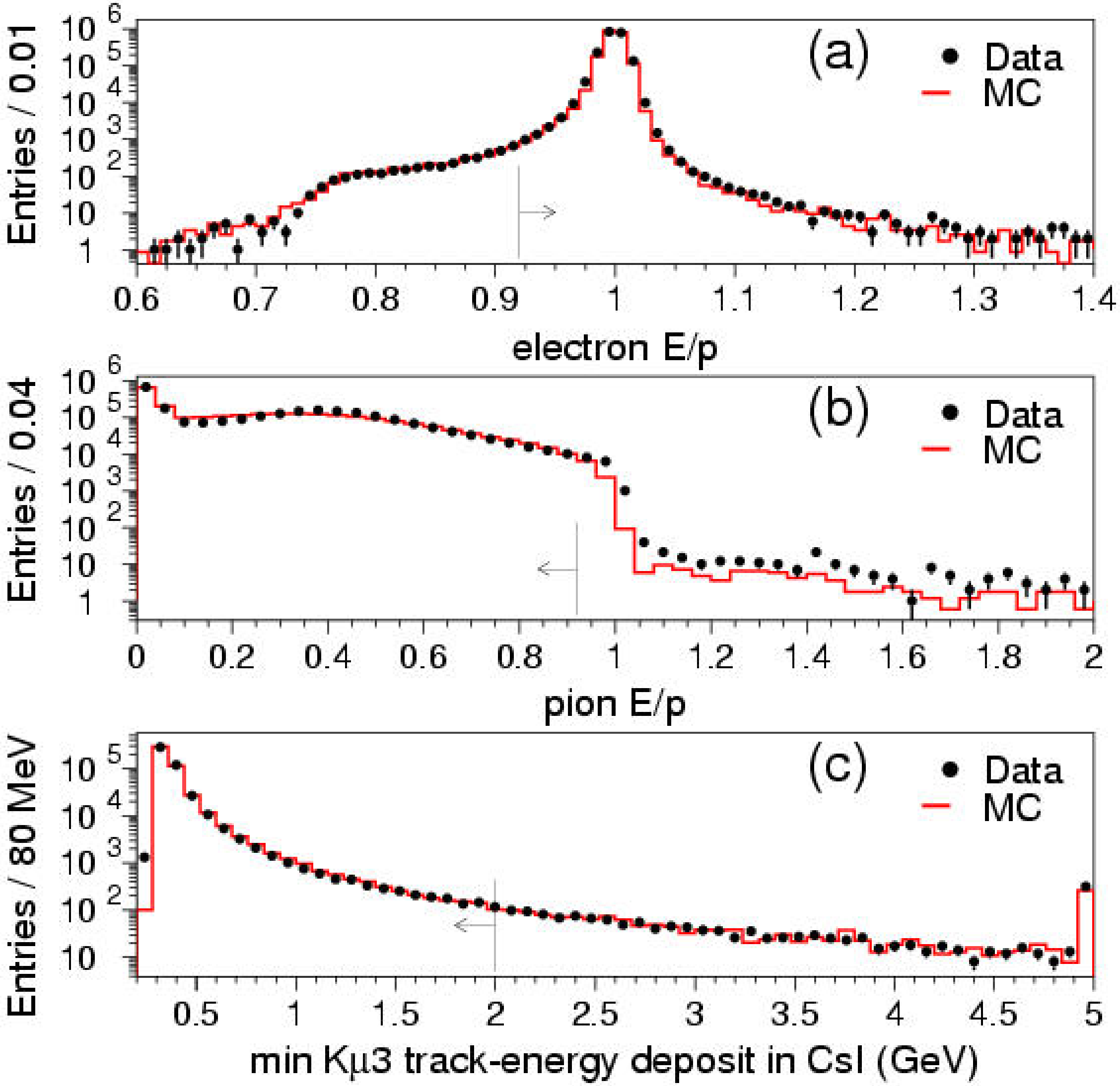
- Select two oppositely charged tracks from a single vertex.
- Use particle ID (calorimeter E and spectrometer p) and kinematics to separate 4 decay modes.

Unusual features:

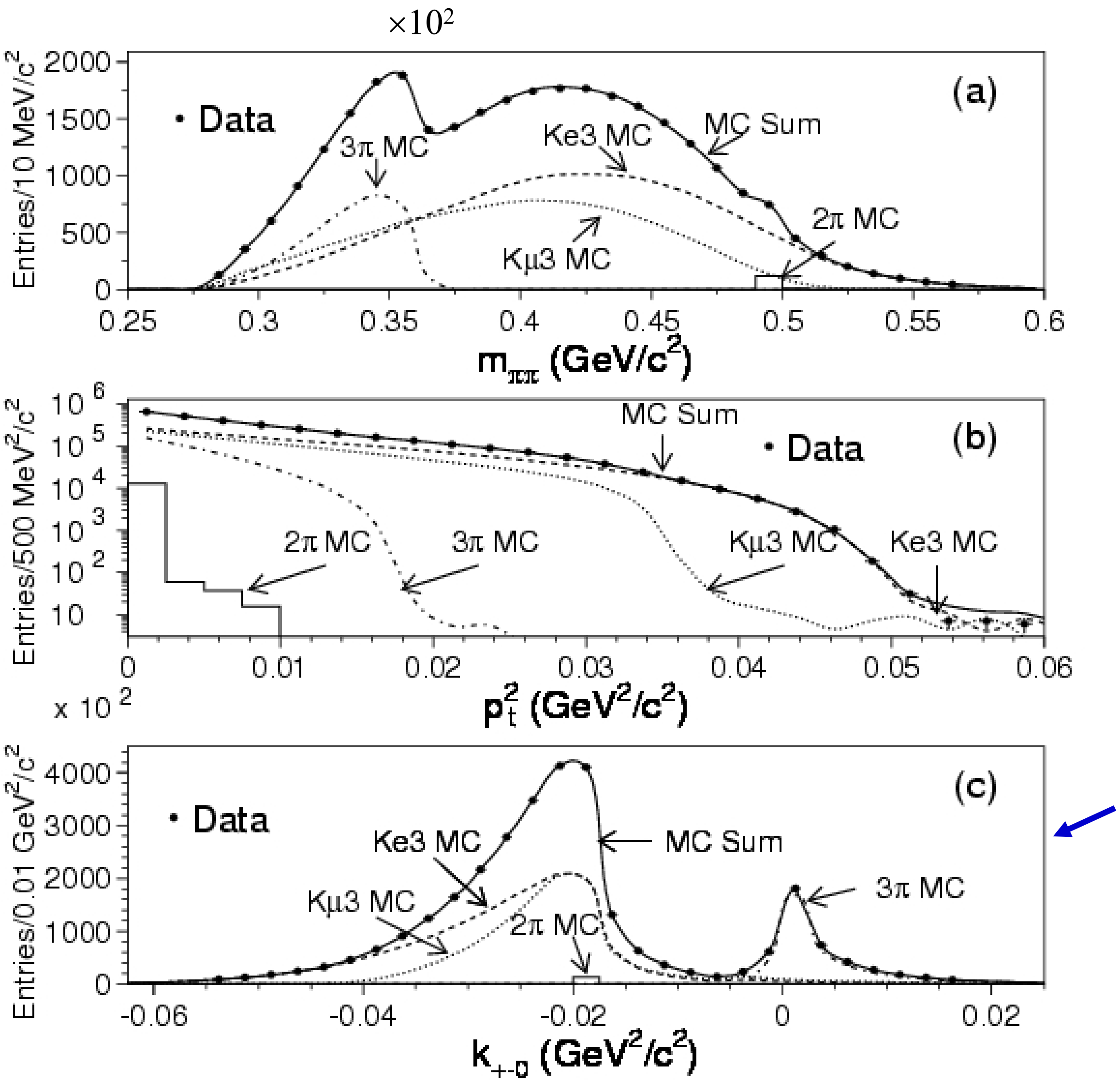
- For $K_L \to \pi\mu\nu$, we do not use muon system.
- For $K_L \to \pi^+\pi^-\pi^0$, we do not reconstruct the $\pi^0 \to \gamma\gamma$ decay.
- For partially reconstructed decays, there are multiple energy solutions; all solutions are required to be between 40 and 120 GeV.

Particle Identification

Energy response tails measured in data and modeled in Monte Carlo.



Kinematic Variables: $m_{\pi\pi}$, p_t^2, k_{+-0}

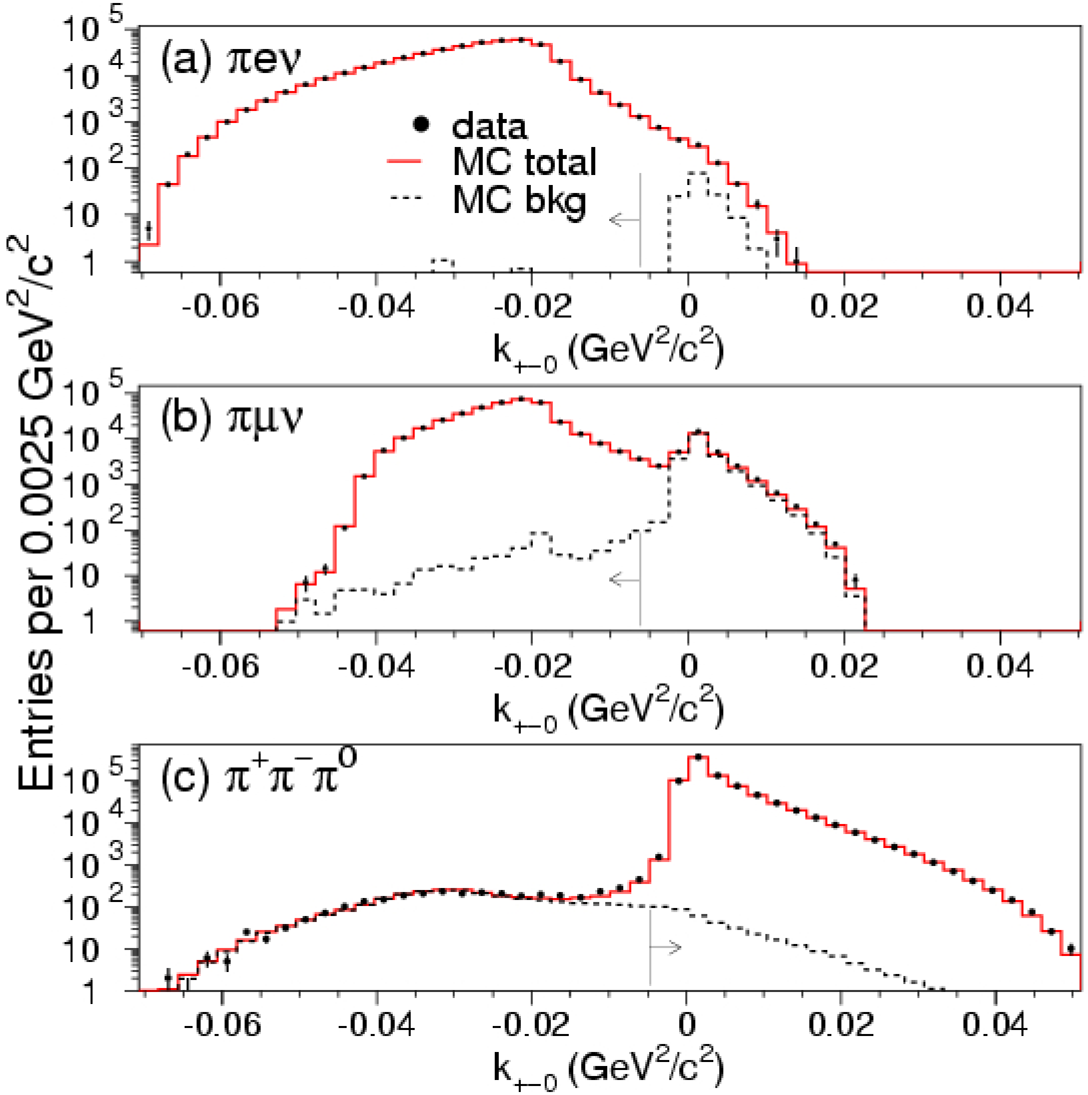


For $K_L \to \pi^+\pi^-\pi^0$ decays, k_{+-0} = longitudinal momentum squared of π^0 in frame where $\pi^+\pi^-$ momentum is orthogonal to K momentum.

$$k_{+-0} > 0 \text{ for } K_L \to \pi^+\pi^-\pi^0$$

$$k_{+-0} < 0 \text{ for } K_L \to \pi^\pm \ell^\mp \nu$$

k_{+-0} for Partially Reconstructed Decays

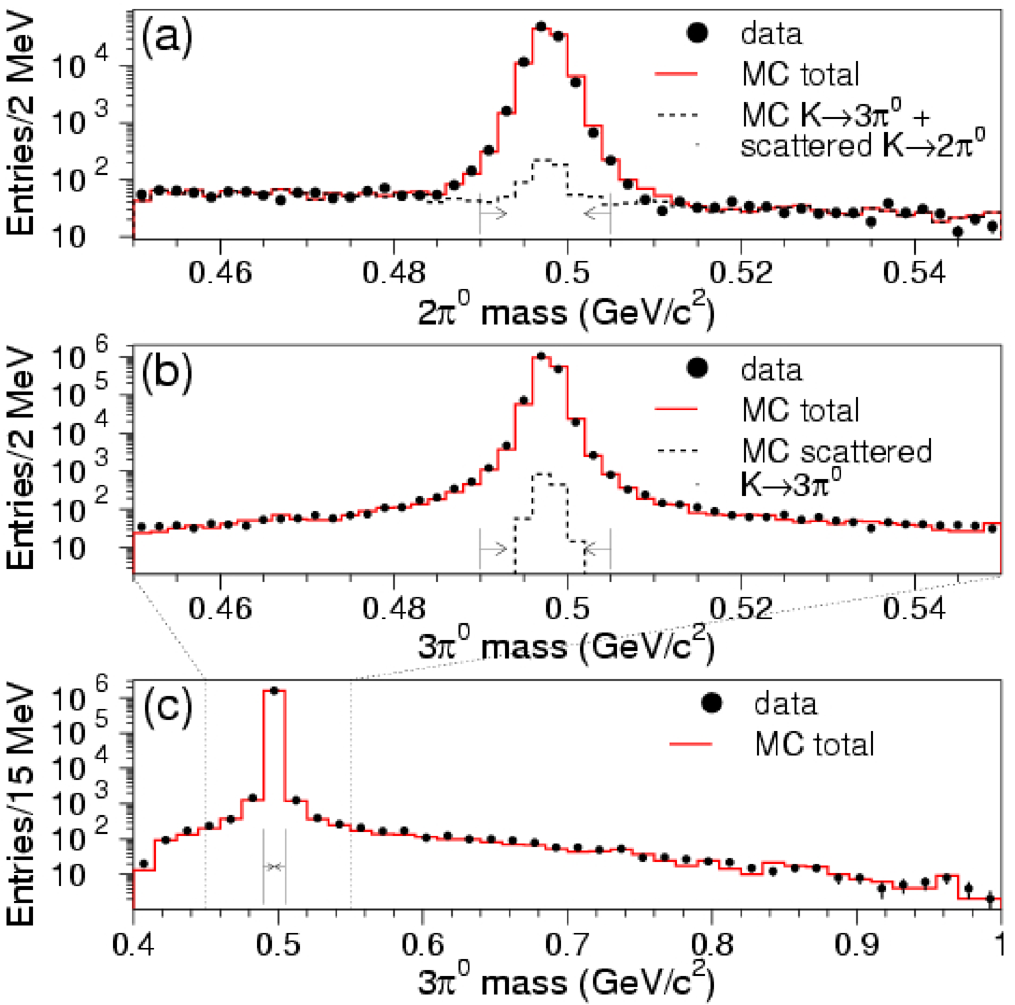


Neutral Decay Modes

$$K_L \to \pi^0\pi^0 \text{ and } K_L \to \pi^0\pi^0\pi^0$$

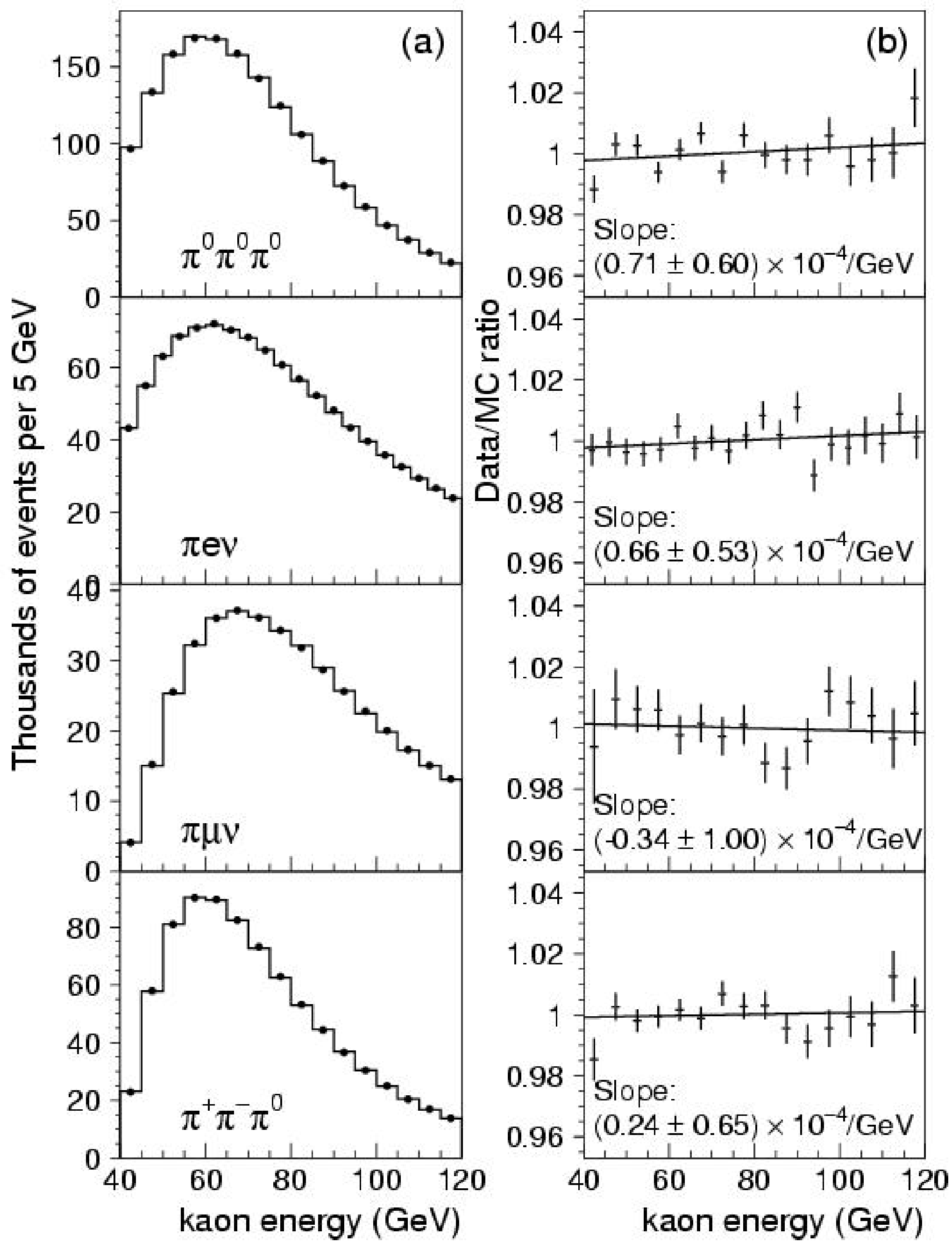
4 or 6 photon-like clusters are paired to reconstruct two or three neutral pions consistent with a single decay vertex.

(Analysis almost identical to ε′/ε analysis.)



Backgrounds

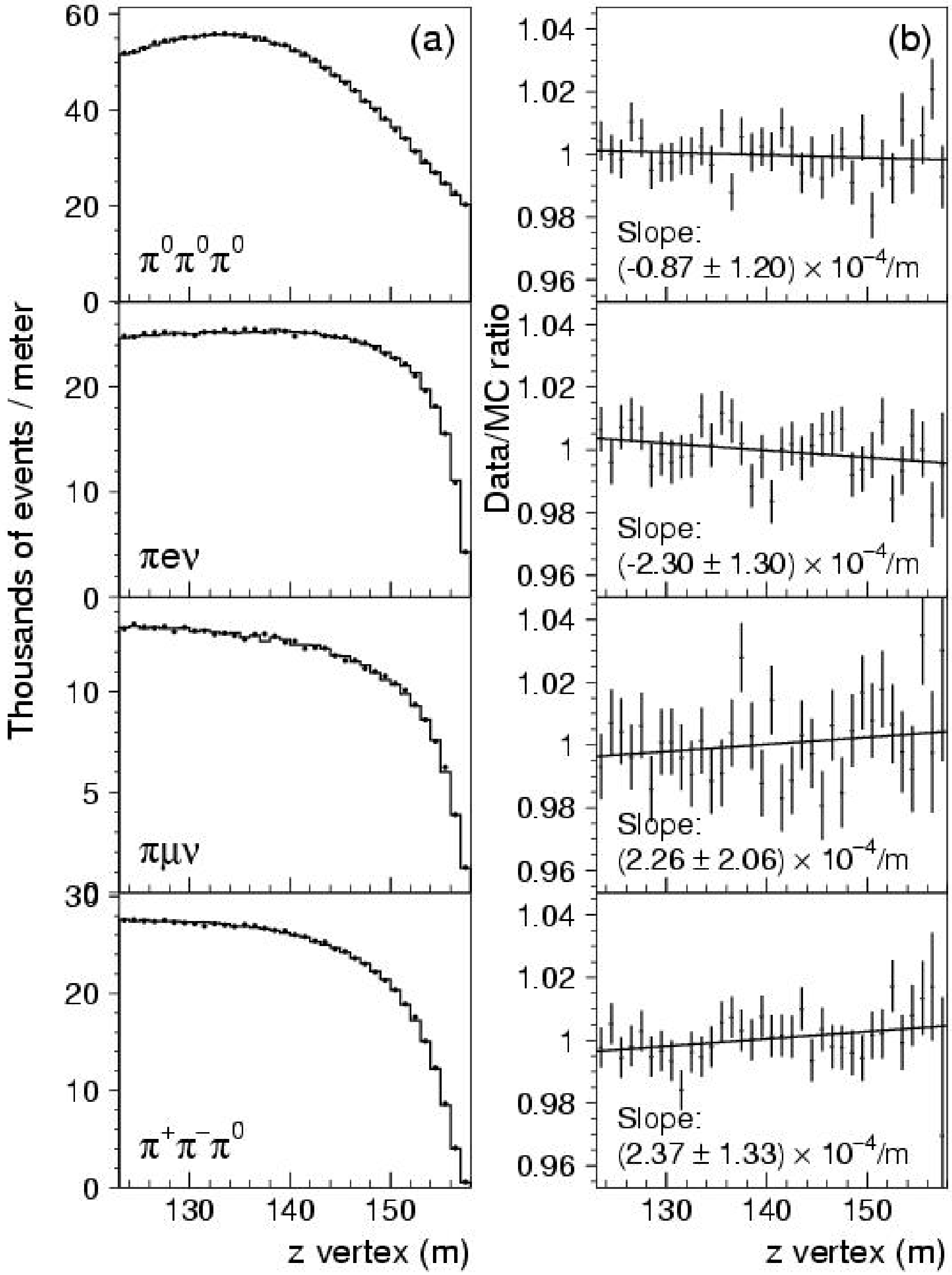
Decay Mode	Background (%)
$K_L \to \pi e \nu$	<0.003
$K_L \to \pi \mu \nu$	0.01
$K_L \to \pi^+ \pi^- \pi^0$	0.05
$K_L \to \pi^0 \pi^0 \pi^0$	None
$K_L \to \pi^+ \pi^-$	0.16
$K_L \to \pi^0 \pi^0$	0.71



Comparison of data and Monte Carlo kaon energy distributions

Monte Carlo spectrum was tuned using $K_L \to \pi^+\pi^-$ events

For partially reconstructed modes, high energy solution is plotted



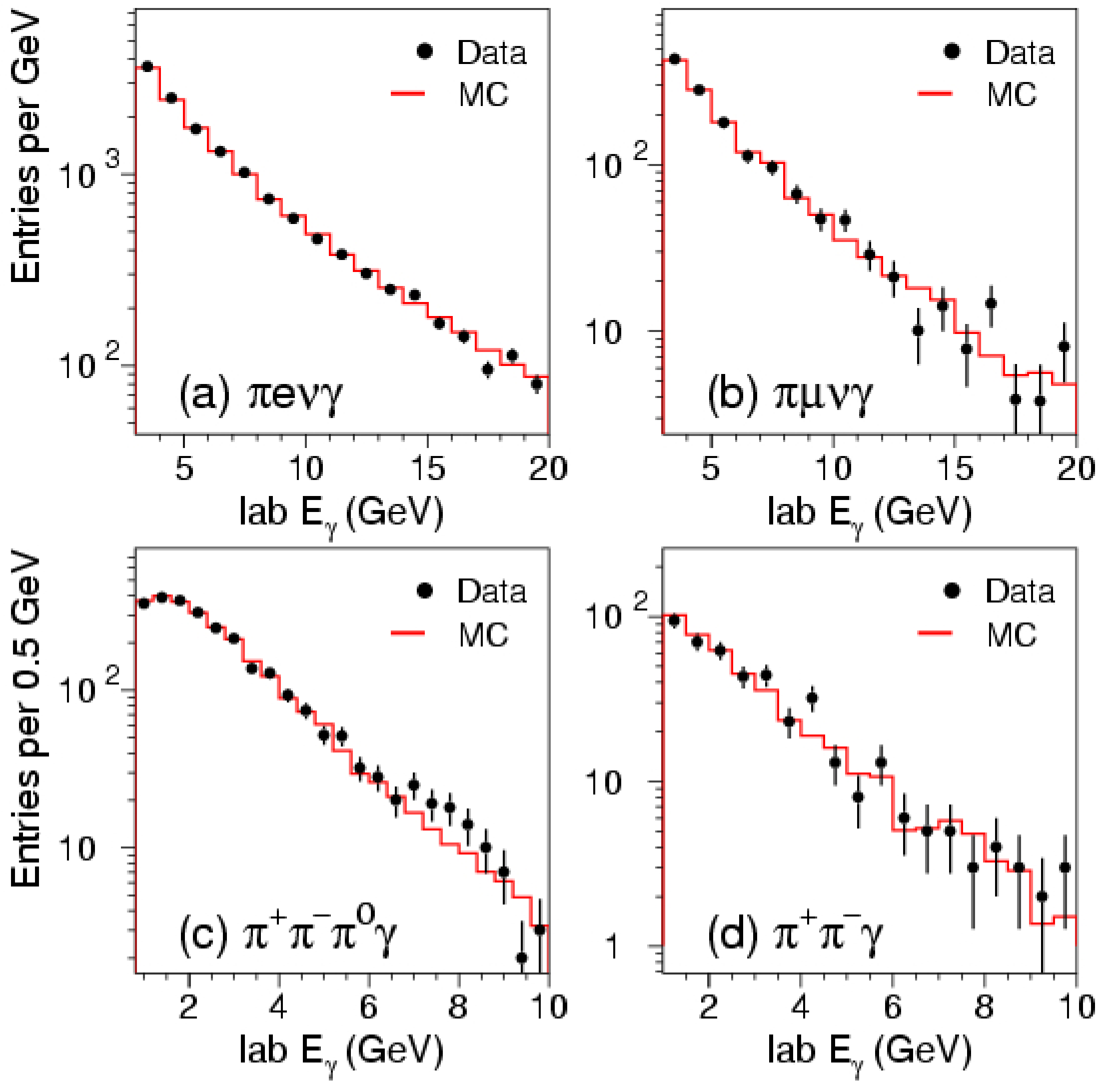
Comparison of data and Monte Carlo decay vertex distributions

Branching fractions include radiated photons:

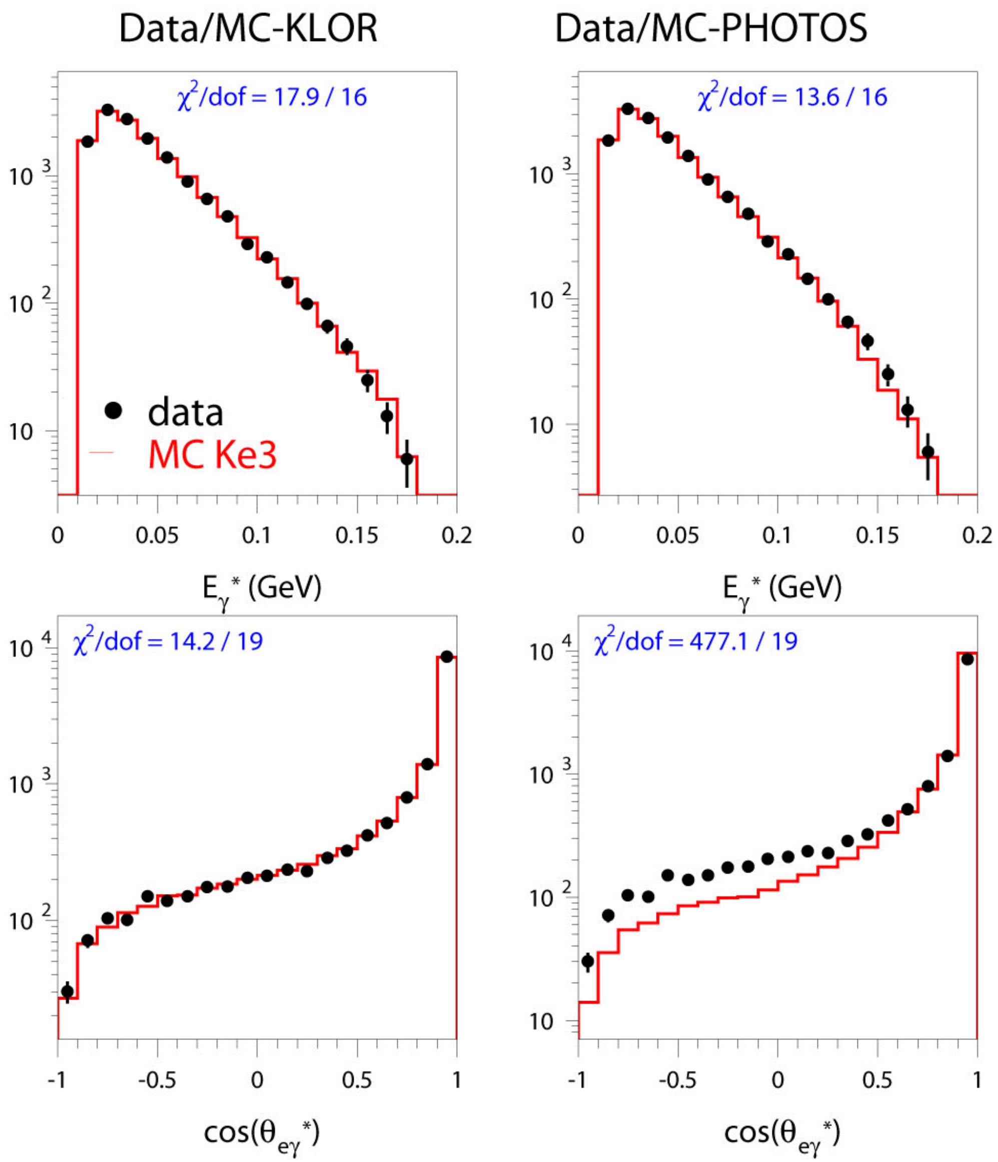
- $K_{e3(\gamma)}$ and $K_{\mu3(\gamma)}$: KLOR written by T. Andre. Includes virtual and real photons.
- $K_{+-0(\gamma)}$: PHOTOS
- $K_{+-(\gamma)}$: KTeV generator includes IB, but ignores direct emission.

Radiation changes Ke3 acceptance by 3%; effect on other modes is $< 0.5\%$.

Data – MC Comparison for Radiative Photon Candidates



KLOR – PHOTOS Comparison for Semileptonic Decays



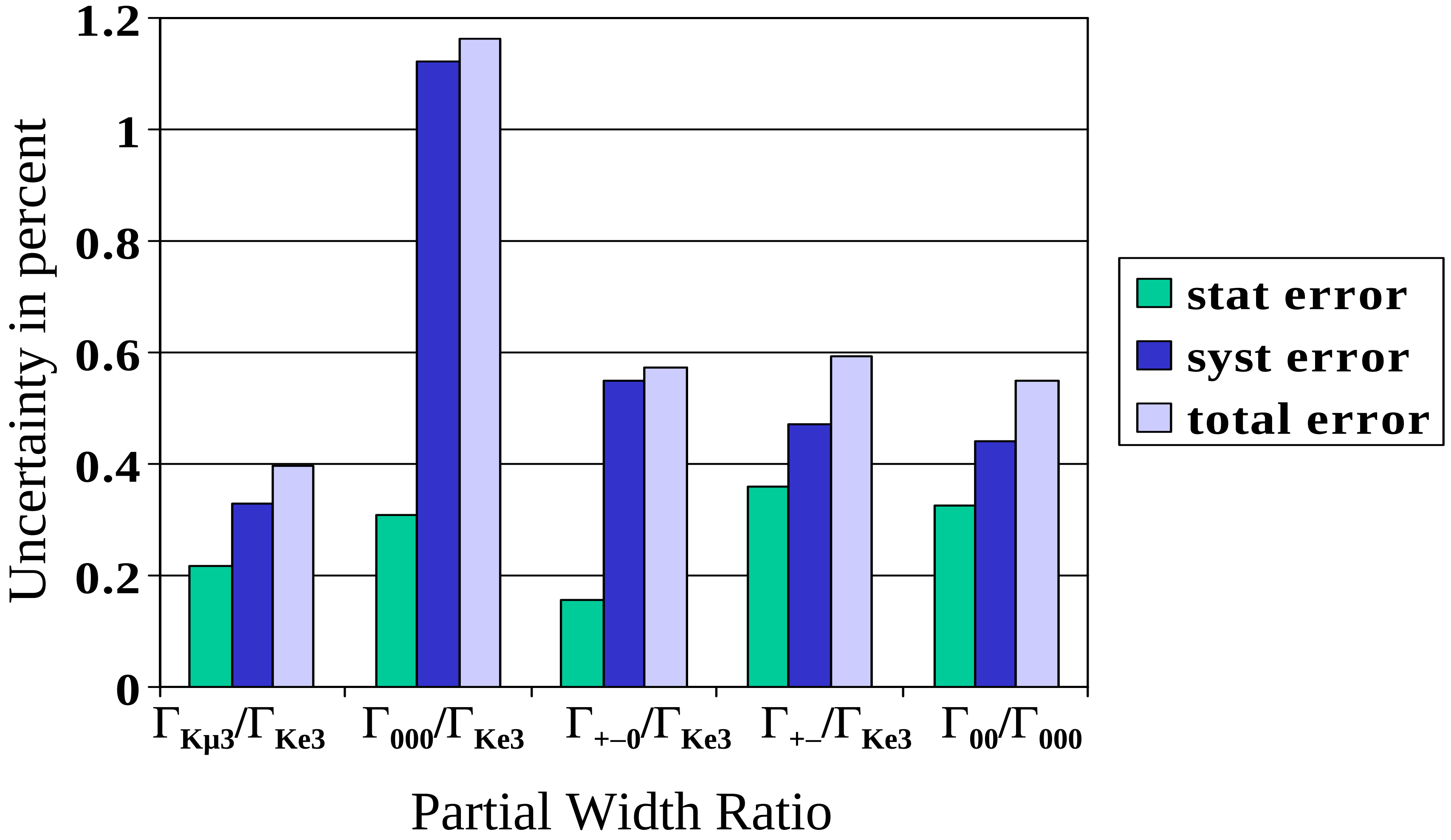
Systematic Uncertainties in Partial Width Ratios in percent

Source of uncertainty	$\Gamma_{K\mu3}/\ \Gamma_{Ke3}$	$\Gamma_{000}/\ \Gamma_{Ke3}$	$\Gamma_{+-0}/\ \Gamma_{Ke3}$	$\Gamma_{+-}/\ \Gamma_{Ke3}$	$\Gamma_{00}/\ \Gamma_{000}$
Acceptance (MC Simulation)					
Event Generation:					
- Kaon energy spectrum	0.02	0.16	0.04	0.02	0.01
- Form factor	0.11	0.08	0.29	0.08	0.00
Radiative corrections:					
-	0.15	0.20	0.14	0.14	0.00
Particle Propagation:					
- Detector material	0.10	0.56	0.33	0.33	0.15
- Detector geometry	0.02	0.39	0.05	0.02	0.08
Detector Response:					
- Accidental activity	0.00	0.22	0.04	0.02	0.03
- Trigger	0.00	0.07	0.10	0.07	0.28
- $e^{\pm}, \mu^{\pm}, \pi^{\pm}$ reconstruction	0.21	0.70	0.24	0.26	0.00
- π^0 reconstruction	0.00	0.37	0.00	0.00	0.23
Background	0.10	0.00	0.02	0.04	0.04
$B(\pi^0 \to \gamma\gamma)$	0.00	0.10	0.10	0.00	0.03
Monte Carlo Statistics	0.10	0.12	0.05	0.13	0.16
Total	0.33	1.12	0.55	0.47	0.44

Main Systematic Uncertainties

- $\Gamma_{000}/\Gamma_{Ke3}$ ratio:
  => 0.6% two-track efficiency uncertainty
  => 0.4% uncertainty in $3\pi^0$ recon
  => 0.6% uncertainty from detector material
- 0.35% uncertainty in loss from π-interactions for ratios with different number of charged π

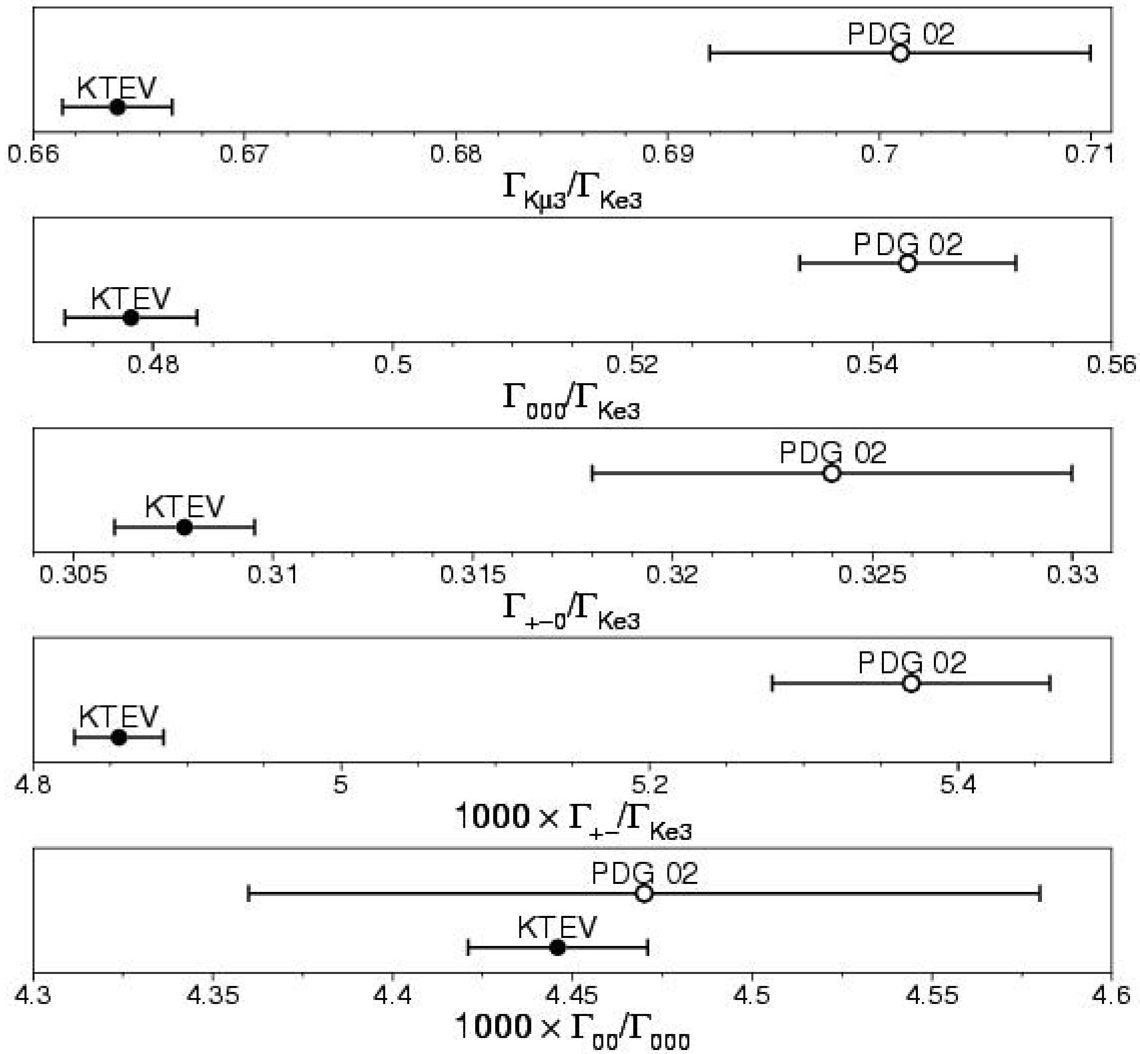
Statistical and Systematic Errors in Partial Width Ratios



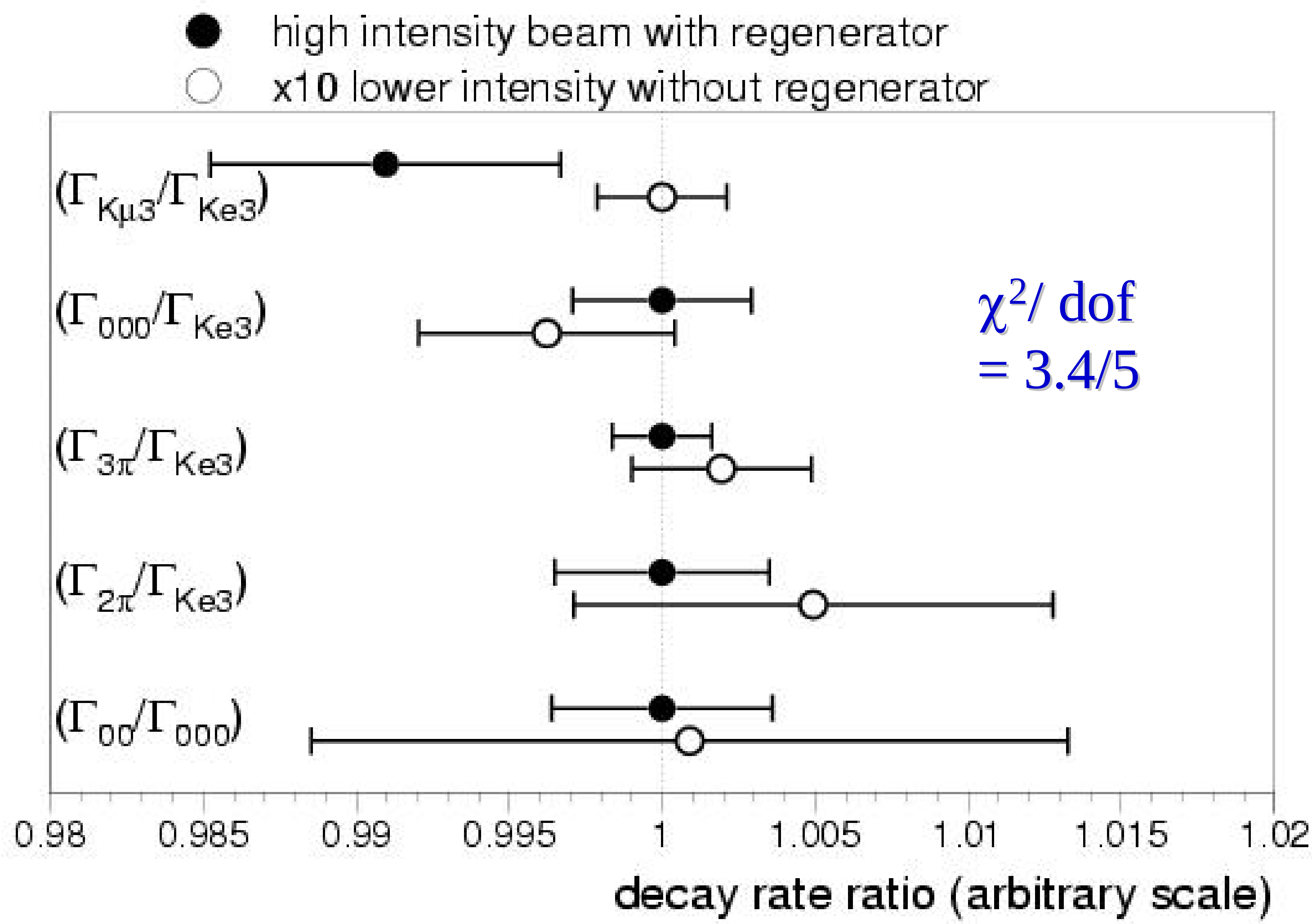
Measured Partial Width Ratios

Decay Modes	Partial Width Ratio
$\Gamma_{K\mu3} / \Gamma_{Ke3}$	$0.6640 \pm 0.0014 \pm 0.0022$
$\Gamma_{000} / \Gamma_{Ke3}$	$0.4782 \pm 0.0014 \pm 0.0053$
$\Gamma_{+-0} / \Gamma_{Ke3}$	$0.3078 \pm 0.0005 \pm 0.0017$
$\Gamma_{+-} / \Gamma_{Ke3}$	$(4.856 \pm 0.017 \pm 0.023) \times 10^{-3}$
$\Gamma_{00} / \Gamma_{000}$	$(4.446 \pm 0.016 \pm 0.019) \times 10^{-3}$

Comparison of KTeV and PDG Partial Width Ratios



Cross Checks: Width Ratios with High and Low Intensity



Cross Checks: $K \to \pi\mu\nu$ and $K \to \pi^+\pi^-\pi^0$ Analysis

- $K \to \pi\mu\nu$ yields without/with μ system agree to $(0.08 \pm 0.02\text{stat})\%$

- $K \to \pi^+\pi^-\pi^0$ yields without/with $\pi^0 \to \gamma\gamma$ reconstruction in CsI agree to $(0.03 \pm 0.028_{stat})\%$.

  Acceptance in two analyses differs by factor of 5!

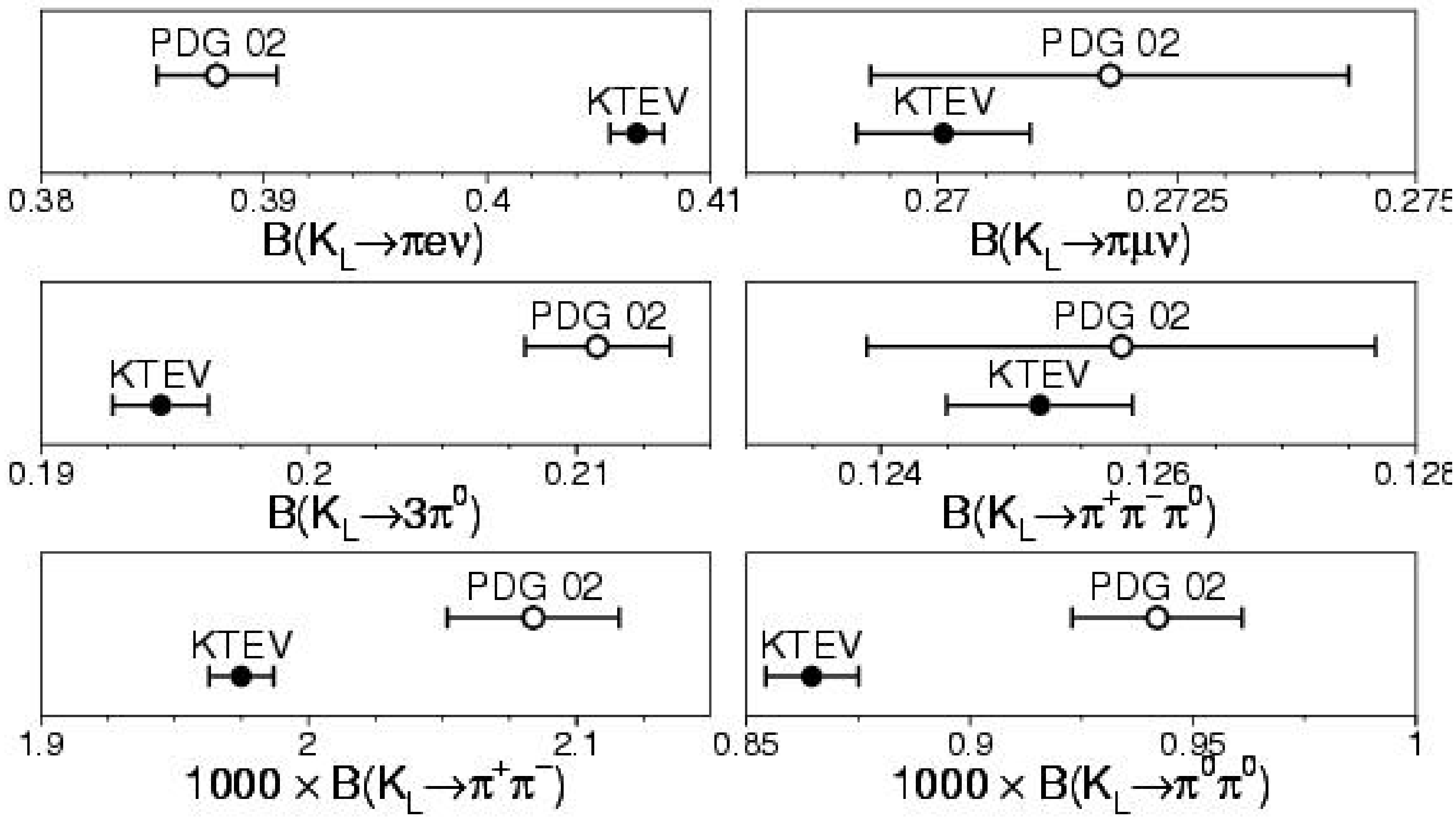
- $\Gamma_{+-0}/(\Gamma_{Ke3} + \Gamma_{K\mu3} + \Gamma_{+-0})$ may be determined by fitting the k_{+-0} distribution. The difference with the nominal analysis is $(0.35 \pm 0.51)\%$.

Branching Fraction and Partial Width Results

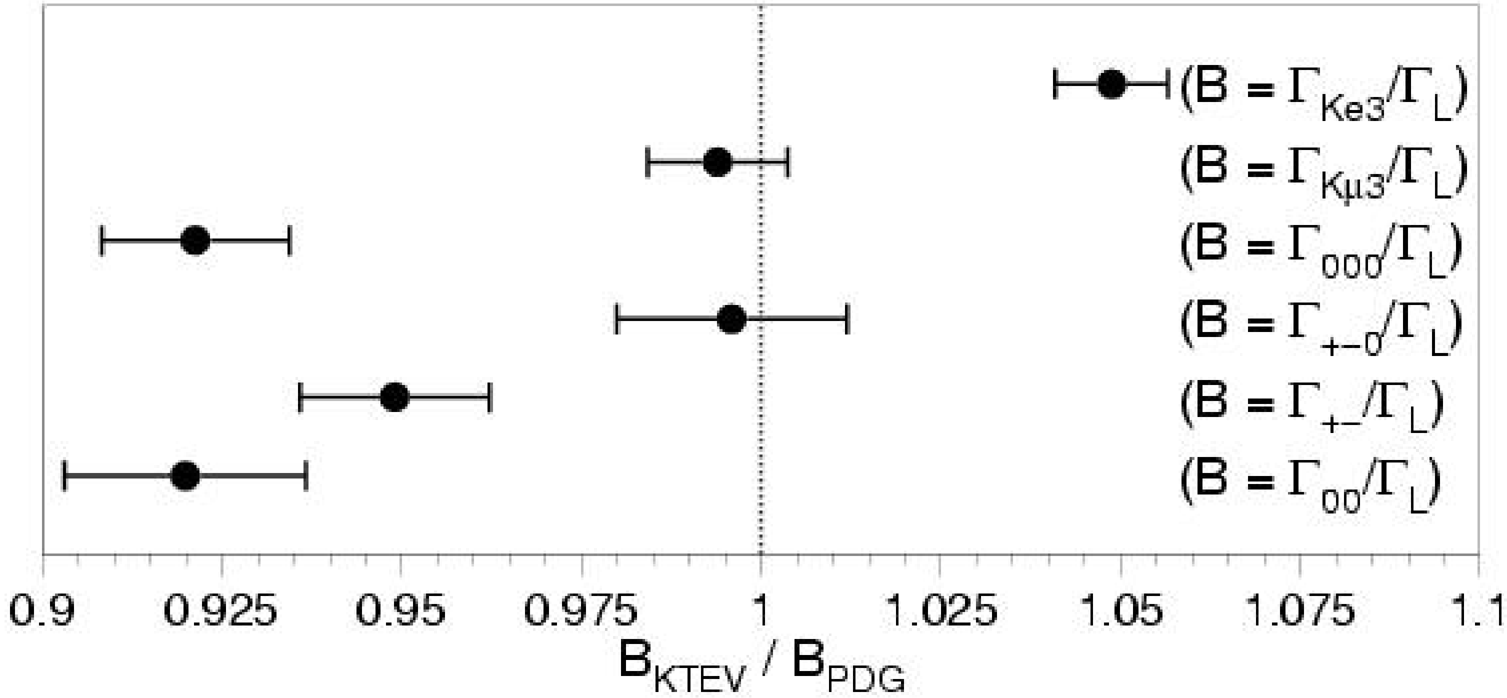
Decay Mode	Branching Fraction	Γ_i (10^7 s^{-1})
$K_L \to \pi e \nu$	0.4067 ± 0.0011	0.7897 ± 0.0065
$K_L \to \pi \mu \nu$	0.2701 ± 0.0009	0.5244 ± 0.0044
$K_L \to \pi^+ \pi^- \pi^0$	0.1252 ± 0.0007	0.2431 ± 0.0023
$K_L \to \pi^0 \pi^0 \pi^0$	0.1945 ± 0.0018	0.3777 ± 0.0045
$K_L \to \pi^+ \pi^-$	$(1.975 \pm 0.012) \times 10^{-3}$	$(3.835 \pm 0.038) \times 10^{-3}$
$K_L \to \pi^0 \pi^0$	$(0.865 \pm 0.010) \times 10^{-3}$	$(1.679 \pm 0.024) \times 10^{-3}$

Partial widths use K_L lifetime of $\tau_L = (5.15 \pm 0.04) \times 10^{-8}$ sec.

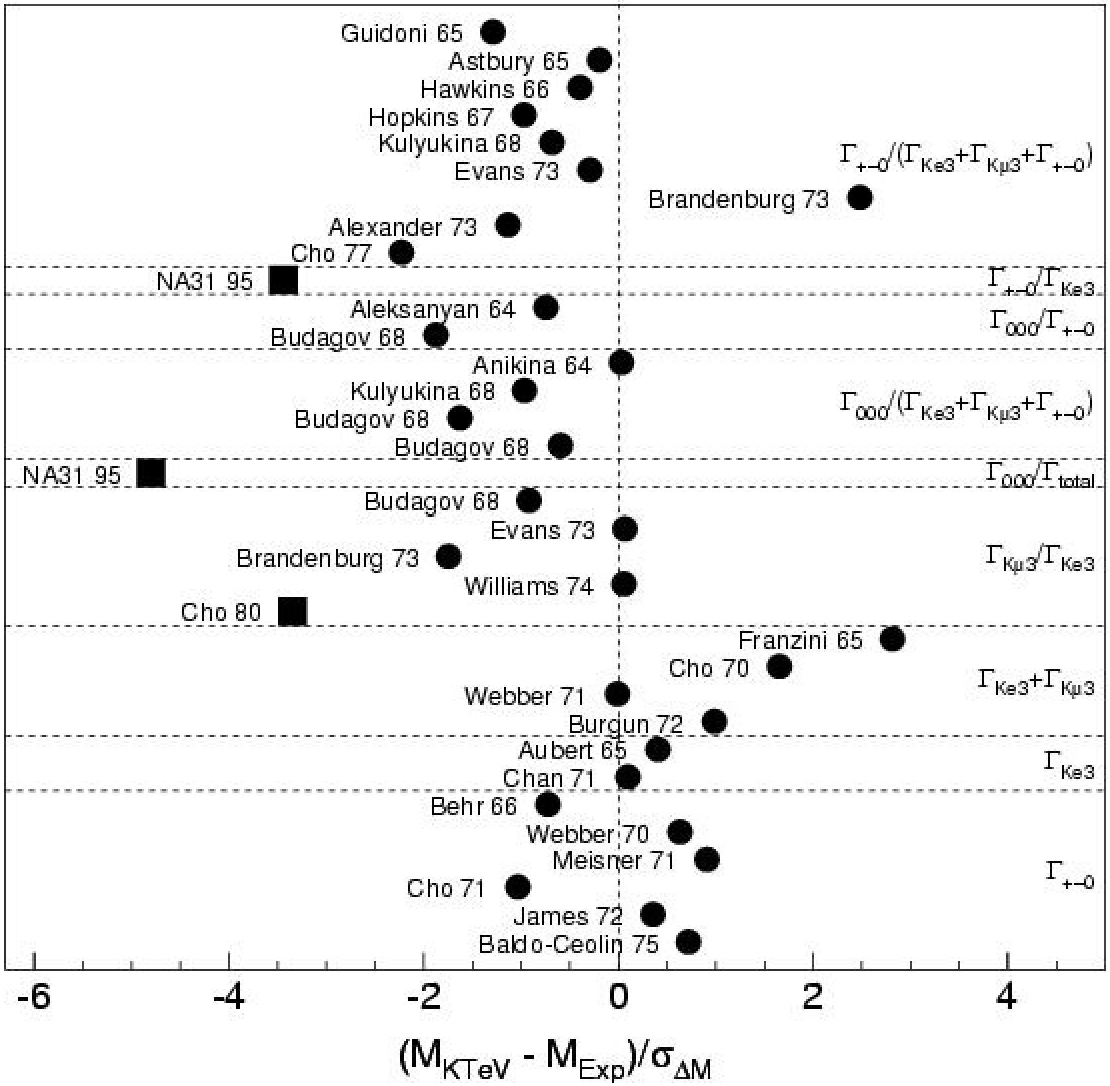
Comparison of KTeV and PDG Branching Fractions



Ratio of KTeV / PDG Branching Fractions

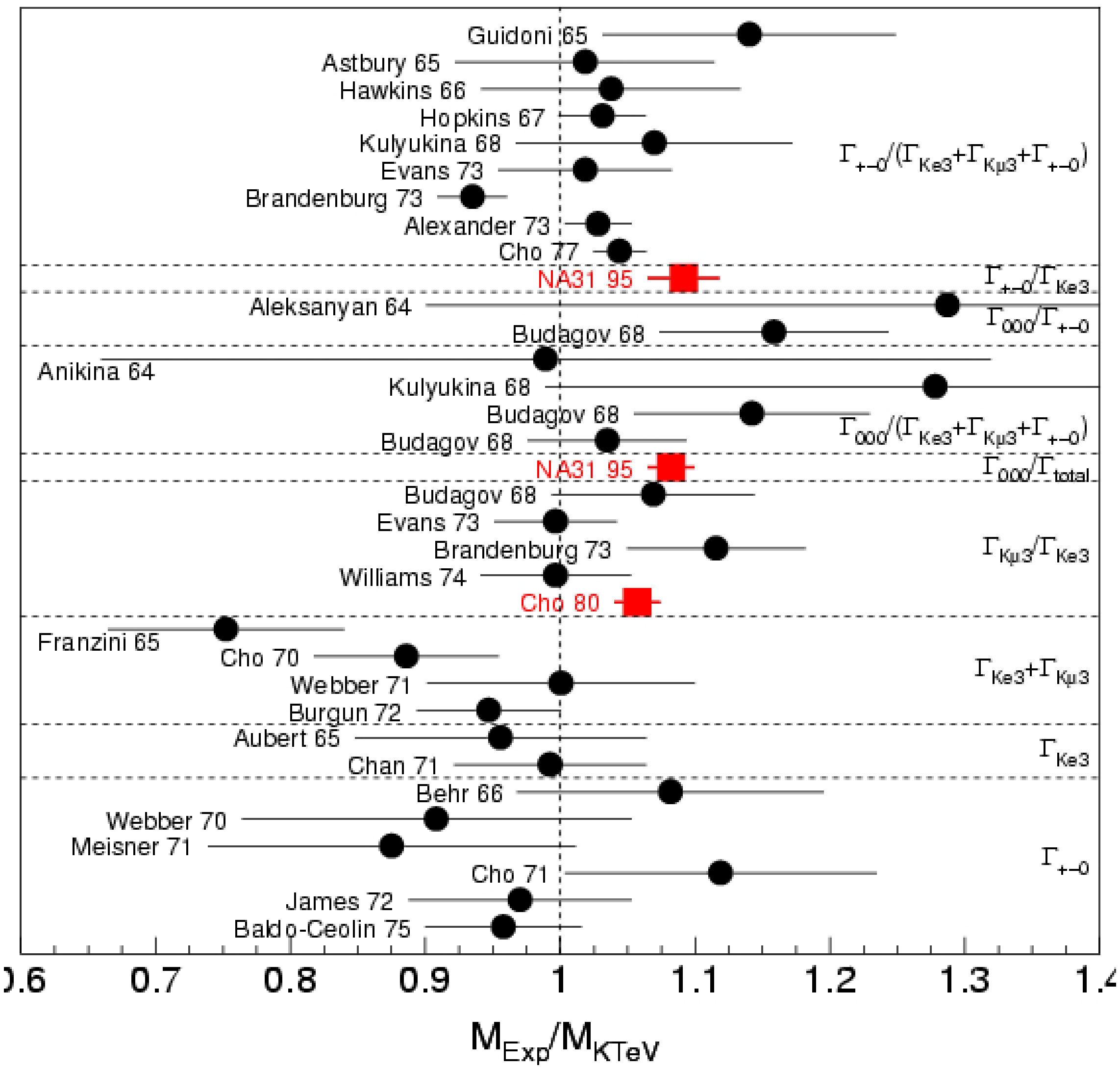


Comparison with Individual Experiments



The dashed line at 0 represents the value based on KTeV's measured partial widths.

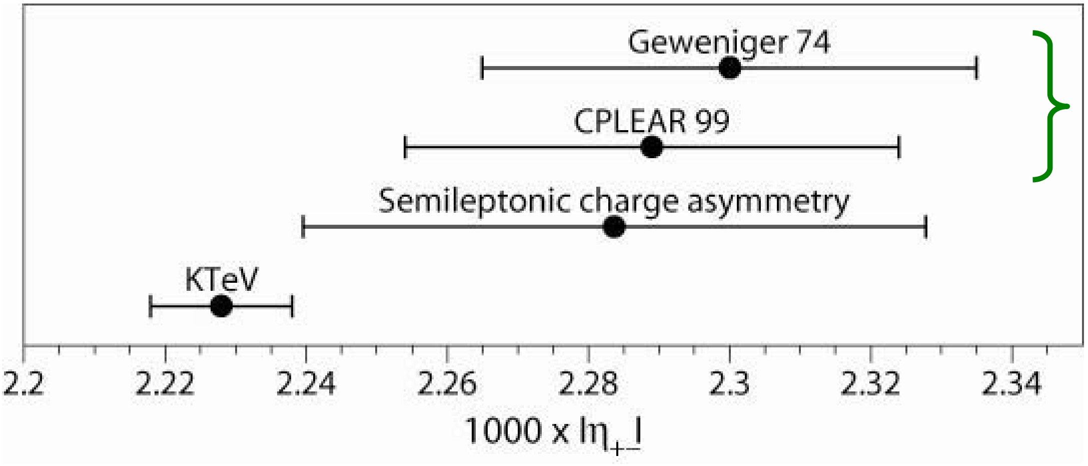
Comparison with Individual Experiments



Determination of $|\eta_{+-}|$ Using $B(K_L \to \pi\pi)$

$$|\eta_{+-}|^2 = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} = \frac{\tau_S}{\tau_L} \frac{B^L_{\pi^+\pi^-} + B^L_{\pi^0\pi^0}\left[1+6\,\mathrm{Re}(\varepsilon'/\varepsilon)\right]}{1-B^S_{\pi\ell\nu}}$$

KTeV: $|\eta_{+-}| = \left(2.228 \pm 0.005_{KTeV} \pm 0.009_{EXT}\right)\times 10^{-3}$



K_L-K_S Interference

Other implications of new branching fractions:

Many rare K_L decays are normalized to decays we have remeasured.

- $K_L \to \mu^+\mu^-$ is normalized to $K_L \to \pi^+\pi^-$ which changes by 5% compared to PDG.
- $K_L \to \gamma\gamma$ is normalized to $K_L \to 2\pi^0$ $(3\pi^0)$, which changes by 8% relative to PDG.
- $\Gamma(K_L \to \mu^+\mu^-) / \Gamma(K_L \to \gamma\gamma)$ changes by ~3%.

Semileptonic Form Factor Measurements

(to determine I_K integrals)

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1+\delta_K^\ell) C^2 |V_{us}|^2 \; f_+^2(0) I_K^\ell$$

I_K depends on the two independent semileptonic FFs:

f+ and f– or f_+ and f_0

We use the following parametrization:

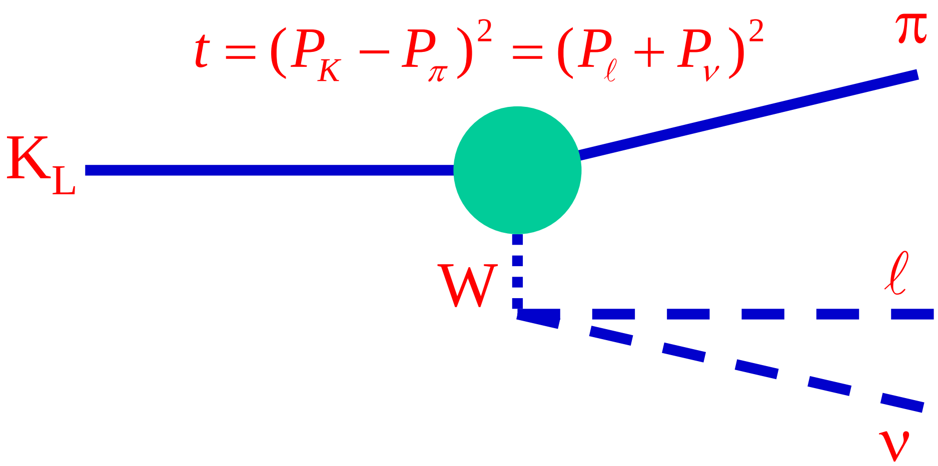
$$f_+(t) = f_+(0)\left(1 + \lambda_+' \frac{t}{M_\pi^2} + \frac{1}{2}\lambda_+'' \frac{t^2}{M_\pi^4}\right)$$

$$f_0(t) = f_+(0)\left(1 + \lambda_0 \frac{t}{M_\pi^2}\right),$$

where $t = (P_K - P_\pi)^2 = (P_\ell + P_\nu)^2$

Method to Extract Semileptonic Form Factors

$$t = (P_K - P_\pi)^2 = (P_\ell + P_\nu)^2$$

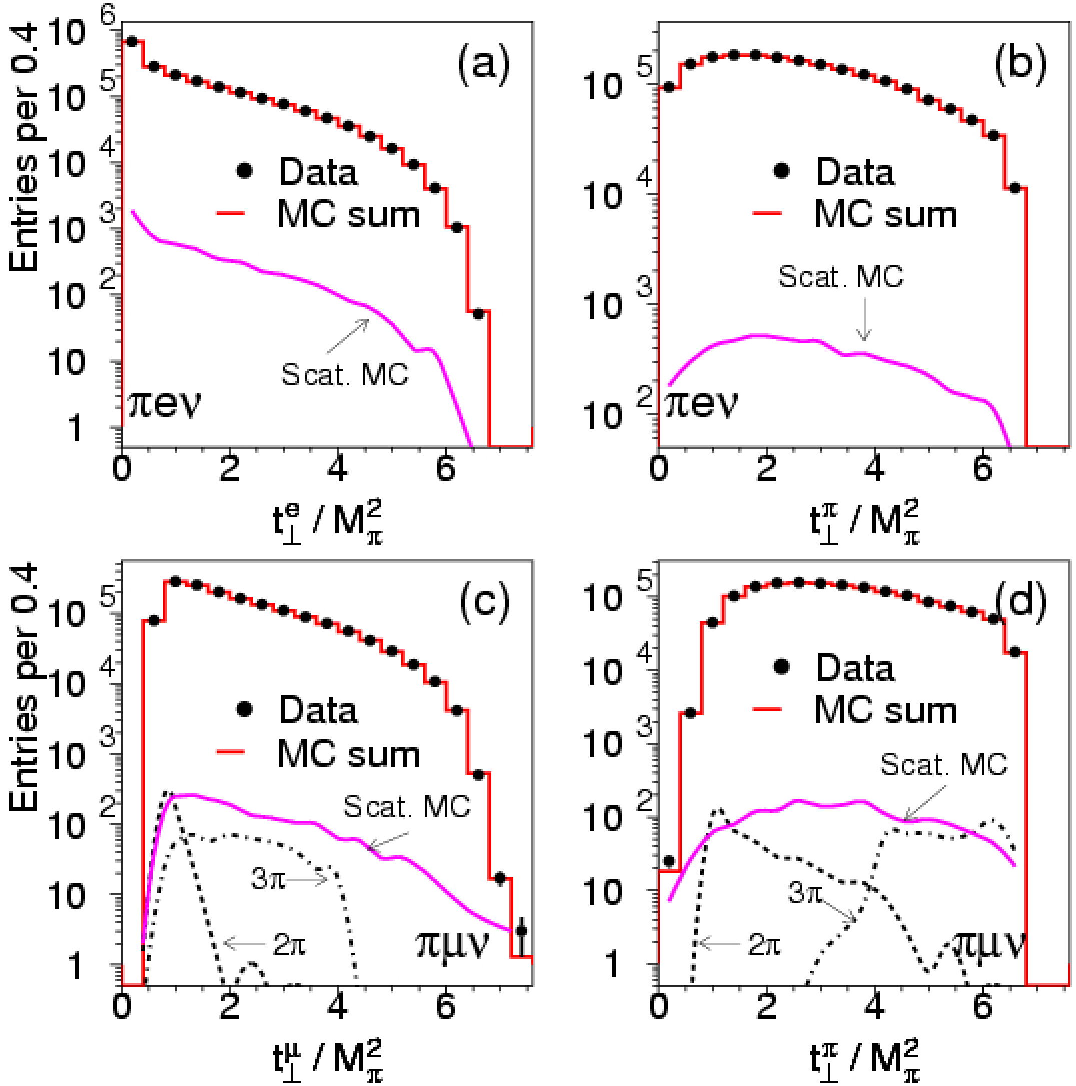


Since the kaon E is not known and the neutrino is undetected, there are two possible t values

To avoid this ambiguity, we instead study $t_\perp$ based on components of particle momenta transverse to the the kaon momentum.

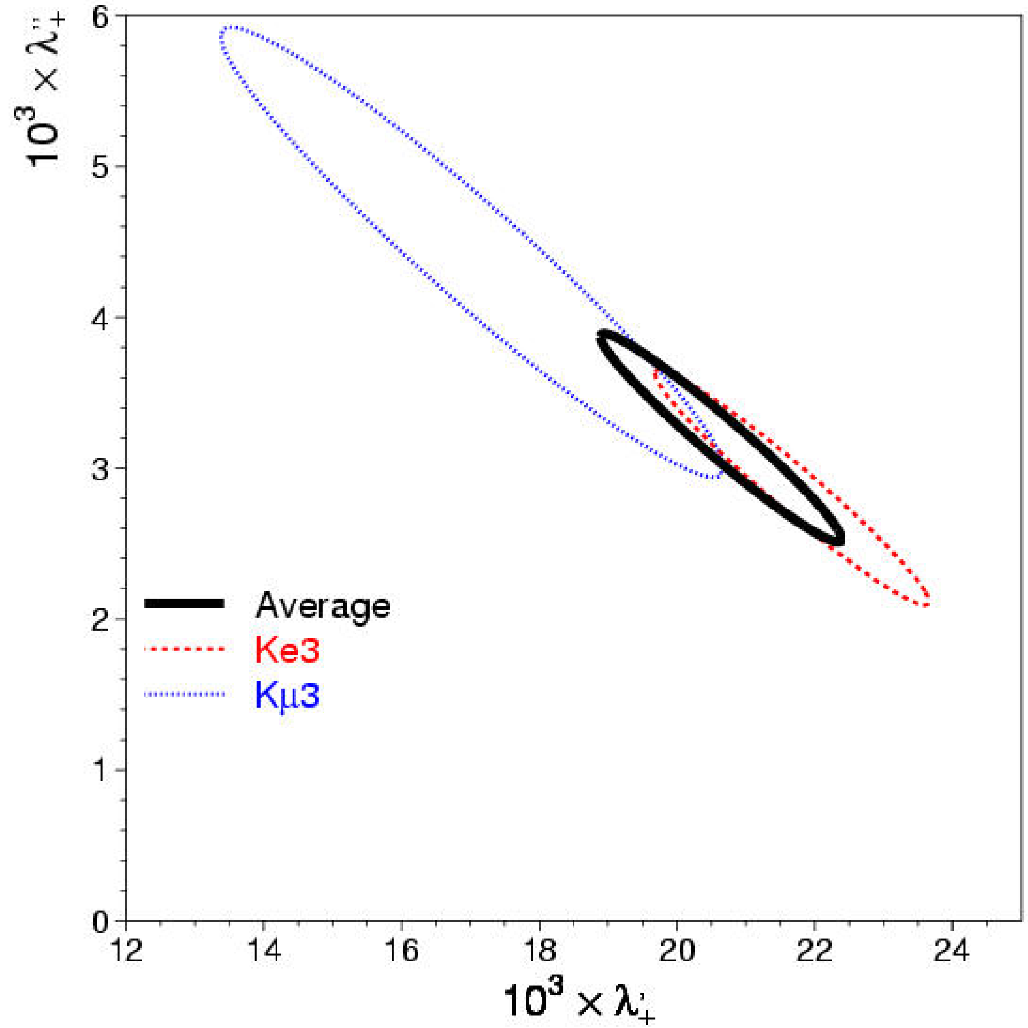
We use a Monte Carlo simulation to determine the detector acceptance as a function of $t_\perp$ and to calculate radiative corrections.

$t_\perp$ Distributions

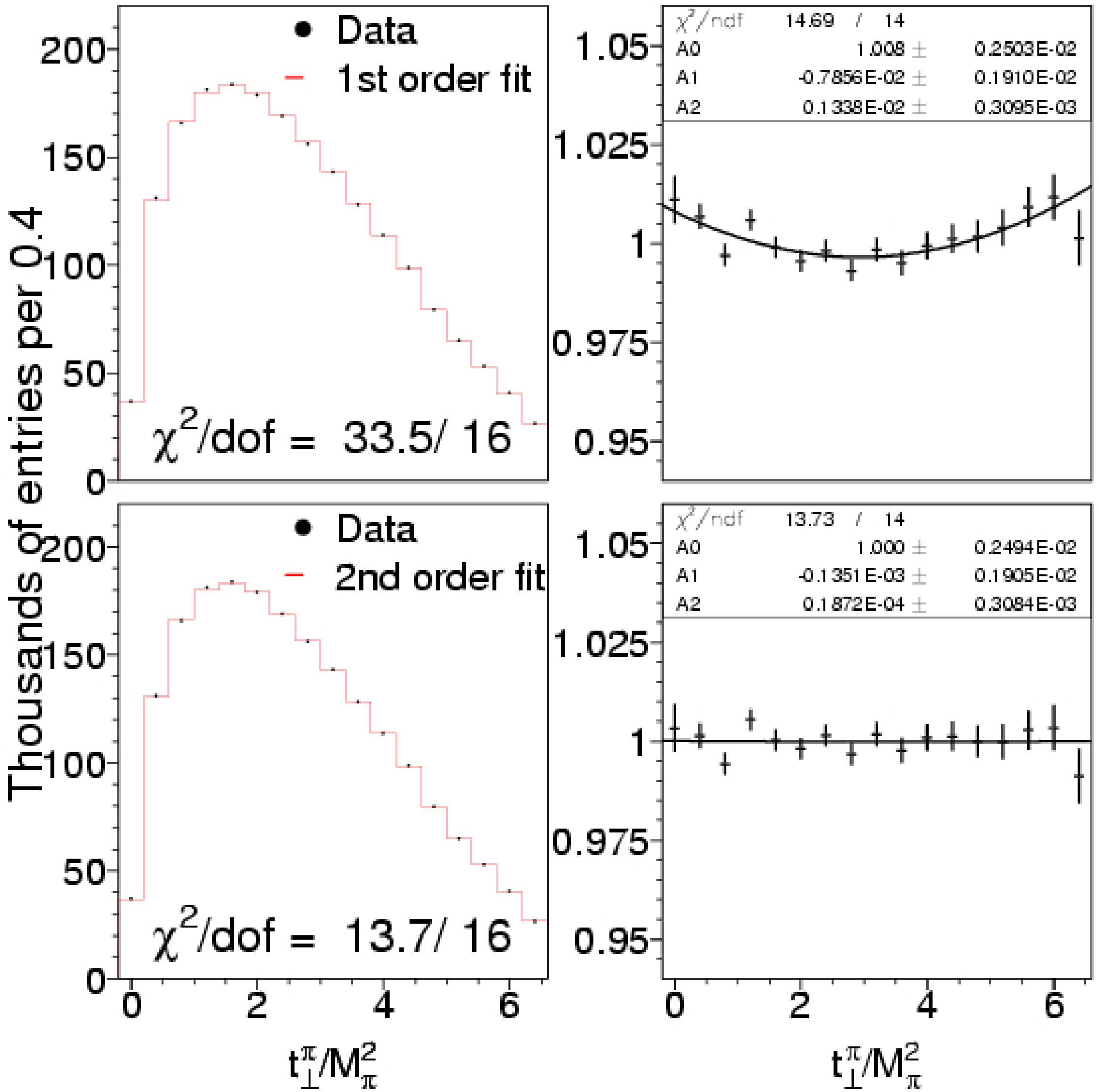


Form Factor Results

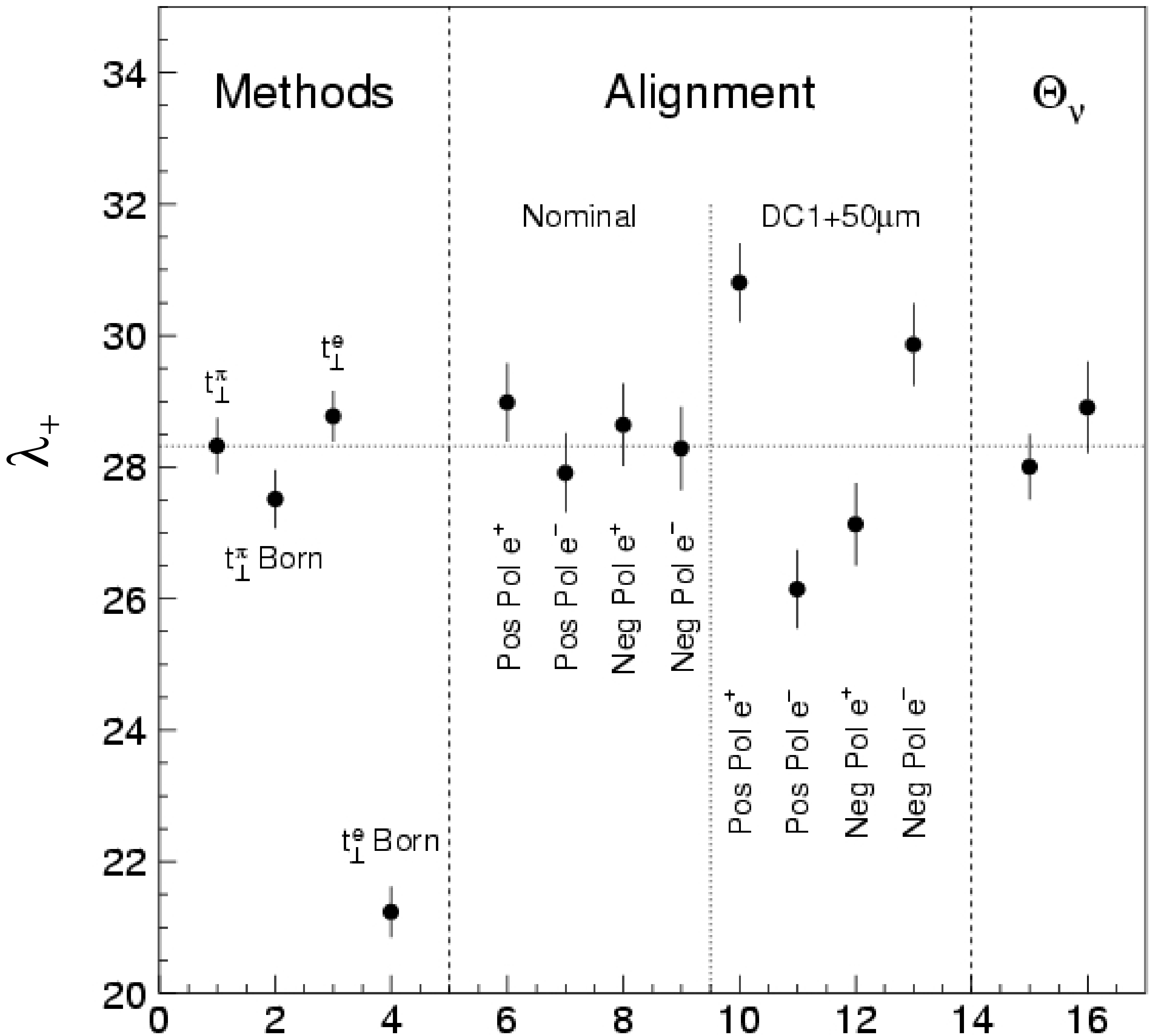
Parameter	Value ($\times 10^{-3}$)
λ_+'	20.64 ± 1.75
λ_+''	3.20 ± 0.69
λ_0	13.72 ± 1.31



First and Second Order Fits to K→πeν

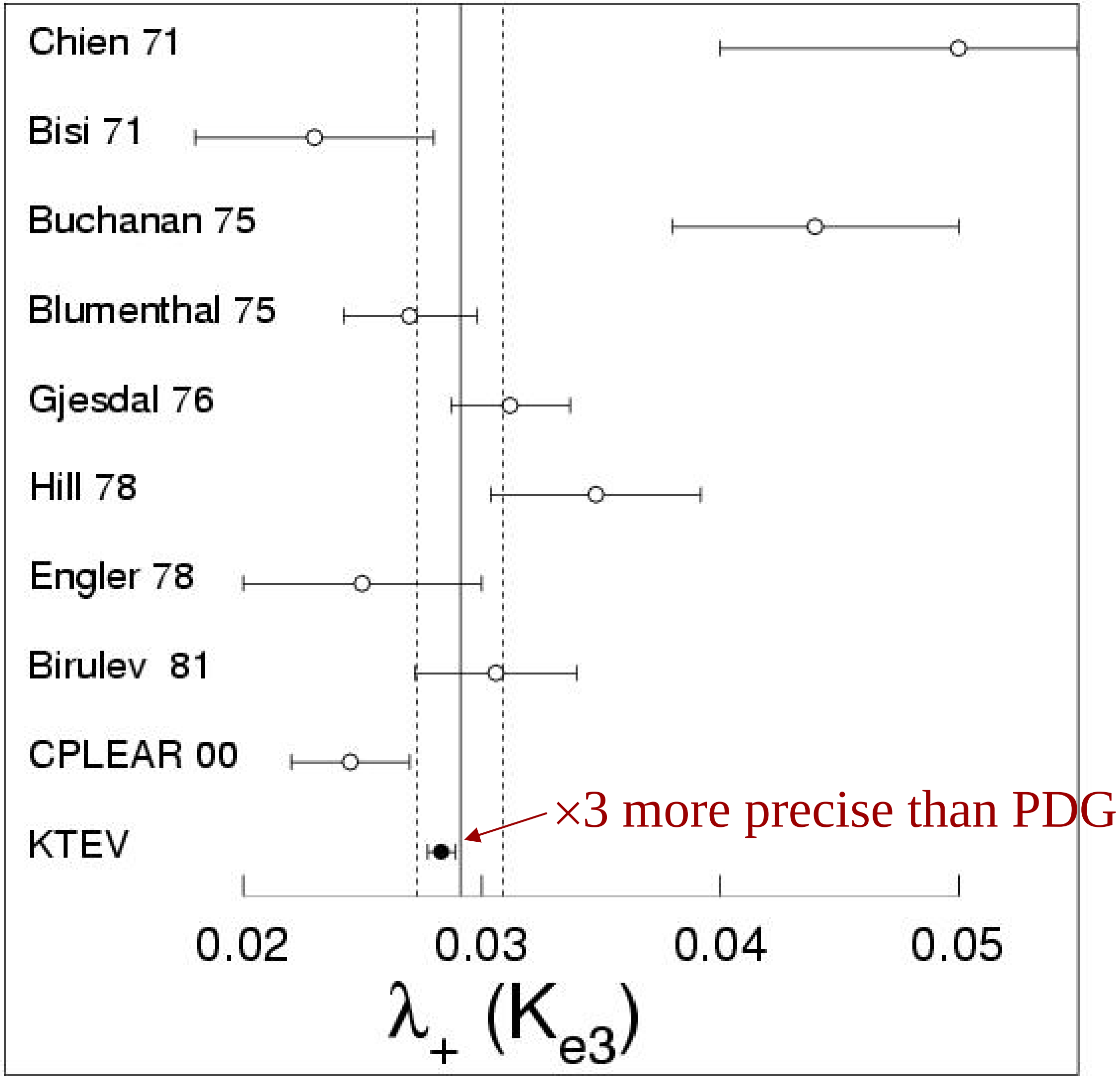


K_{e3} Form Factor Cross Checks

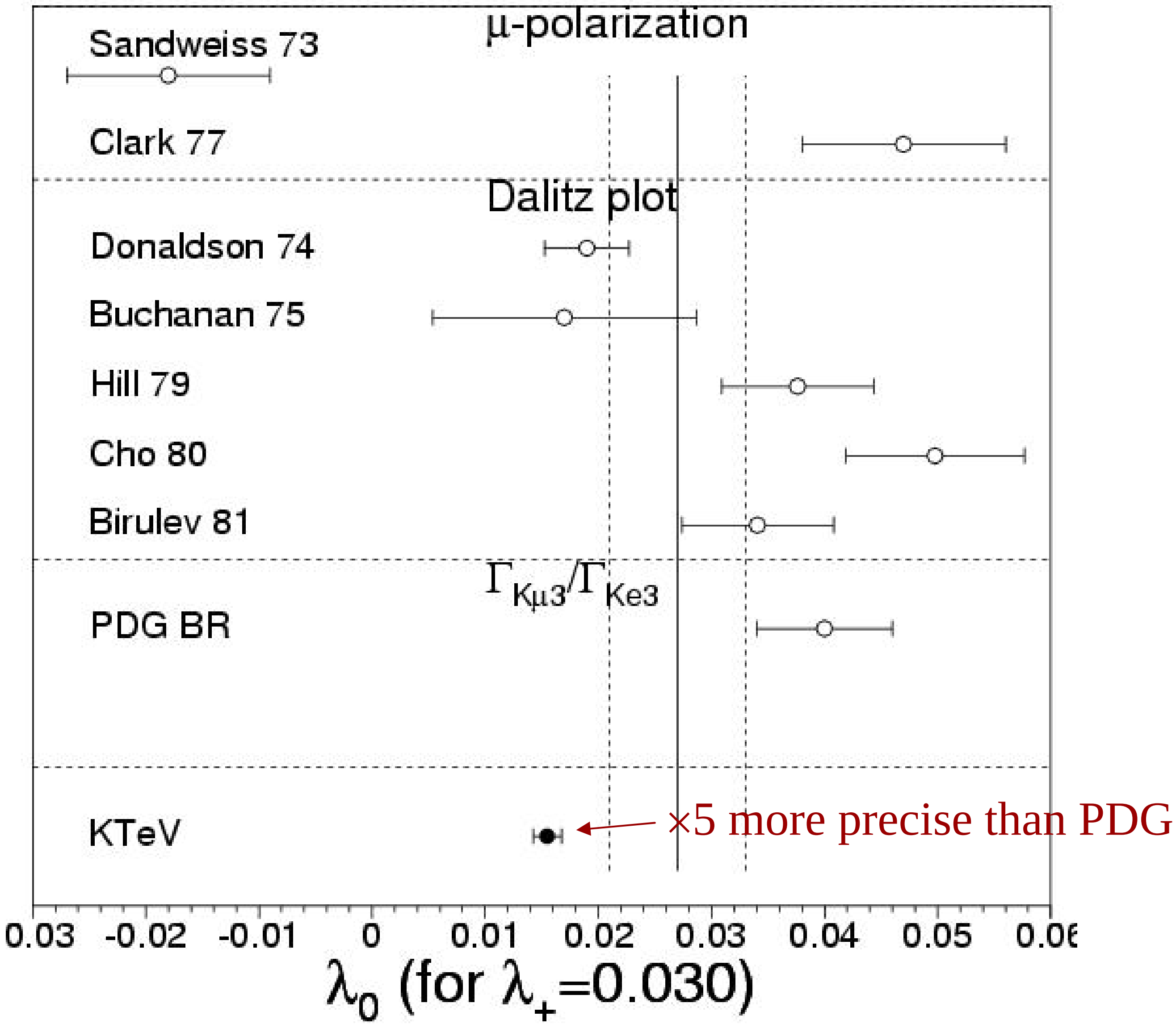


Semileptonic Form Factors: λ_+

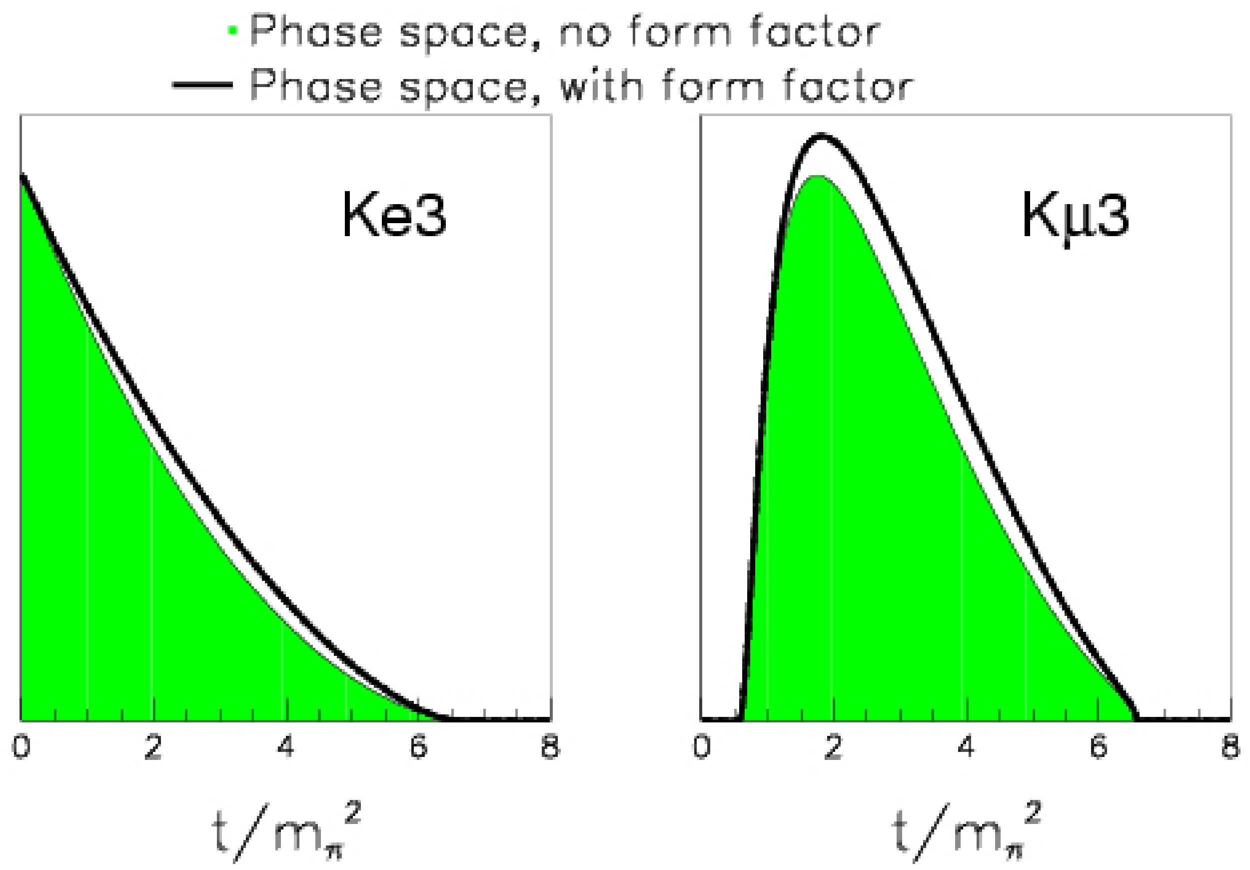
We use the linear parametrization to compare with previous measurements



Semileptonic Form Factors: λ_0



Phase Space Integrals



$$I_K^e = 0.15350 \pm 0.00044 \pm 0.00095 \qquad I_K^\mu = 0.10165 \pm 0.00039 \pm 0.00070$$

Second error is additional 0.7% uncertainty from model dependence (pole vs. quadratic); not included in previous evaluations.

Consistency of Branching Fraction and Form Factor Results with Lepton Universality

Compare $\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1+\delta_K^\ell) |V_{us}|^2 f_+^2(0) I_K^\ell$ for K_{e3} and $K_{\mu 3}$

$$\left[\frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}}\right]_{PRED} = \left(\frac{1+\delta_K^\mu}{1+\delta_K^e}\right)\left(\frac{I_K^\mu}{I_K^e}\right)$$

1.0058(10) from Andre

0.6622(18) from KTeV

$$\left[\frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}}\right]_{MEAS} \Big/ \left[\frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}}\right]_{PRED} = 0.9969 \pm 0.0048 = \left(\frac{G_F^\mu}{G_F^e}\right)^2$$

Same test with PDG widths and FF gives 1.0270±0.0182

Summary of Vus Changes from KTeV Measurements

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1+\delta_K^\ell) \left|V_{us}\right|^2 f_+^2(0) I_K^\ell$$

Compared to PDG:

Γ_{Ke3} increases by 5%
$\Gamma_{K\mu 3}$ doesn’t change

I^e decreases by 1.7%
I^μ decreases by 4.2%
(both include -1% shift from λ_+'')

Theory Input Needed to extract $|V_{us}|$

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1+\delta_K^\ell) \left|V_{us}\right|^2 f_+^2(0) I_K^\ell$$

- S_{EW} (short-distance rad. corr) = 1.022 (Marciano, Sirlin)

- Long-distance radiative corrections:
  δ^e=0.013 ± 0.003 (Andre)
  δ^μ=0.019 ± 0.003 (Andre)

- $f_+(0)$= 0.961 ± 0.008 (Leutwyler – Roos) + recent calculations

$|V_{us}|$ Results

For $K_L \to \pi e \nu$: $|V_{us}| = 0.2253 \pm 0.0023$

For $K_L \to \pi \mu \nu$: $|V_{us}| = 0.2250 \pm 0.0023$

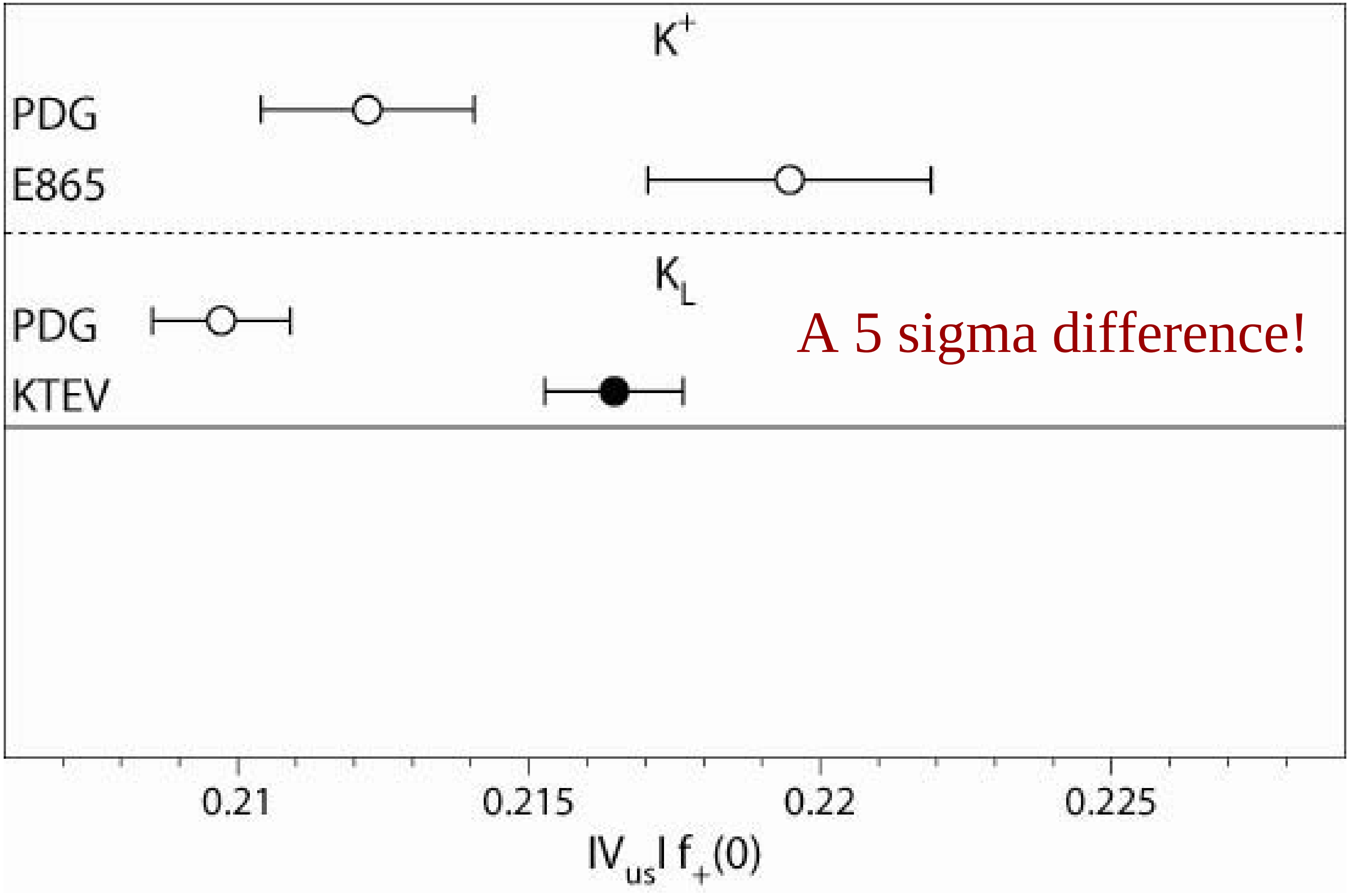
Averaging these results (accounting for correlations):

$$|V_{us}| = 0.2252 \pm 0.0008_{\mathrm{KTeV}} \pm 0.0021_{\mathrm{ext}}$$

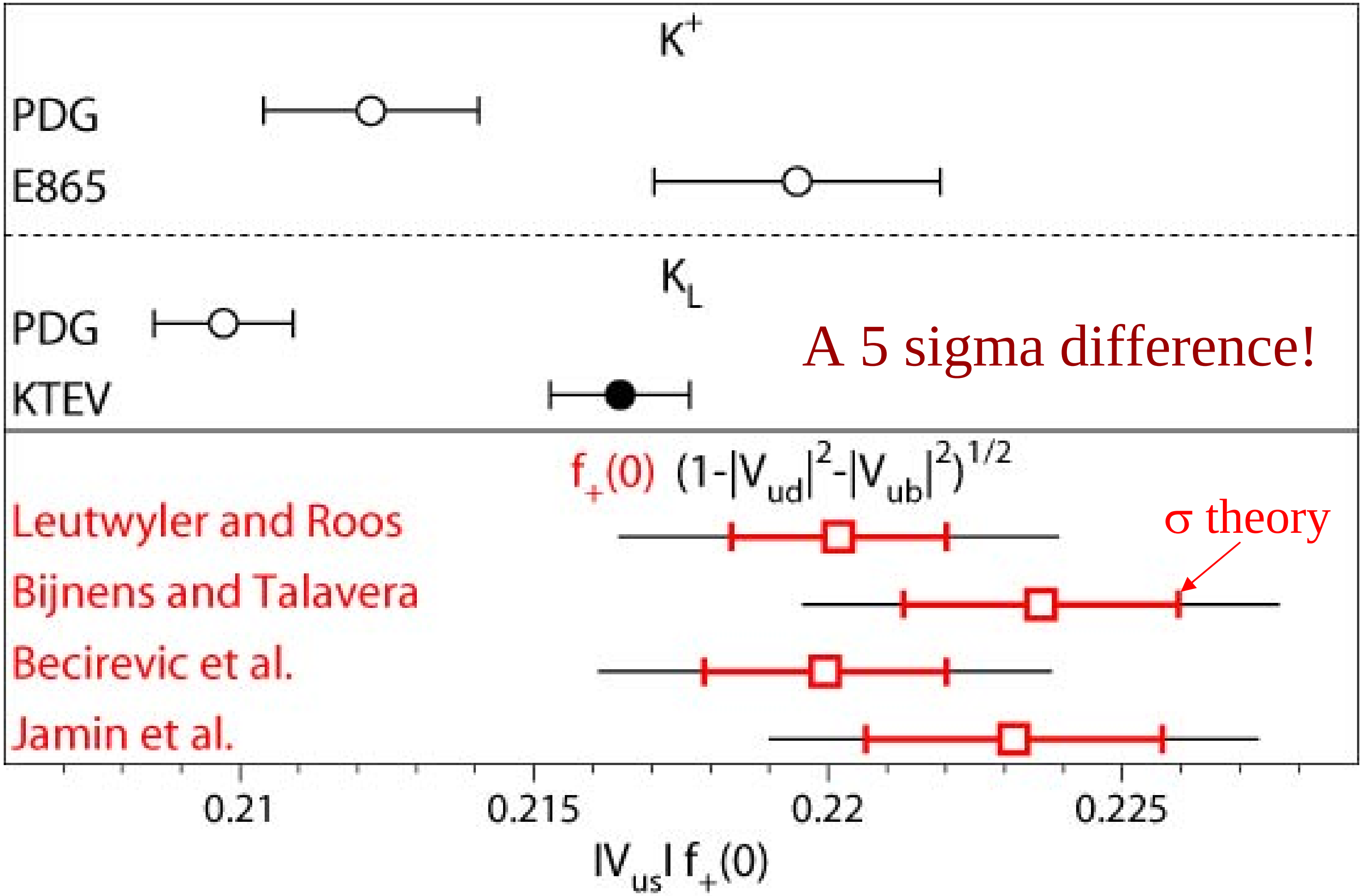
KTeV error: branching fractions, form factors

Ext error: $f_+(0)$, K_L lifetime, radiative corrections

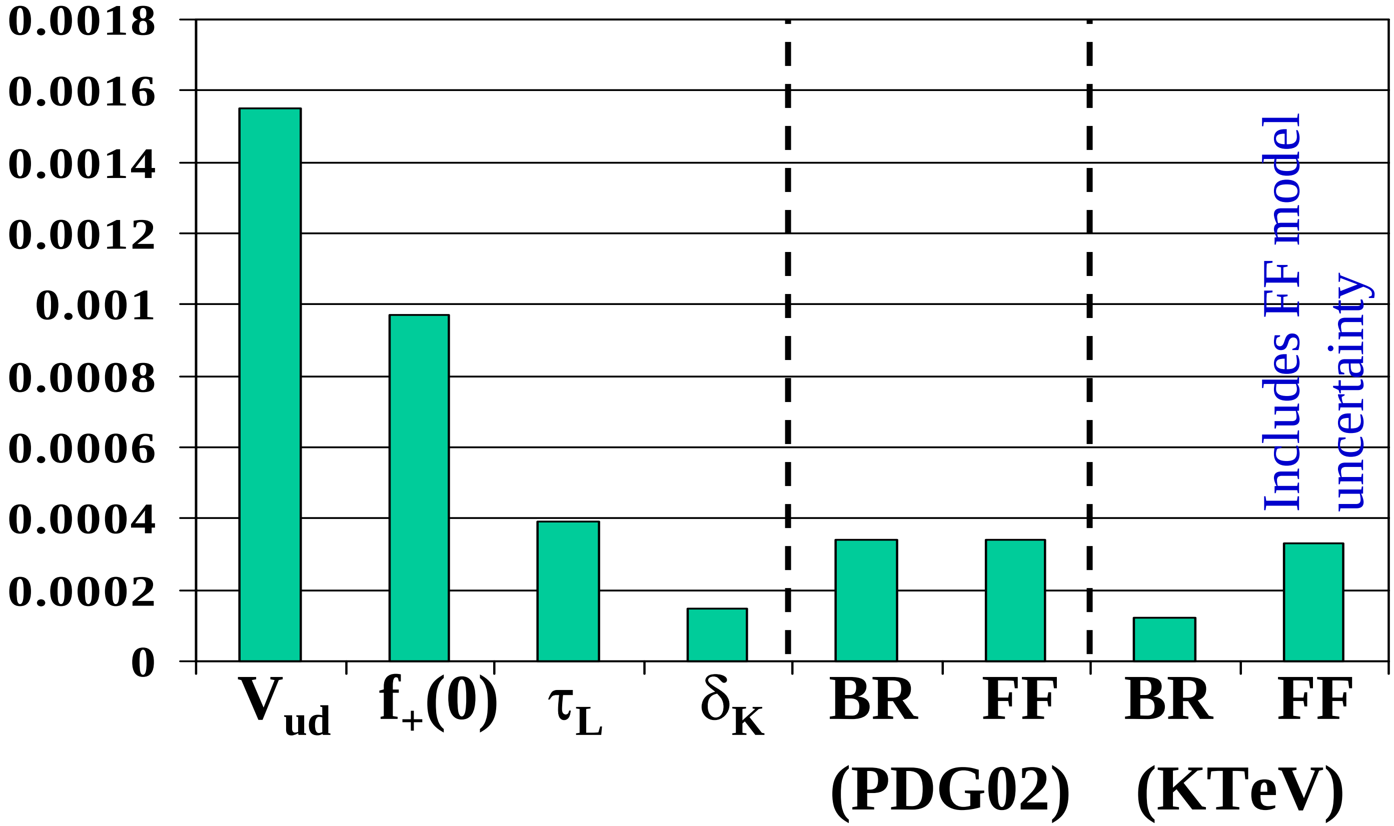
To compare with other measurements, we consider $|V_{us}|f_+(0)$:



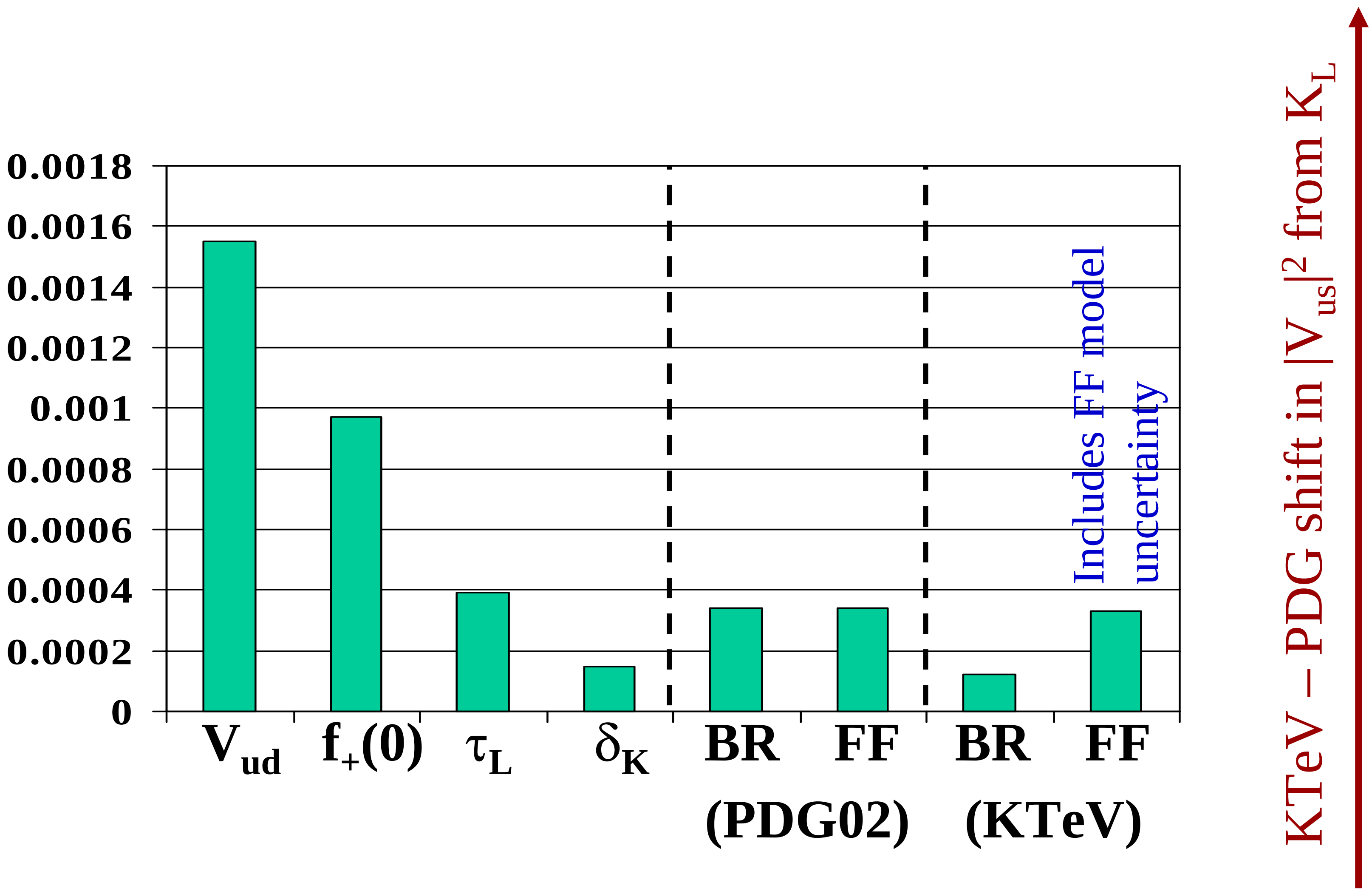
Comparison with Unitarity



Uncertainties on $|V_{ud}|^2 + |V_{us}|^2$



Uncertainties on $|V_{ud}|^2 + |V_{us}|^2$



Conclusions

- We've made improved measurements of the six largest K_L branching fractions and semileptonic FFs; four of the six branching fractions differ from PDG by 5-8%.

- KTeV measurements result in +3% shift in $|V_{us}|$ compared to PDG (from K_L decays); KTeV-PDG difference in is 5σ.

- Our $|V_{us}|$ result (based on both K_{e3} and $K_{\mu3}$) is consistent with unitarity:

$$1-\left(\left|V_{ud}\right|^2+\left|V_{us}\right|^2+\left|V_{ub}\right|^2\right)=0.0018\pm0.0019$$

- KTeV $|V_{us}|$ consistent with both PDG average and BNL E865 results using K^+.

- Our $|\eta_{+-}|$ value is 2.6% lower than PDG.

KTeV Publications

- T. Alexopoulos et al (KTeV), A Determination of the CKM Parameter $|V_{us}|$, hep-ex/0406001, submitted to Phys. Rev. Lett.

- T. Alexopoulos et al (KTeV), Measurements of K_L Branching Fractions and the CP Violation Parameter $|\eta_{+-}|$, hep-ex/0406002, submitted to Phys. Rev. D

- T. Alexopoulos et al (KTeV), Measurements of Semileptonic K_L Decay Form Factors, hep-ex/0406003, submitted to Phys. Rev. D.

Supporting publication:

T. C. Andre, Radiative Corrections in $K^0_{\ell 3}$ Decays, hep-ph/0406006, to be submitted to Phys. Rev. D.