Recent Determinations of $|V_{us}|$

Ed Blucher
University of Chicago

- Introduction to $|V_{us}|$
- New measurements from K_L decay:
  KTeV, NA48, KLOE
- Results and conclusions

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:

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

PDG $|V_{ux}|$ Evaluations

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

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

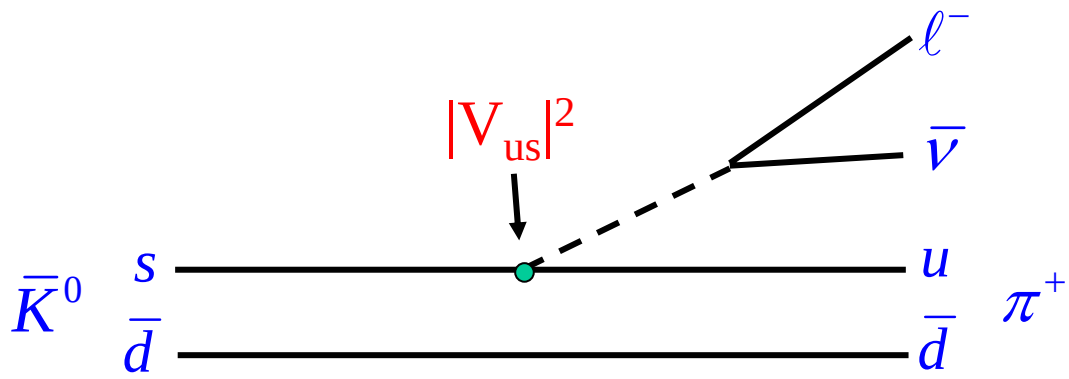
$|V_{ub}| = (3.6 \pm 0.7) \times 10^{-3}$ from semileptonic B decay

---

2003 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 Decays



Experiment:
B(K→πeν) and
B(K→πμν)

Experiment:
form factors needed
to calculate phase
space integrals

$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} \underbrace{S_{EW}(1+\delta_K^\ell)}_{\text{Rad. Corrections (theory)}} C^2 \underbrace{|V_{us}|^2}_{\text{Red Arrow}} f_+^2(0) I_K^\ell$$

$C = 1$ for K_L
$C = 1/2$ for $K^\pm$

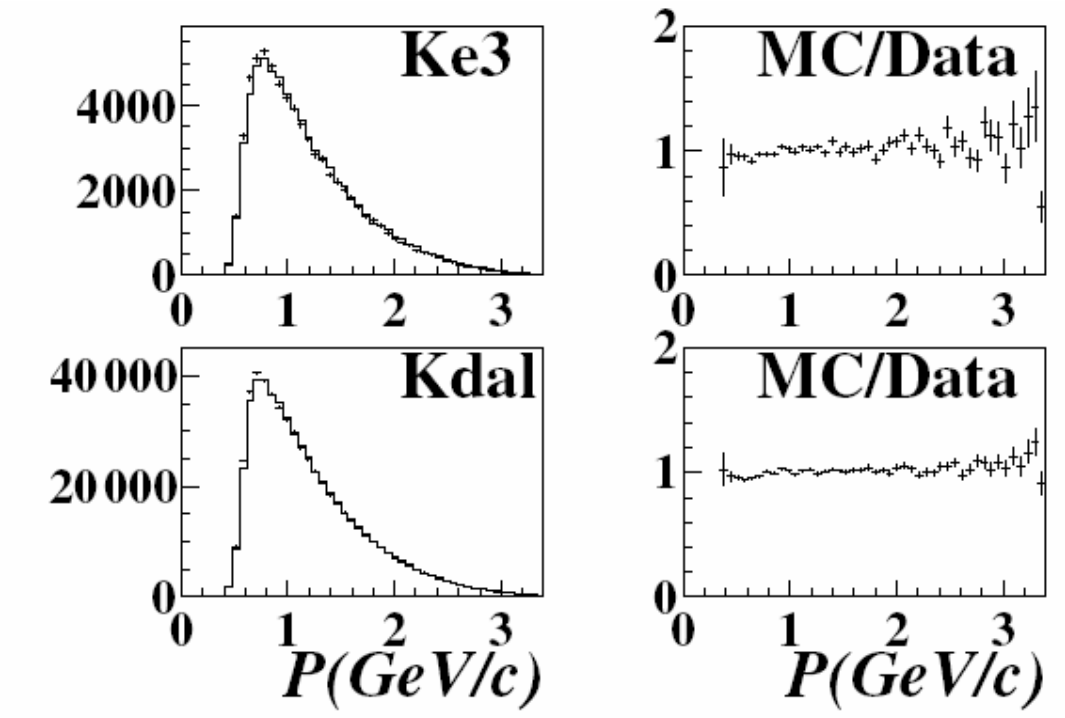
Form factor
at t=0
(theory)

2003: BNL E865 Measurement of $B(K^+ \to \pi^0 e^+ \nu)$

- Using 70,000 K^+_{e3} decays normalized to $K^+ \to \pi^+\pi^0$, $K^+ \to \pi^0 \mu^+ \nu$, $K^+ \to \pi^+\pi^0\pi^0$, they found $B(K^+_{e3})$ 5% higher than PDG.

- Result consistent with CKM unitarity at 1% level.

- Assumes other K^+ branching ratios are correct; $B(K^+_{e3})$ is only 5%.



Data/MC comparison for e^+ momentum from $\pi^0 \to e^+e^-\gamma$ decay for signal and normalization decay modes.

New Measurements in 2004

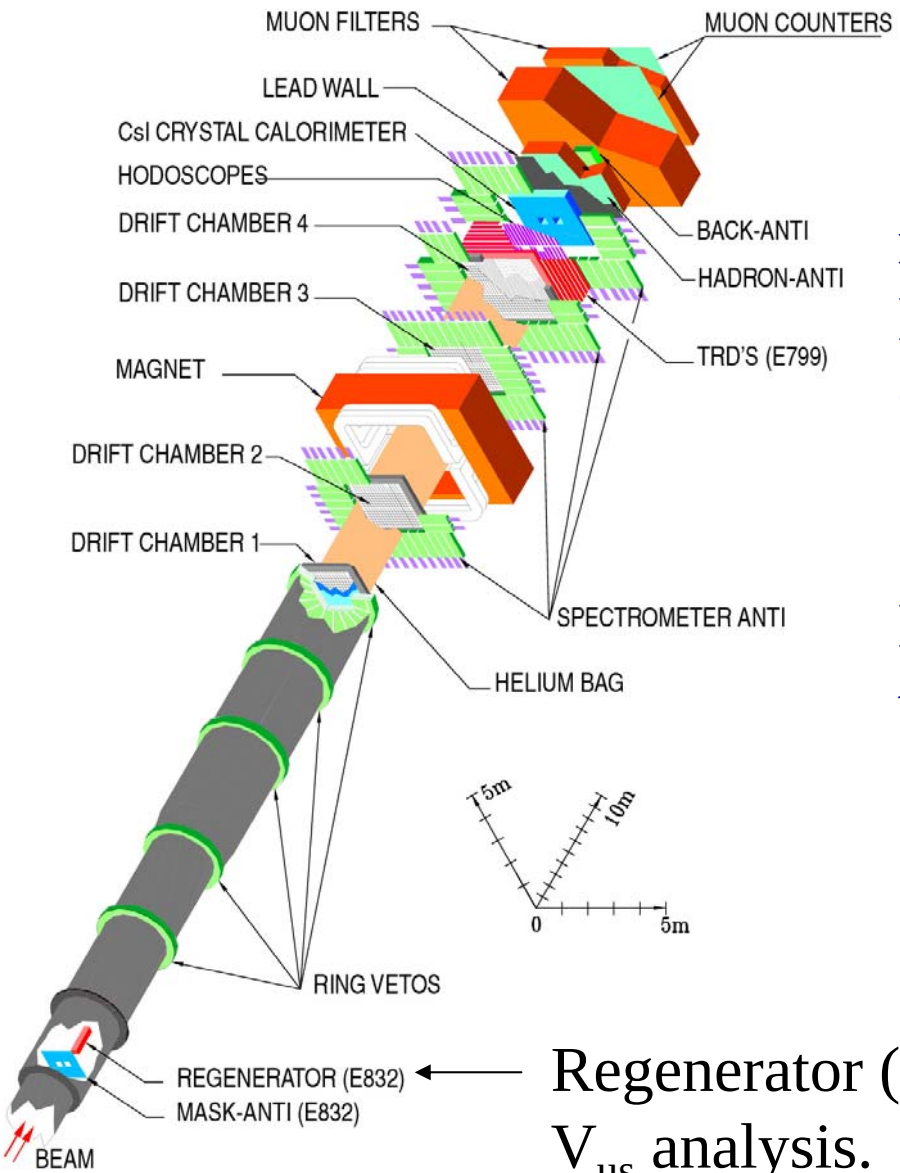
- KTeV measured 6 largest K_L branching fractions and K_L semileptonic form factors.

- NA48 measured $K_L \rightarrow \pi e \nu$/charged fraction and K_{e3} FF.

- KLOE measured main K_L branching fractions and K_L lifetime (preliminary)

- Also, new K^+_{e3} measurement from NA48, new K^+ FF results from ISTRA+.

KTeV Experiment: Designed to measure Re(ε′⁄ε)

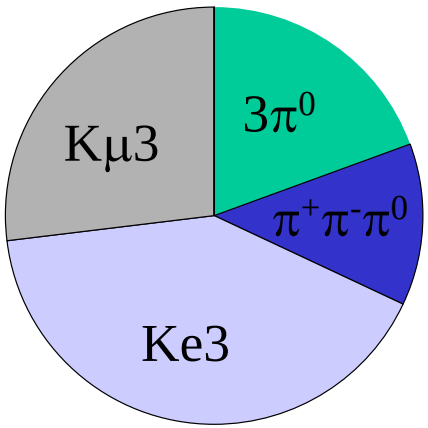


- Charged particle momentum resolution < 1% for p>8 GeV/c; Momentum scale known to 0.01% from $K \rightarrow \pi^+\pi^-$.

- 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 V_{us} analysis.

To determine the semileptonic widths, KTeV measures the following 5 ratios:



$$\Gamma_{K\mu 3}/\Gamma_{Ke3} = \Gamma(K_L \to \pi^{\pm}\mu^{\mp}\nu)/\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)$$

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

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

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

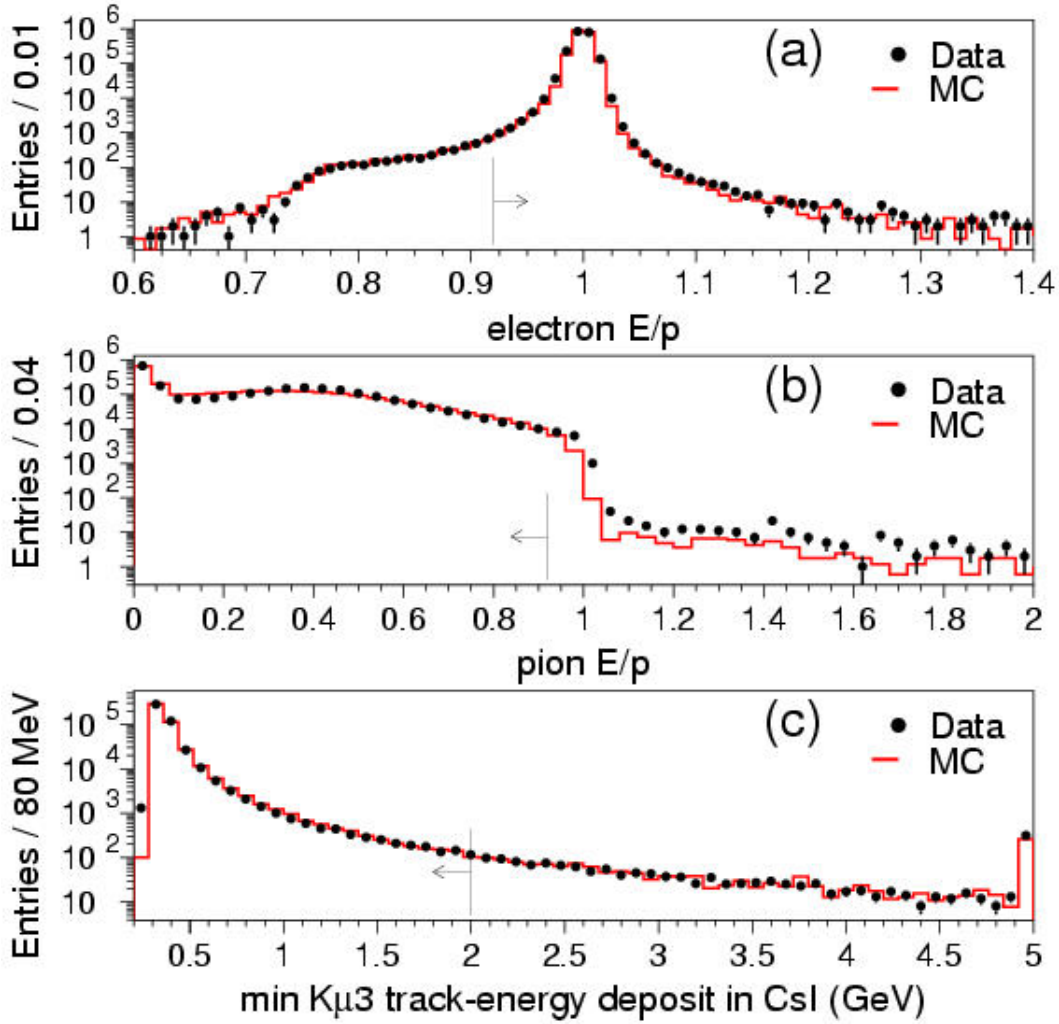
$$\Gamma_{00}/\Gamma_{000} = \Gamma(K_L \to \pi^{0}\pi^{0})/\Gamma(K_L \to \pi^{0}\pi^{0}\pi^{0})$$

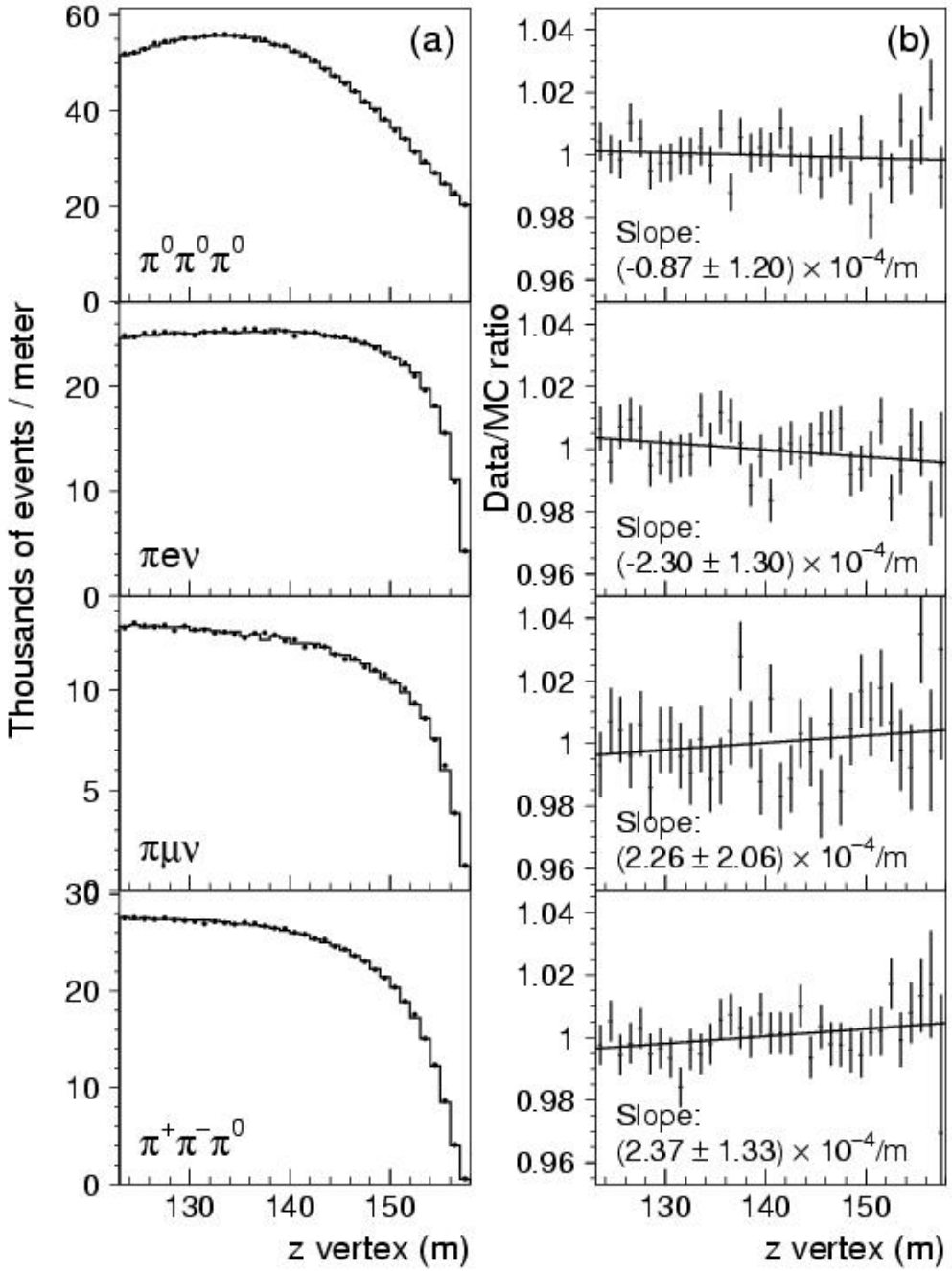
These six decay modes account for 99.93% of K_L decays, so ratios may be combined to determine branching fractions.

E.g.,
$$B_{Ke3} = \frac{0.9993}{1+\frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}}+\frac{\Gamma_{000}}{\Gamma_{Ke3}}+\frac{\Gamma_{+-0}}{\Gamma_{Ke3}}+\frac{\Gamma_{+-}}{\Gamma_{Ke3}}+\frac{\Gamma_{00}}{\Gamma_{Ke3}}}$$

KTeV Branching Fraction Analysis

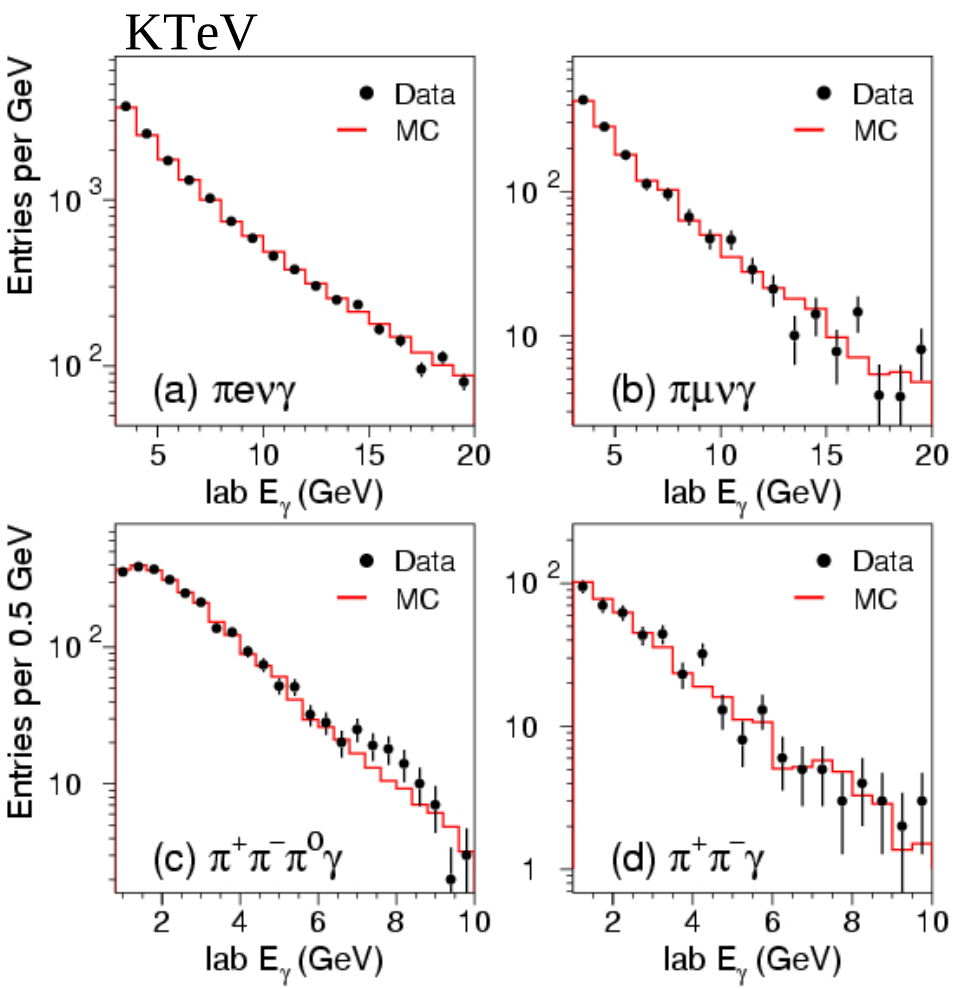
Simple event reconstruction and selection may be used to distinguish different decay modes with very little background (<0.1%).





KTeV:
Comparison of data and Monte Carlo decay vertex distributions

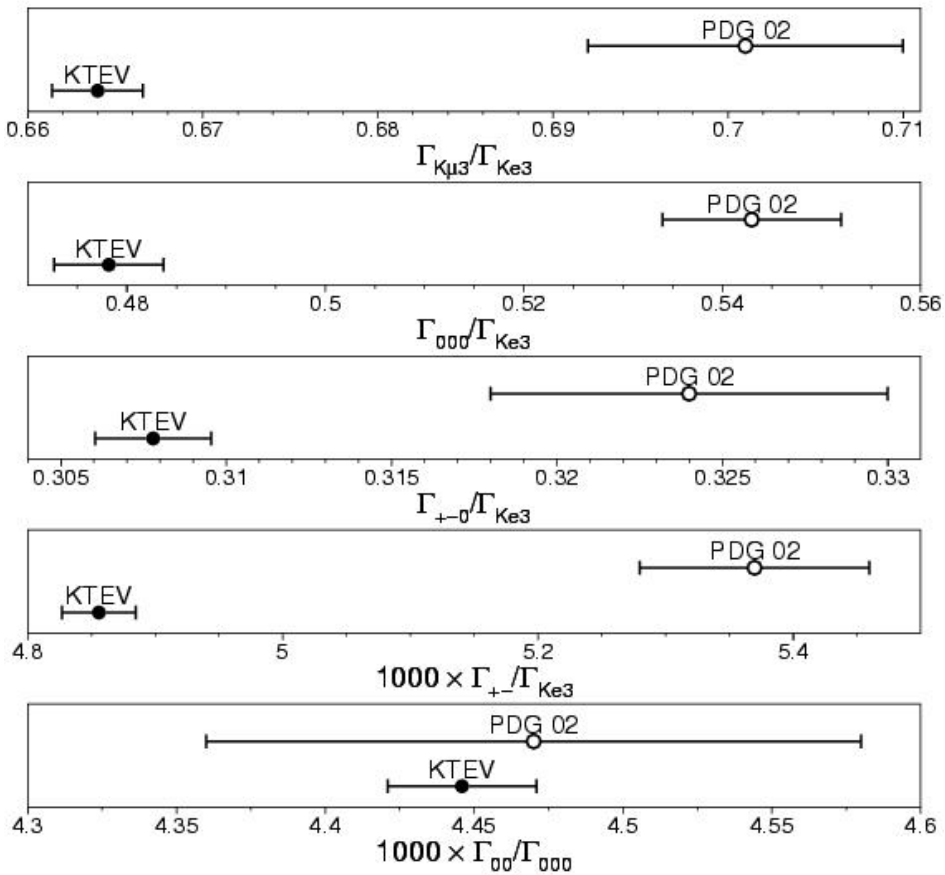
Data – MC Comparison for Radiative Photon Candidates



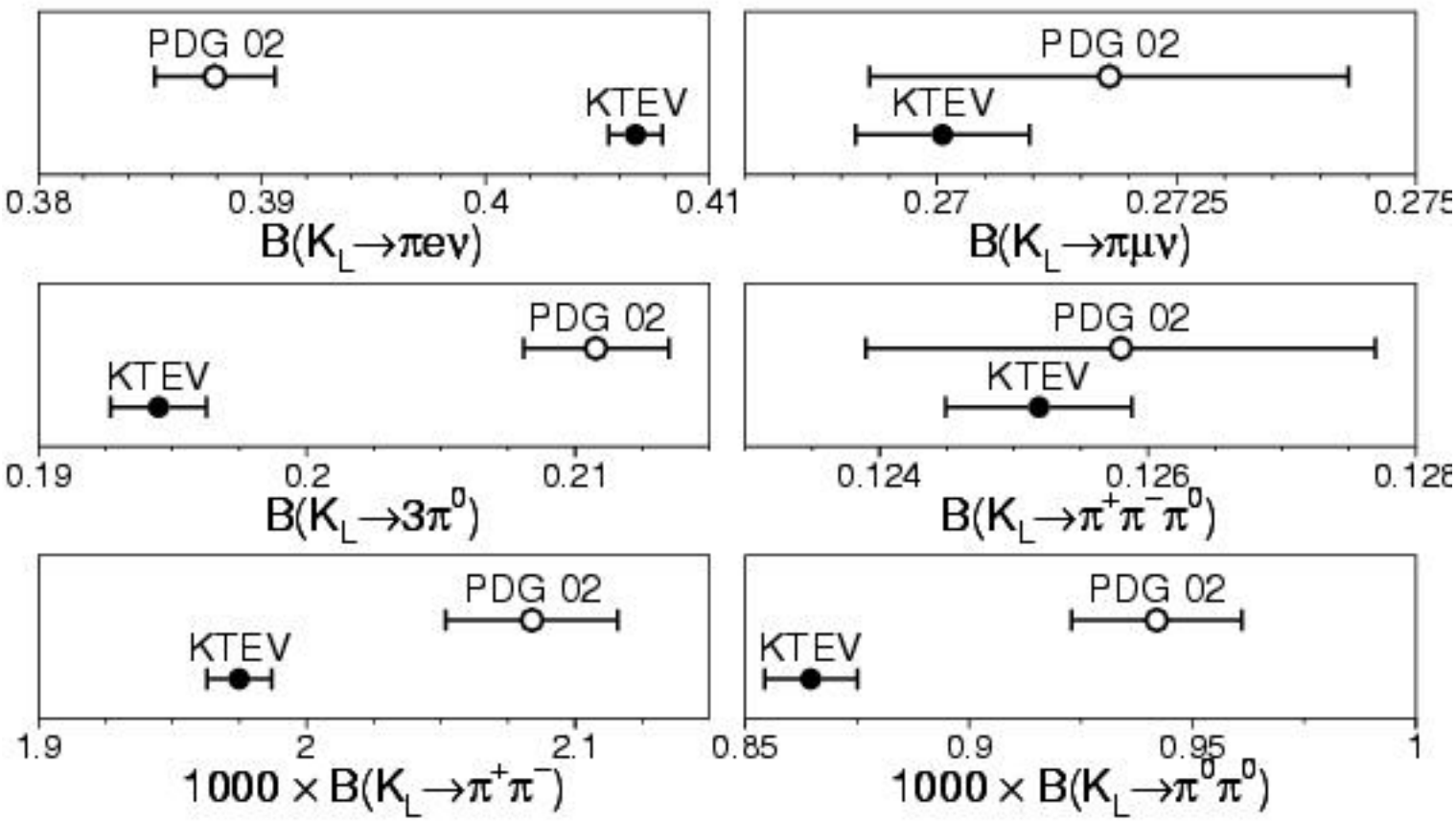
Radiation changes K_{e3} acceptance by 3%; effect on other modes is < 0.5%.

KTeV Measured Partial Width Ratios

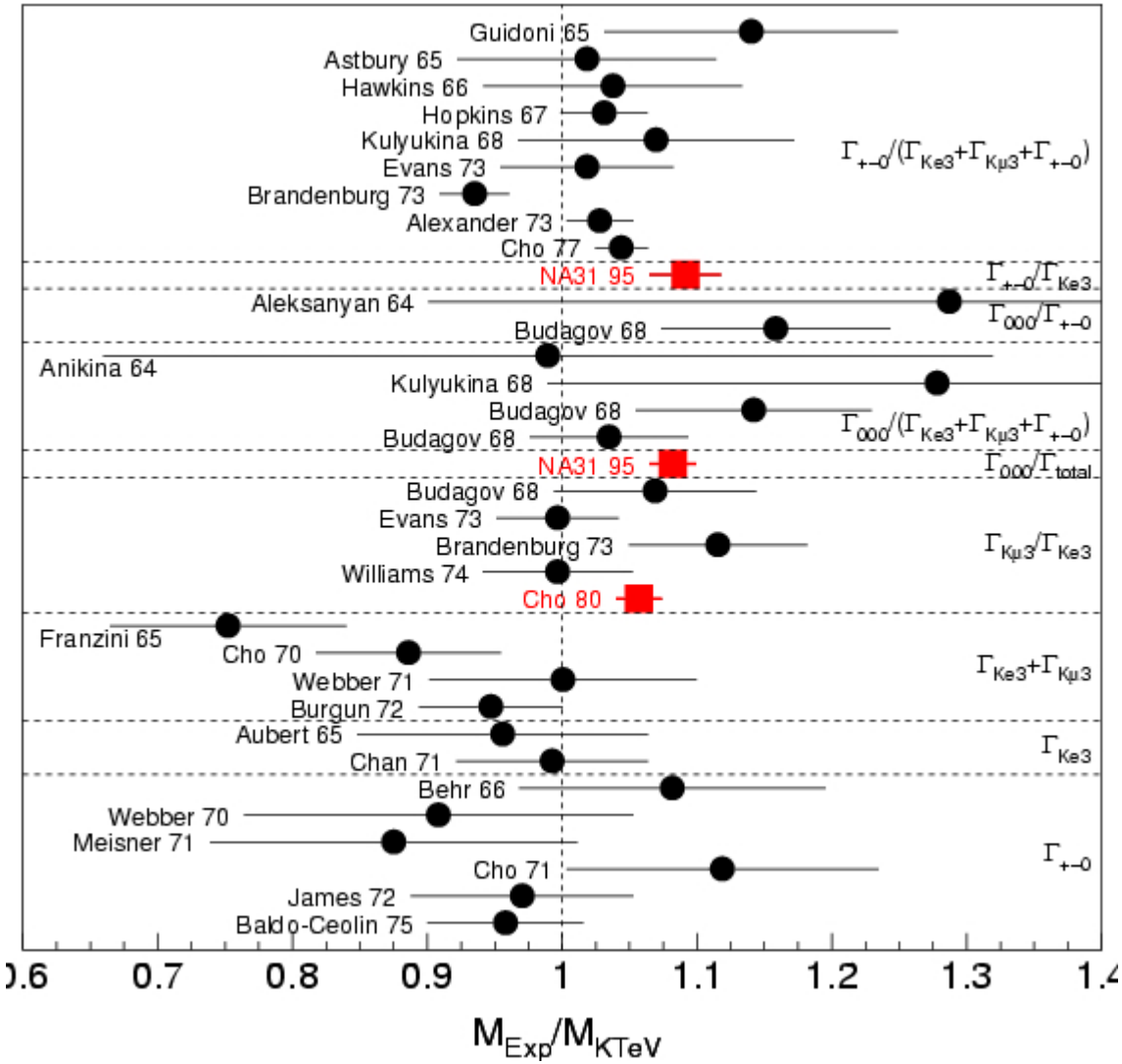
Modes	Partial Width Ratio
$\Gamma_{K\mu 3} / \Gamma_{Ke3}$	$0.6640 \pm 0.0014 \pm 0.0022$
$\Gamma_{000} / \Gamma_{Ke3}$	$0.4782 \pm 0.0014 \pm 0.0053$
$\Gamma_{+-0} / \Gamma_{Ke3}$	$0.3078 \pm 0.0005 \pm 0.0017$
$\Gamma_{+-} / \Gamma_{Ke3}$	$(4.856 \pm 0.017 \pm 0.023) \times 10^{-3}$
$\Gamma_{00} /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



Comparison of KTeV and PDG Branching Fractions



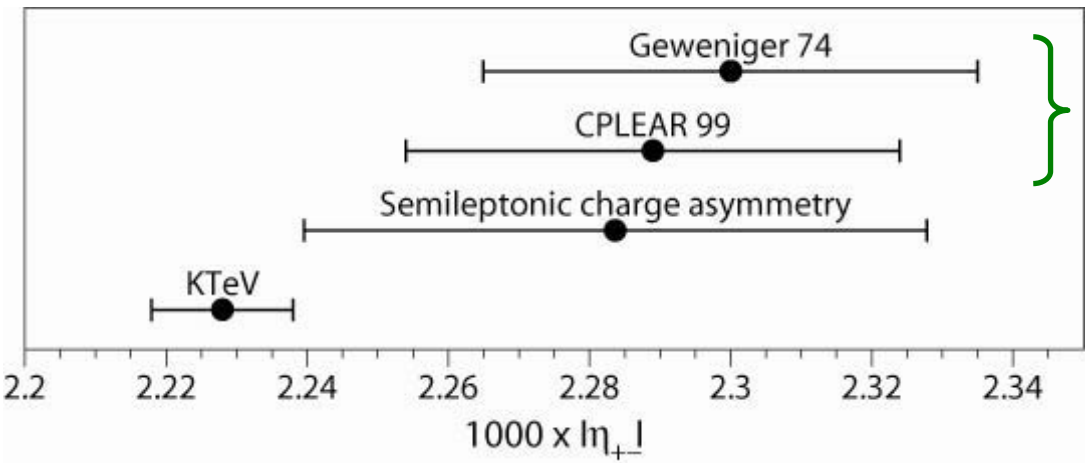
Comparison with Individual Experiments



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



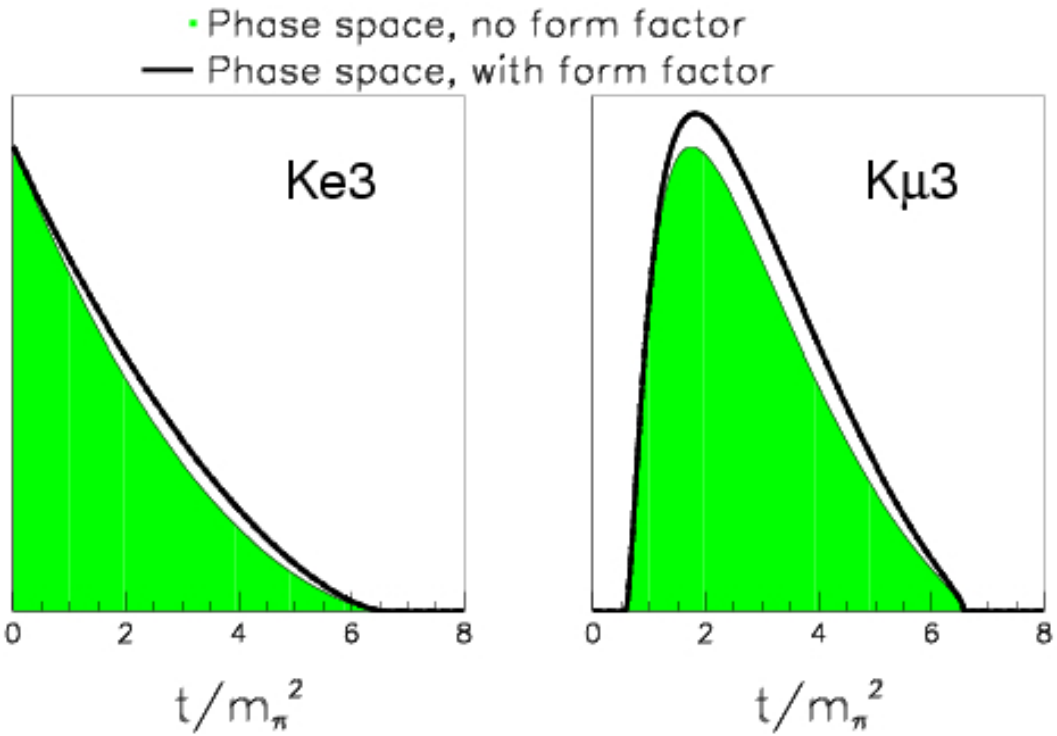
K_L-K_S Interference

Semileptonic Form Factor Measurements

(to determine I_K integrals)

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

I_K depends on the two independent semileptonic FFs: $f_+(t)$, $f_-(t)$



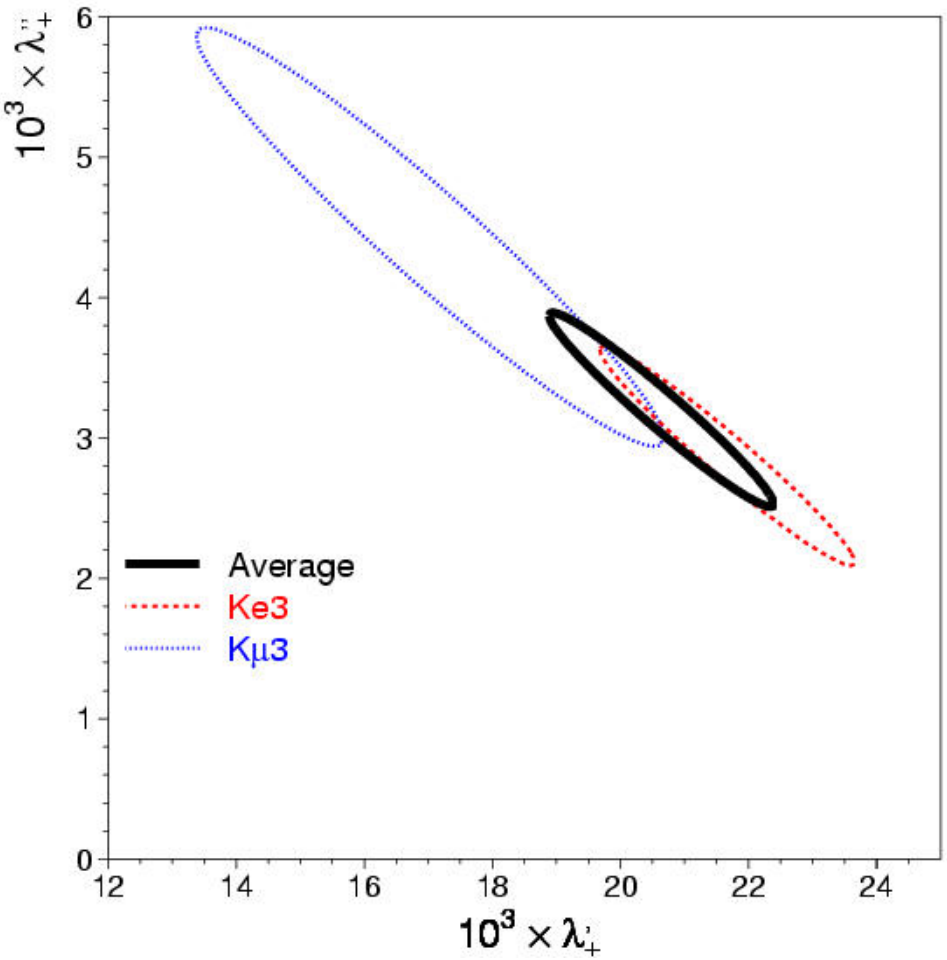
KTeV Form Factor Results

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

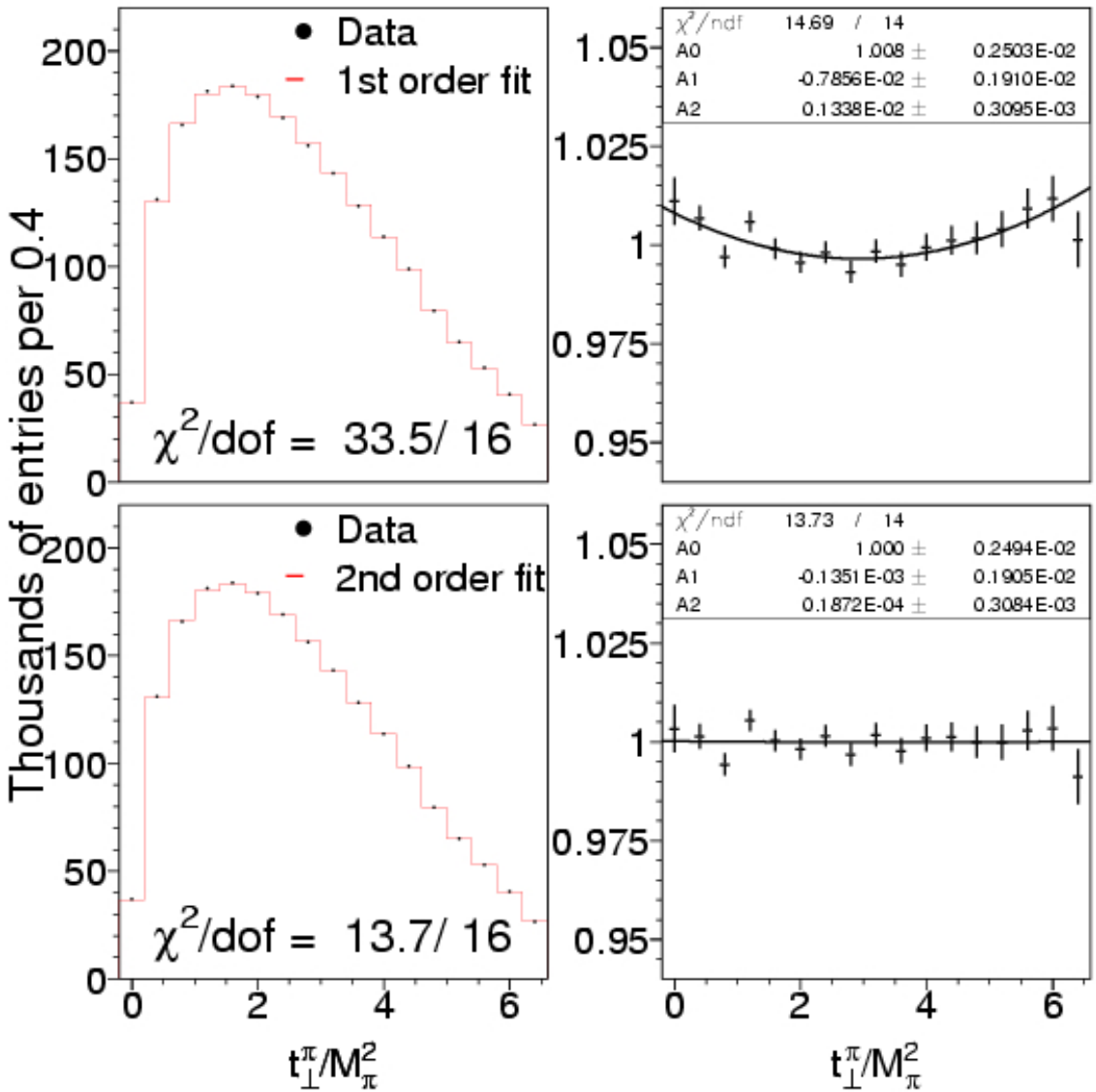
$$f_0(t) = f_+(0)\left(1+\lambda_0\frac{t}{M_\pi^2}\right),$$

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

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



Consistency of Branching Fraction and Form Factor Results with Lepton Universality

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

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

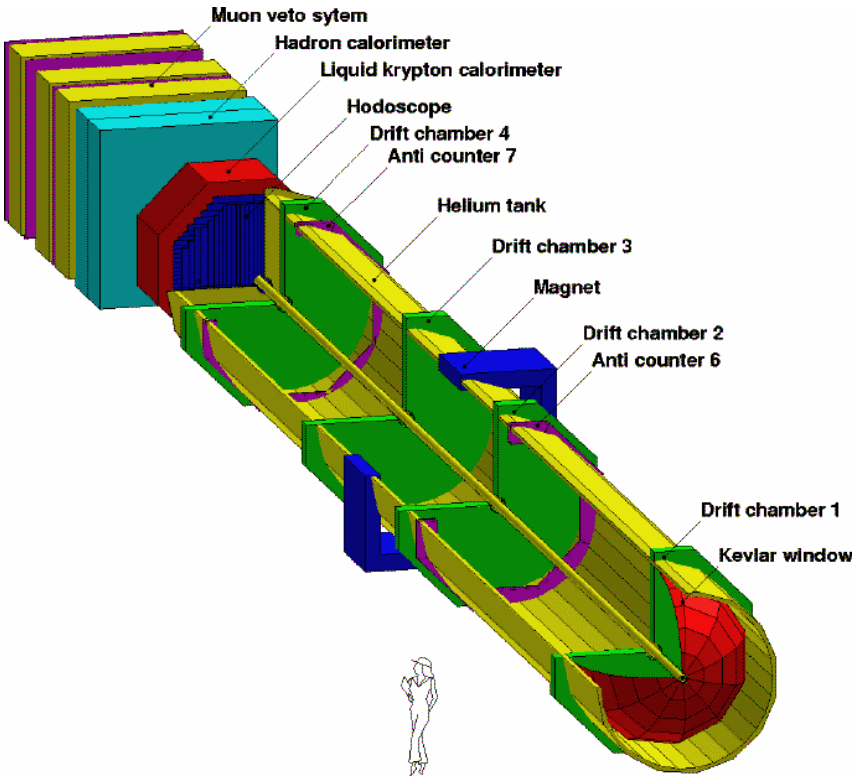
1.0058(10) from Andre

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

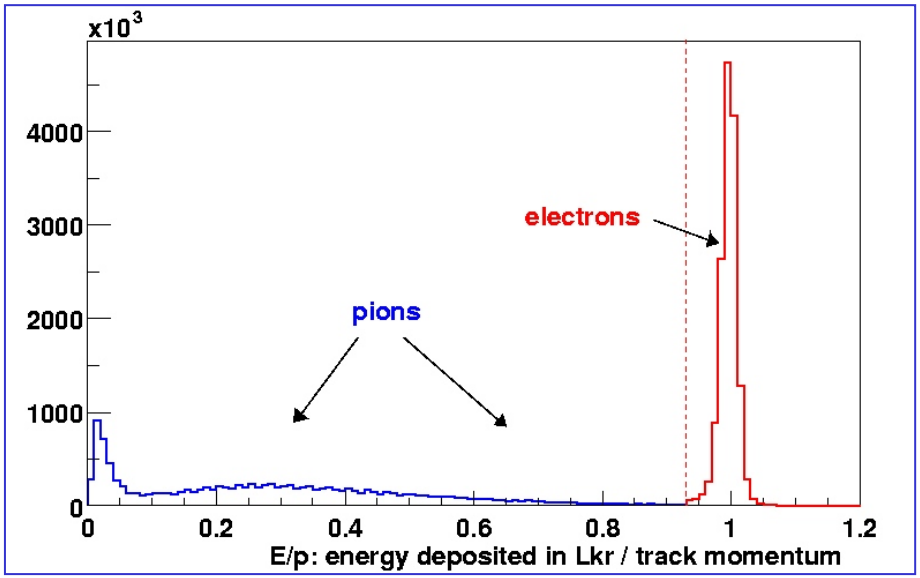
NA48 Experiment: Designed to measure Re(ε′⁄ε)

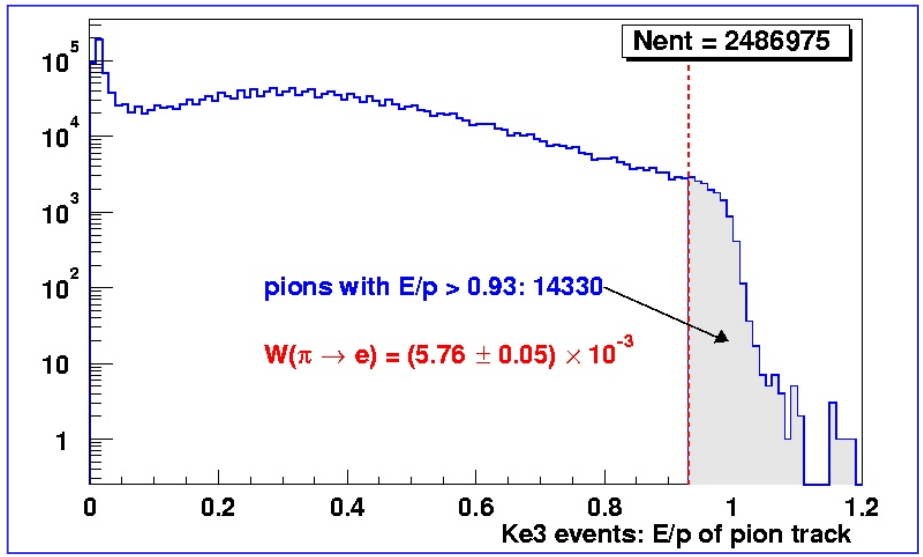


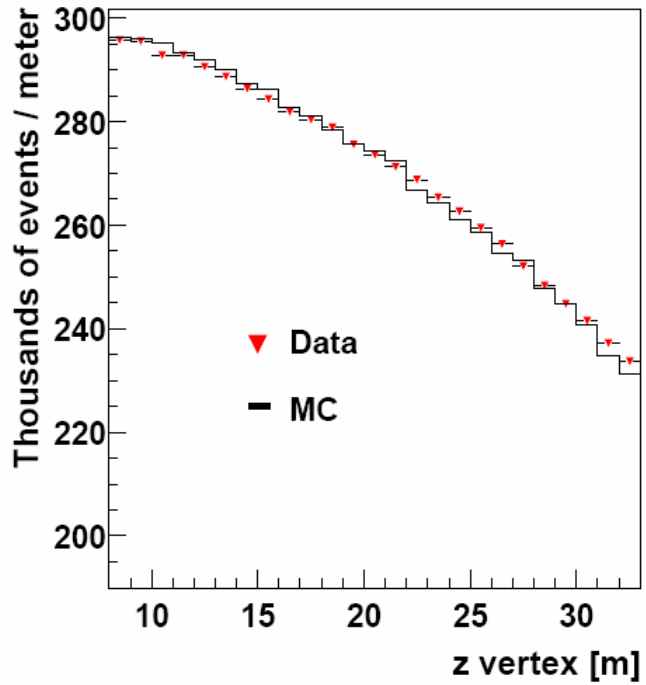
- $\dfrac{B(K_L \to \pi e \nu)}{B(all\ \ 2\ track)} = 0.4978 \pm 0.0035$
- $B(K_L \to \pi^0\pi^0\pi^0) = 0.1966 \pm 0.0034$
- Measurement of K_{e3} form factor (linear parametrization):
  $\lambda_+ = 0.0288 \pm 0.0012$
- $B(K^{\pm}_{e3}) = 0.0514 \pm 0.0006$

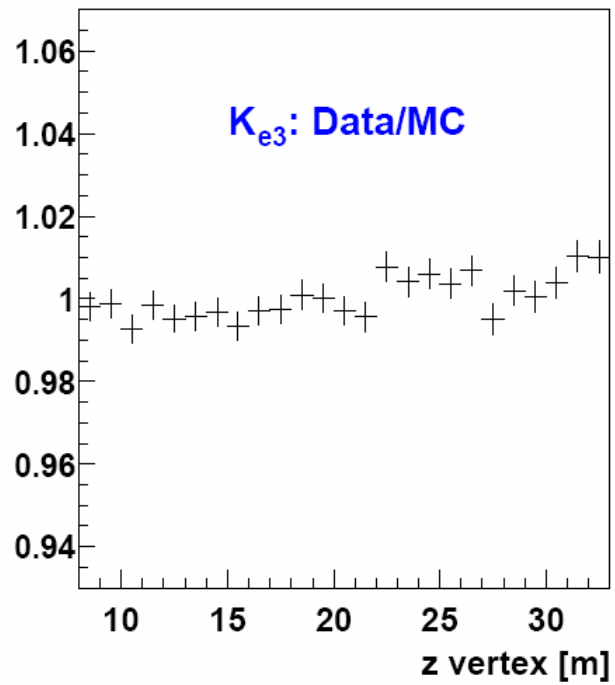
K_L measurements consistent with KTeV; $K^{\pm}$ result consistent with E865,

NA48: Electron-Pion Separation:



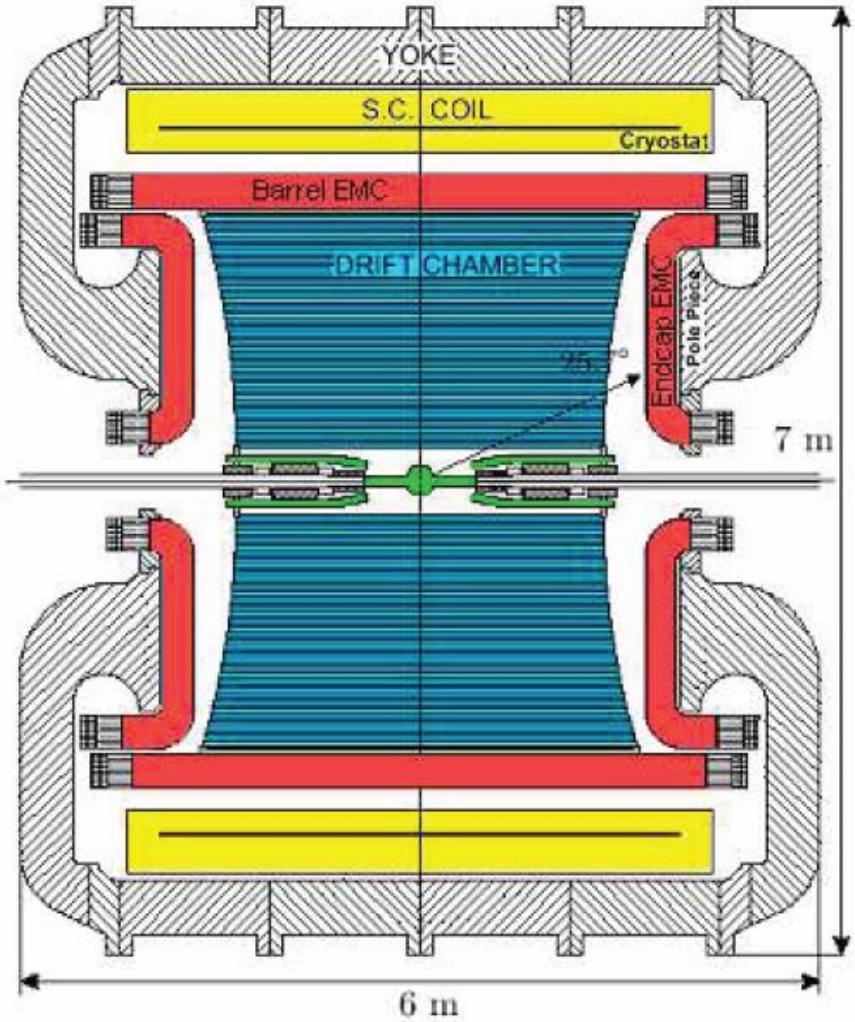






NA48: Data-MC comparison of decay vertex distributions.

KLOE Experiment: $e^+e^- \rightarrow \phi \rightarrow K^+K^-$, $K_L K_S$



"Ideal" experiment for branching ratio measurements: can tag one kaon and measure absolute branching fractions using accompanying kaon.

Preliminary Results:

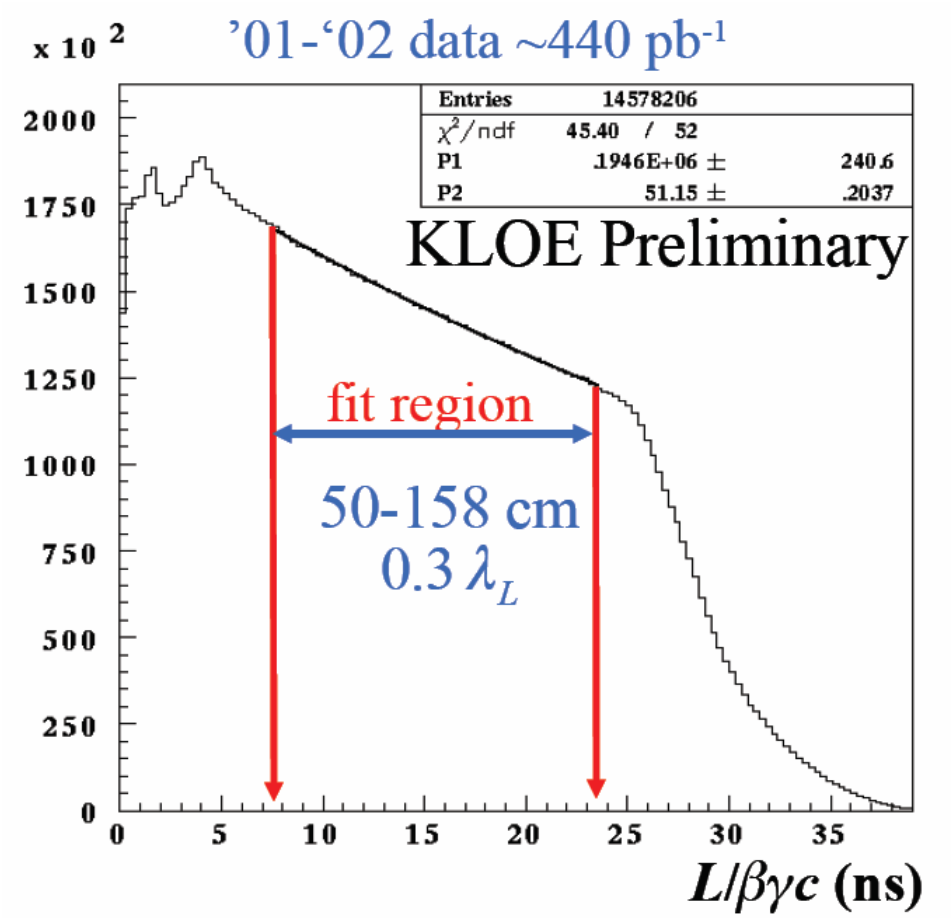
$B(K_L \rightarrow \pi e \nu) = 0.3985 \pm 0.0035$

$B(K_L \rightarrow \pi \mu \nu) = 0.2702 \pm 0.0025$

$B(K_L \rightarrow \pi^0 \pi^0 \pi^0) = 0.2010 \pm 0.0022$

$B(K_L \rightarrow \pi^+ \pi^- \pi^0) = 0.1268 \pm 0.0011$

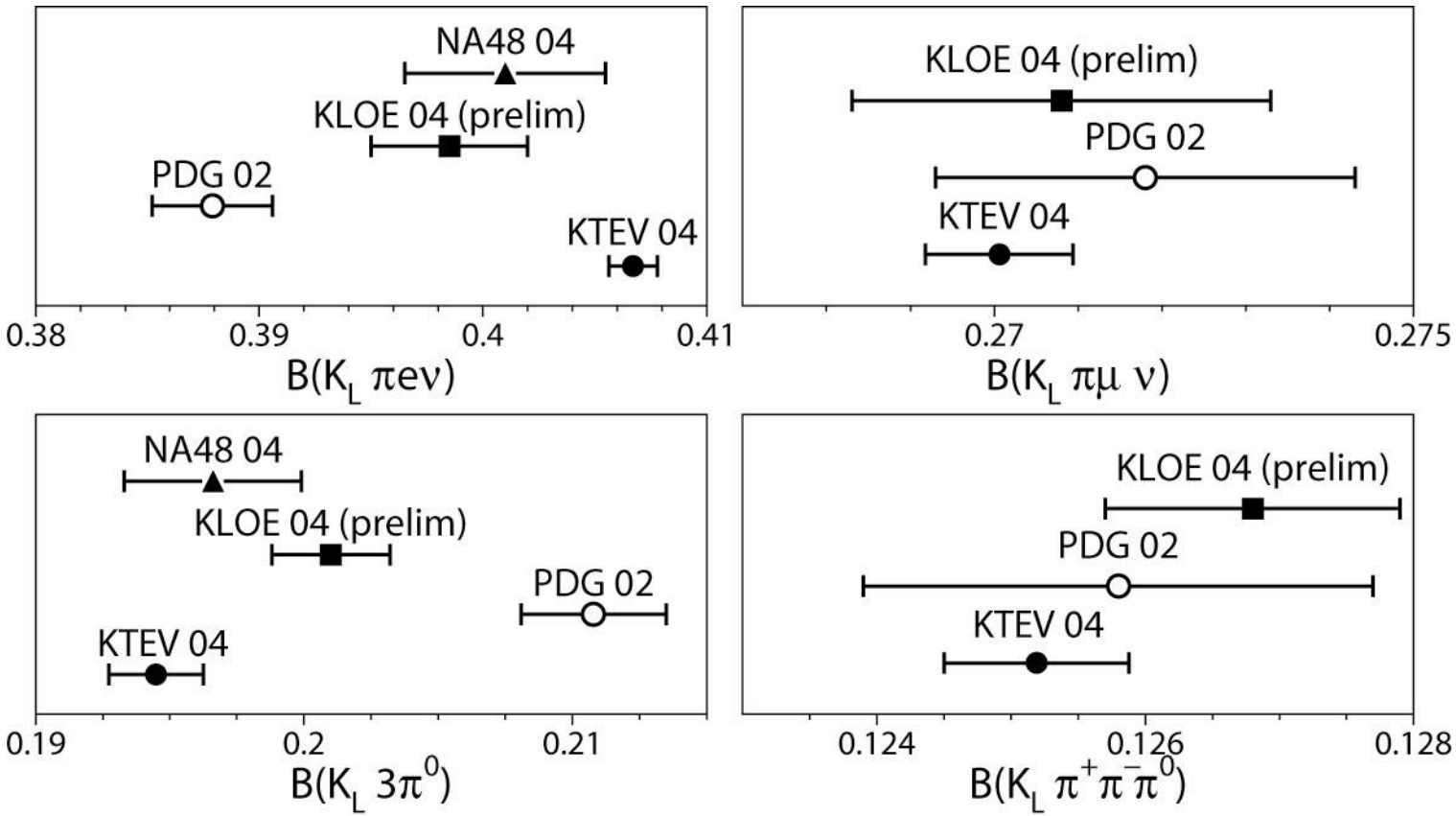
New Measurement of K_L Lifetime from KLOE using $K_L \to \pi^0\pi^0\pi^0$



KLOE Preliminary: $\tau_L = (51.15 \pm 0.2 \pm 0.3)$ns

PDG Average: $\tau_L = (51.5 \pm 0.4)$ns

Comparison KTeV, NA48, KLOE, PDG Branching Fractions



Experimental Input to $|V_{us}|$

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

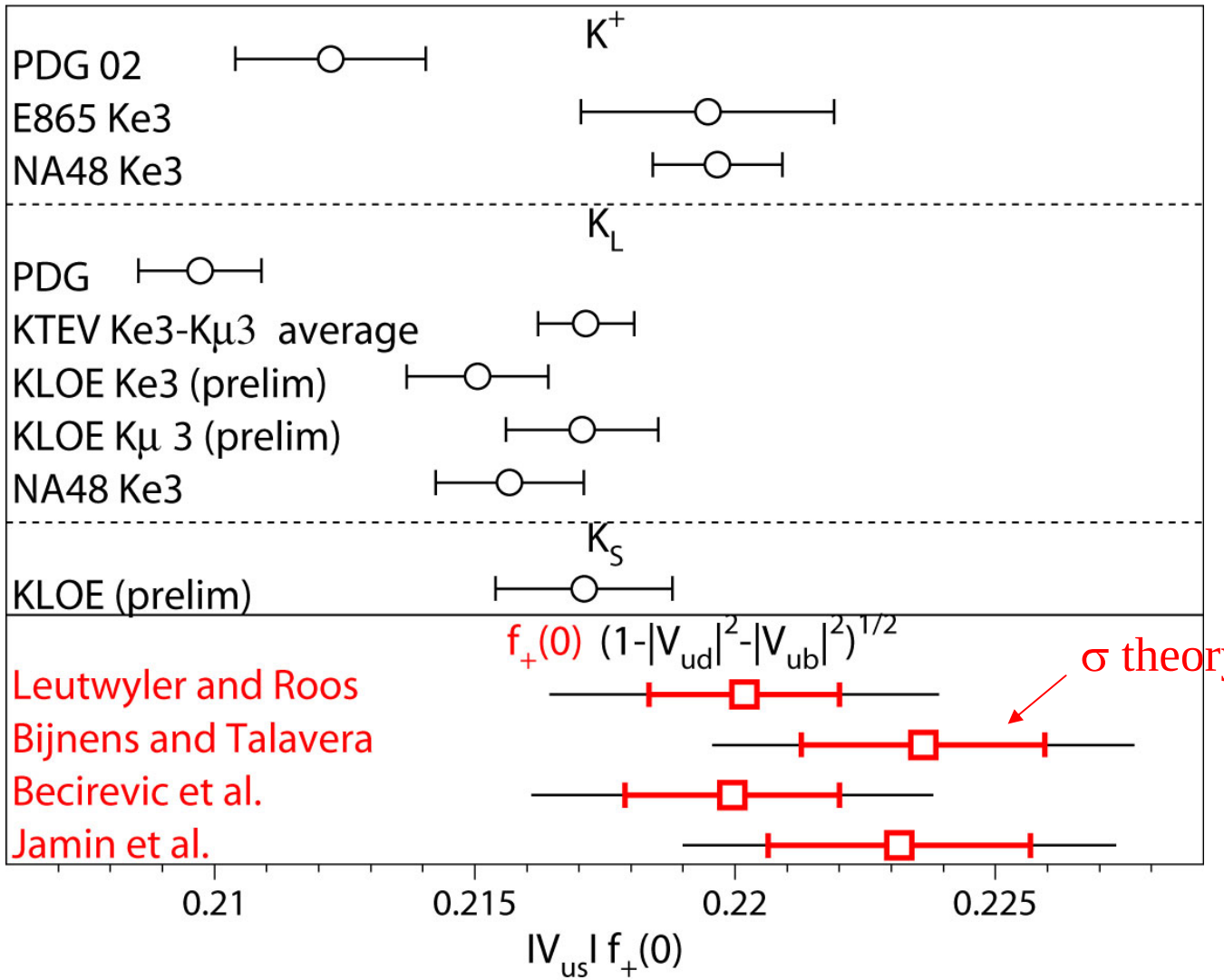
Result	**Source of B(Kℓ3)**	**Source of form factor**	**Source of lifetime**
BNL-$\|V_{us}\|$ K^+_{e3}	BNL+PDG	PDG	PDG
KTeV-$\|V_{us}\|$ $K_{L\ e3}$	KTeV	KTeV	PDG
KTeV-$\|V_{us}\|$ $K_{L\ \mu 3}$	KTeV	KTeV	PDG
NA48-$\|V_{us}\|$ $K_{L\ e3}$	Na48+KTeV+PDG	NA48	PDG
KLOE $\|V_{us}\|$ $K_{L,S}$, K^+ (e, μ)	KLOE (prelim)	KTeV (KLOE later?)	KLOE (prelim)

Theory Input to $|V_{us}|$

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

- S_{EW} (short-distance rad. corr) = 1.022 (Sirlin)
- Long-distance radiative corrections: (Andre, etc.)
  $\delta^e = 0.013 \pm 0.003$
  $\delta^\mu = 0.019 \pm 0.003$
- $f_+(0) = 0.961 \pm 0.008$ (Leutwyler – Roos) + recent calculations

Comparison with Unitarity



Conclusions

- Very large shifts observed in main K_L branching fractions branching fractions differ from PDG by 5-8%.

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

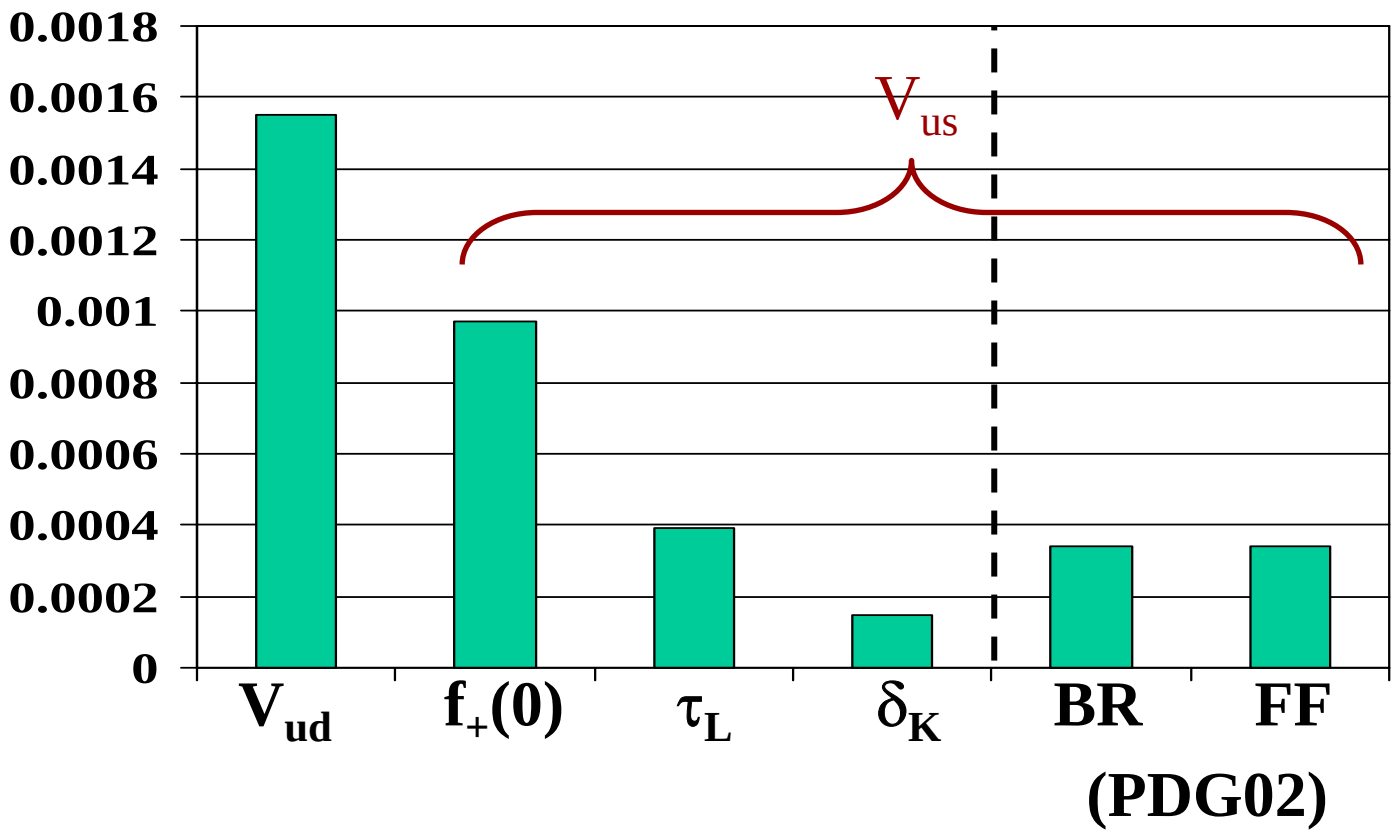
- Recent K_L and K+ results are consistent with CKM unitarity at 1 σ level.

$$|V_{us}| = 0.2262 \pm 0.0023$$

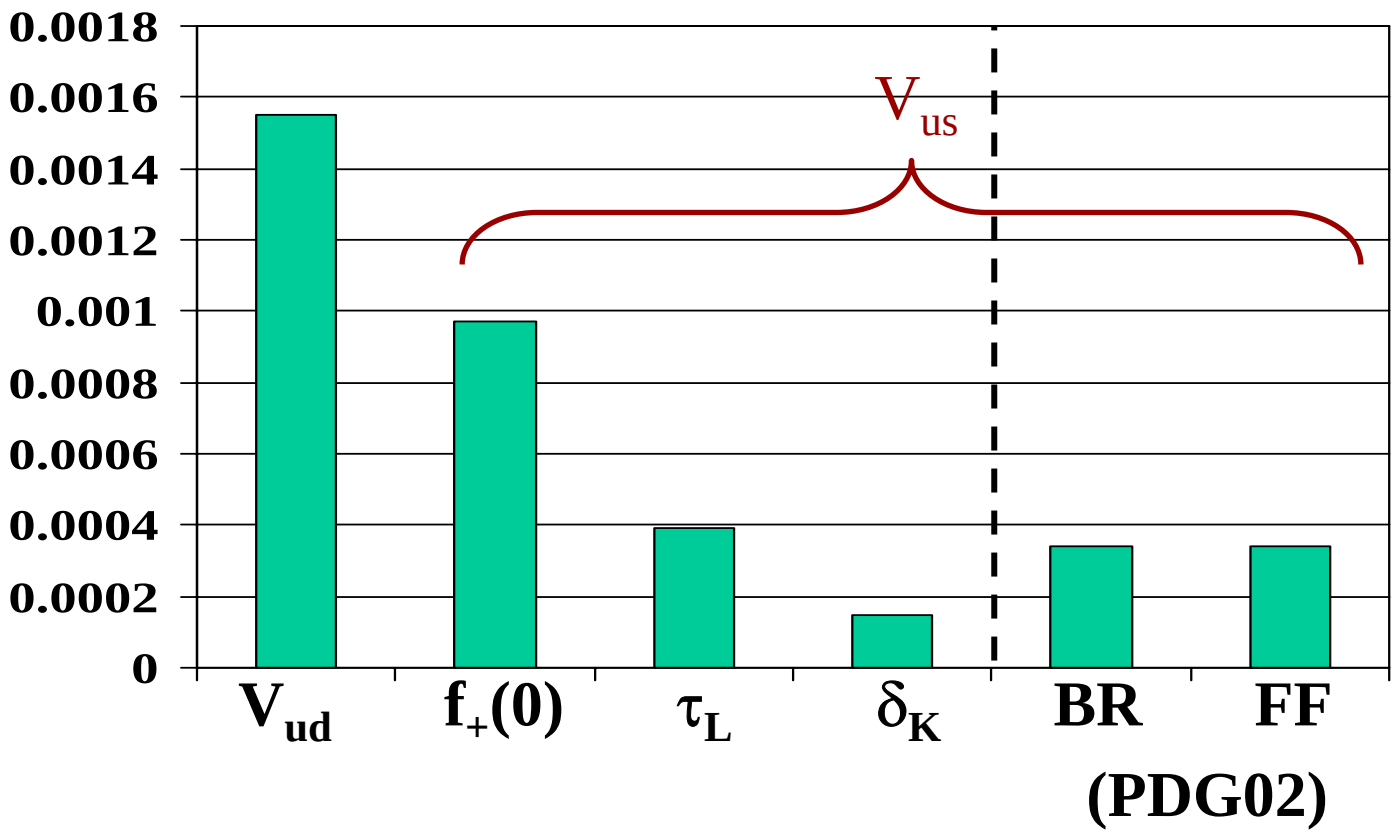
$$1 - \left(|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \right) = 0.0013 \pm 0.0018$$

- Value in repeating old measurements with modern, high statistics experiments.

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



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



Shift in $|V_{us}|^2$ from new K_L measurements