Recent Results From KTeV

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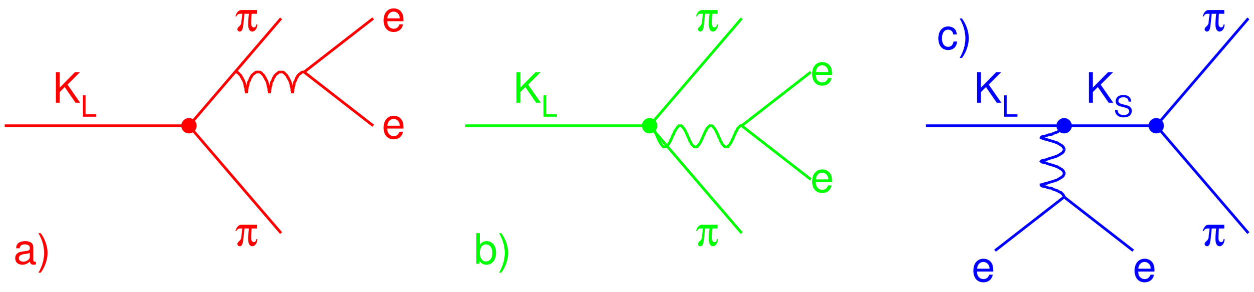
- Updates of the $K_L \to \pi\pi ee$ decay parameters
- Measurement of the CKM parameter $|V_{us}|$
  - Measurement of the six largest K_L branching fractions
  - Measurement of the semileptonic form factors
- New measurements of $K_L \to \pi\ell\nu\gamma$ decay branching fractions.

$K_L \to \pi\pi ee$ decay



a) **Bremesstrahlung** CP violation (as in $K_L \to \pi^+\pi^-$)

b) **Direct emission**. CP conserving + possible CP violation.
– higher e^+e^- pair *energy*

c) Kaon **charge radius**. Present for virtual photons only
– higher e^+e^- pair *invariant mass*

CP violation shows up as an angular asymmetry for the angle ϕ between normals to $\pi^+\pi^-$ and e^+e^- planes in kaon CM.

$K_L \to \pi\pi ee$ Matrix element

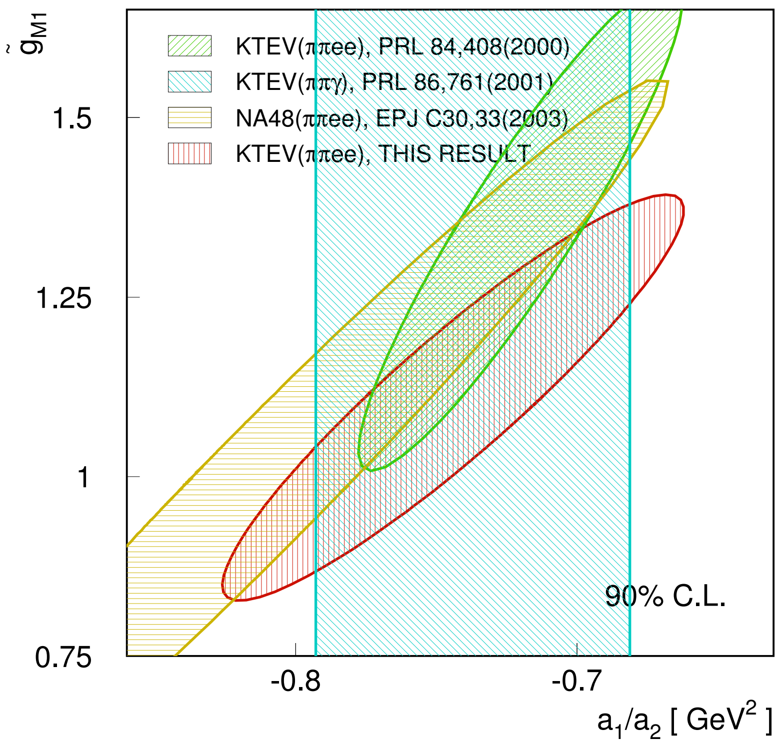
- Inner Bremsstrahlung $g_{Br} = |\eta_{+-}|e^{i(\delta_0(M_K)+\phi_{+-})}$
- Direct Emission
  – M1 (CP conserving) $g_{M1} = i|g_{M1}|e^{i\delta_1(M_{\pi\pi})}$
  – E1 (CP violating) $g_{E1} = -i\frac{|g_{E1}|}{|g_{M1}|}g_{M1}e^{i\phi_{+-}}$
- Charge radius amplitude $g_{CR} = |g_{CR}|e^{i\delta_0(M_{\pi\pi})}$

Strong phases $\delta_{0,1}$ are taken from G.Colangelo et al, Nucl. Phys. **B603**, 125 (2001)
$|g_{M1}|$ is energy dependent:

$$|g_{M1}| = \tilde{g}_{m1}\left[1 + \frac{a_1/a_2}{(M_\rho^2 + M_K^2) + 2M_K E_\gamma^*}\right] \quad (1)$$

KTeV measures $\tilde{g}_{m1}, a_1/a_2, \frac{|g_{E1}|}{|g_{M1}|}$ and g_{CR} parameters in a combined log-likelihood fit.

$K_L \to \pi\pi ee$ measurement of $\tilde{g}_{m1}$ and a_1/a_2



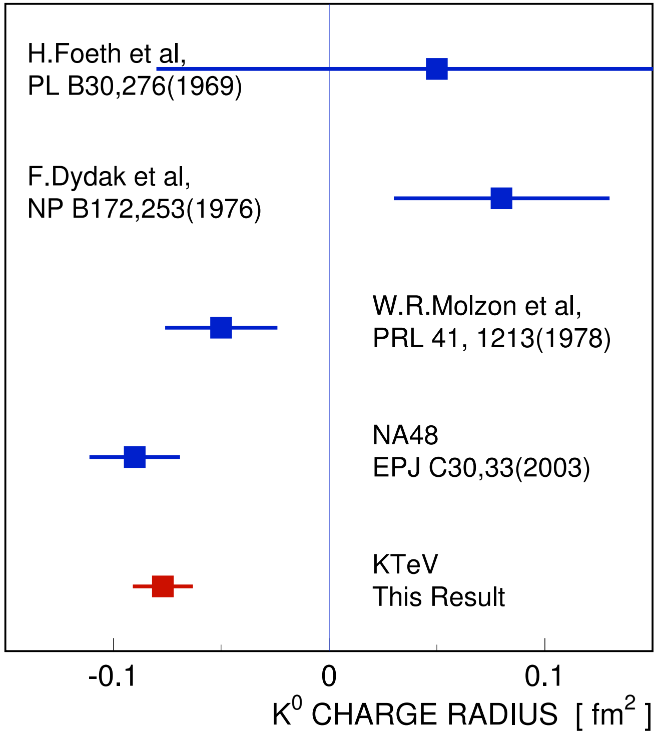
$$\begin{aligned} \tilde{g}_{m1} &= 1.11 \pm 0.12 \text{ stat} \pm 0.07 \text{ syst} \\ a_1/a_2 &= -0.744 \pm 0.022 \text{ stat} \pm 0.032 \text{ syst} \end{aligned} \quad (2)$$

Limit on CP-violating $E1$ direct emission amplitude:

$$\frac{|g_{E1}|}{|g_{M1}|} < 0.04 \text{ (90\%CL)} \quad (3)$$

$K_L \to \pi\pi ee$ measurement of kaon charge radius

$$|g_{CR}| = 0.163 \pm 0.017 \text{ stat} \pm 0.023 \text{ syst} \tag{4}$$

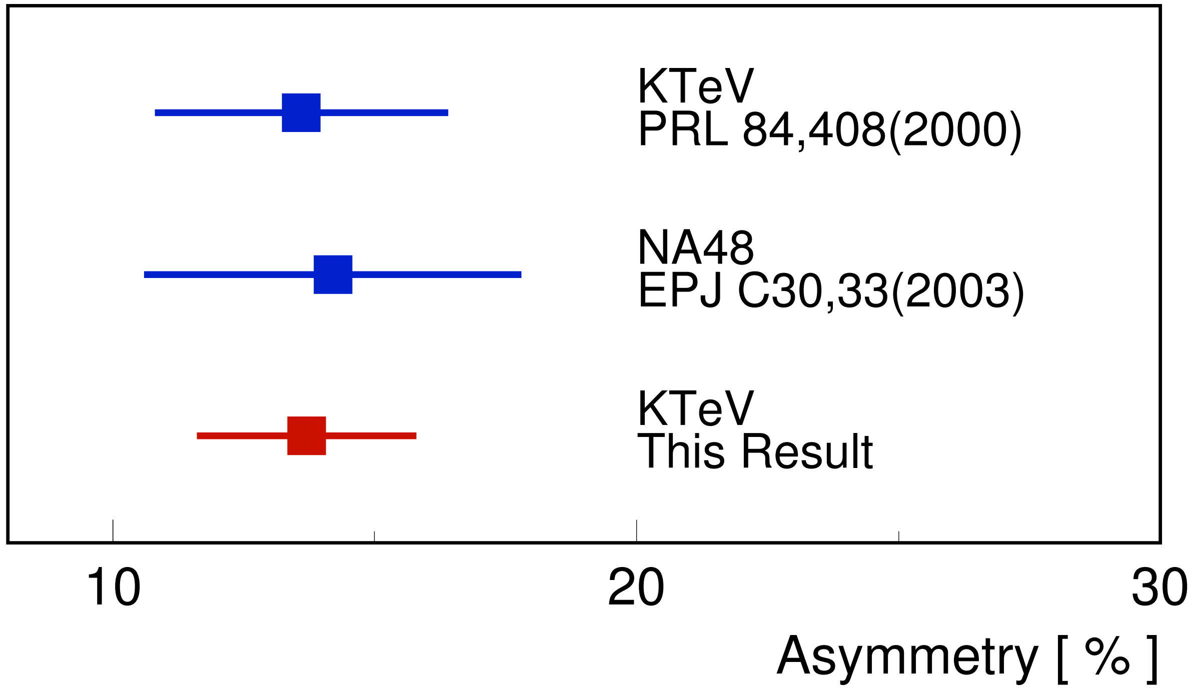


$|g_{CR}| = -\frac{1}{3} \langle R_K^2 \rangle M_K^2$ where $\langle R_K^2 \rangle$ is K^0 charge radius.

Measurements before NA48 and KTeV are based on regeneration on free electrons.

$K_L \to \pi\pi ee$ measurement of CP violating asymmetry

$$A = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}} \tag{5}$$

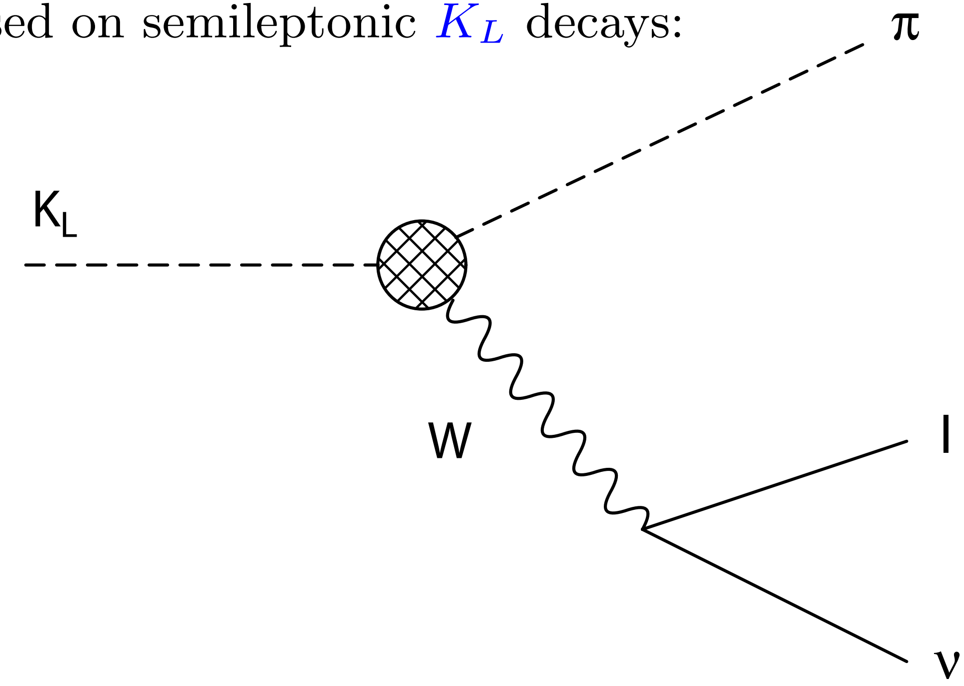


$$A = [13.7 \pm 1.4 \text{ stat} \pm 1.5 \text{ syst}] \tag{6}$$

Predicted at $\sim 14\%$

Measurement of $|V_{us}|$

Measure based on semileptonic K_L decays:



$$\Gamma_{K\ell 3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell)\ |V_{us}|^2\ f_+^2(0) I_K^\ell, \qquad (7)$$

- Experimental input: Decay width ($\Gamma_{K\ell 3}$), decay form factors (affect phase space integrals I_K^ℓ)
- Theoretical input: $f_+(0)$, radiative corrections $S_{EW}(1+\delta_K^\ell)$.

KTeV measures $Br_{K\ell 3}$, I_K^ℓ and checks δ_K^ℓ by measuring $\Gamma_{K\ell 3\gamma, E\gamma>10}$ MeV

Measurement of K_L branching fractions

KTeV can not tag the kaon $\rightarrow$ measure all six largest decay modes in terms of five branching fraction ratios and use the constraint that the remaining width is just 0.03%. Use external τ_L to convert branching fractions into partial widths.

The five measured ratios are:

$$\Gamma_{K\mu3}/\Gamma_{Ke3} \equiv \Gamma(K_L \rightarrow \pi^{\pm}\mu^{\mp}\nu)/\Gamma(K_L \rightarrow \pi^{\pm}e^{\mp}\nu) \quad (8)$$

$$\Gamma_{+-0}/\Gamma_{Ke3} \equiv \Gamma(K_L \rightarrow \pi^{+}\pi^{-}\pi^{0})/\Gamma(K_L \rightarrow \pi^{\pm}e^{\mp}\nu) \quad (9)$$

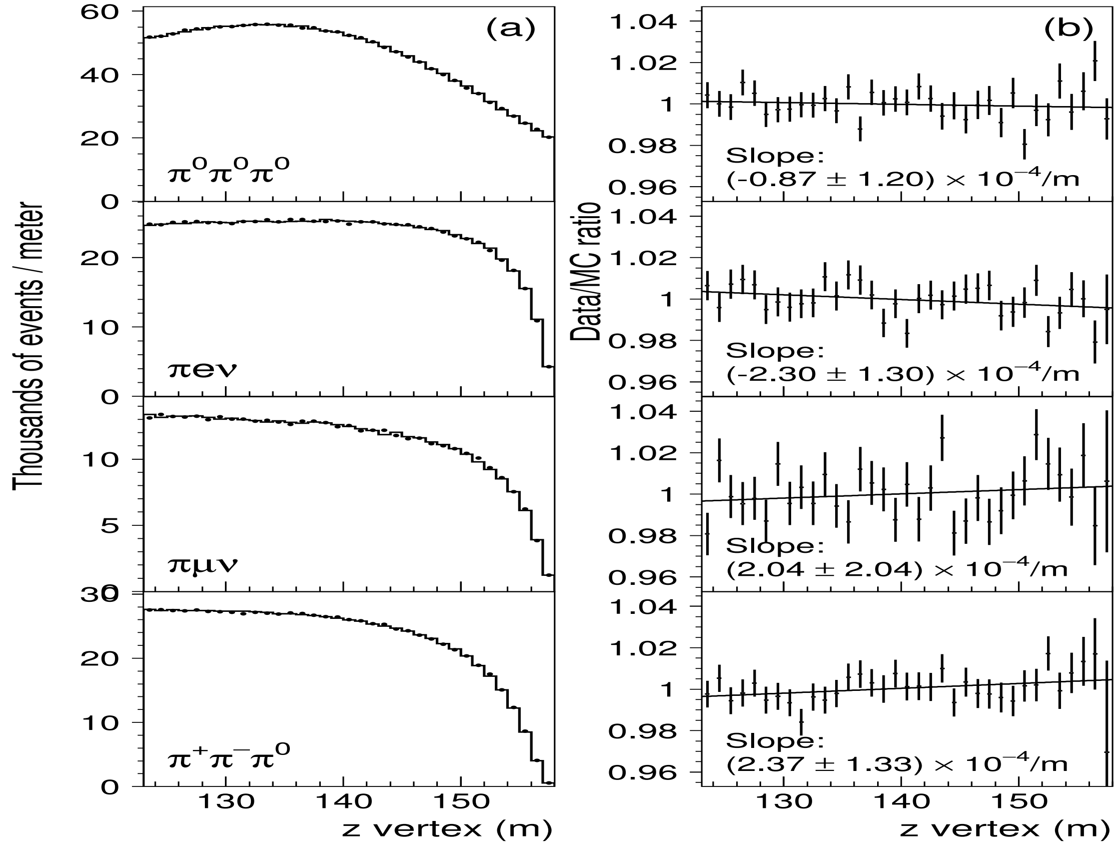
$$\Gamma_{000}/\Gamma_{Ke3} \equiv \Gamma(K_L \rightarrow \pi^{0}\pi^{0}\pi^{0})/\Gamma(K_L \rightarrow \pi^{\pm}e^{\mp}\nu) \quad (10)$$

$$\Gamma_{+-}/\Gamma_{Ke3} \equiv \Gamma(K_L \rightarrow \pi^{+}\pi^{-})/\Gamma(K_L \rightarrow \pi^{\pm}e^{\mp}\nu) \quad (11)$$

$$\Gamma_{00}/\Gamma_{000} \equiv \Gamma(K_L \rightarrow \pi^{0}\pi^{0})/\Gamma(K_L \rightarrow \pi^{0}\pi^{0}\pi^{0}), \quad (12)$$

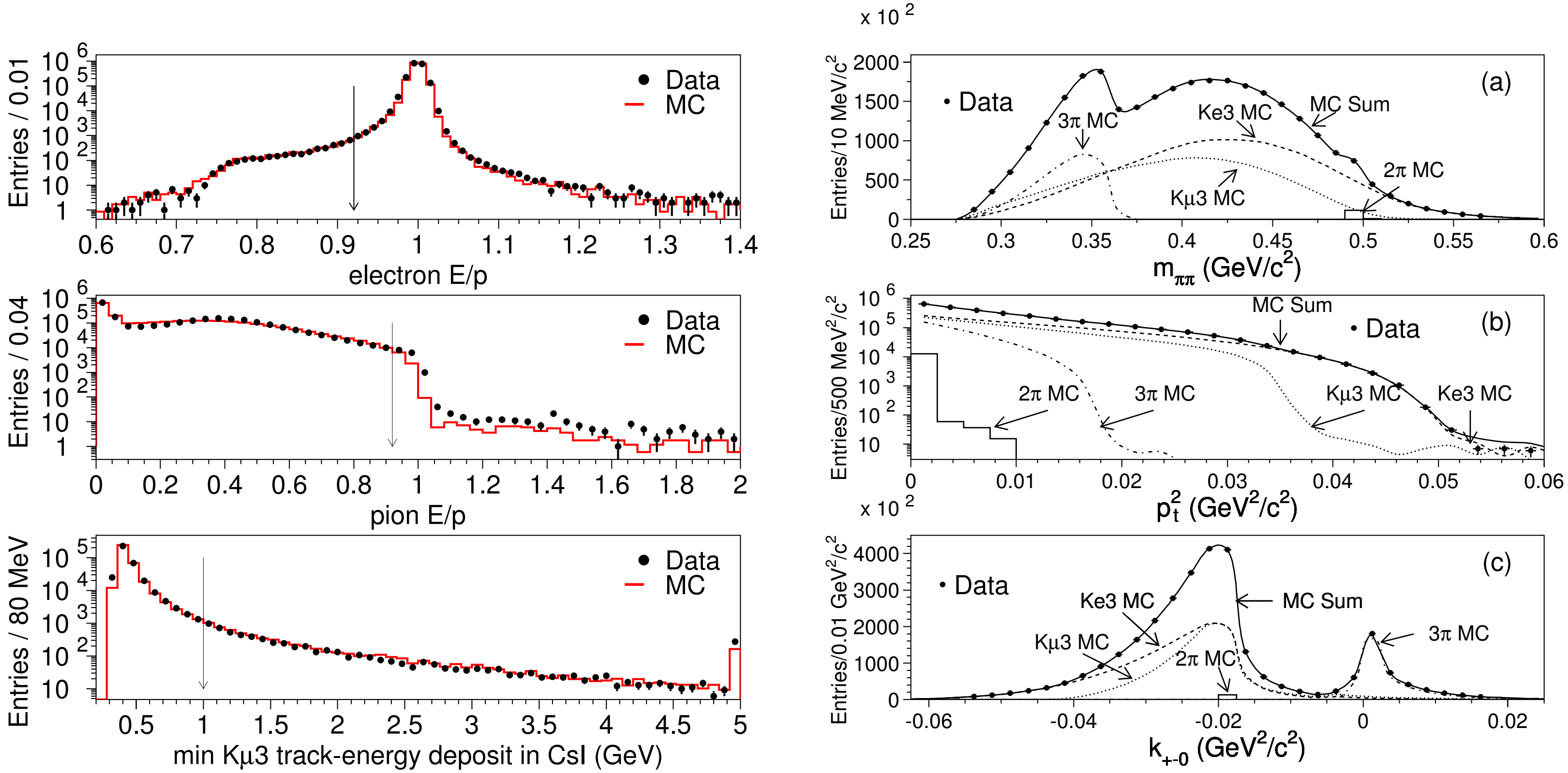
The ratios are formed between **charged** (2-track), **neutral** (0-tracks) decay modes to cancel systematic uncertainties.

KTeV: Acceptance vs Decay Distance



- Acceptance is different for different modes but well described by MC
- Special effort to minimize effects from different particle types (e.g. μ vs π): μ system is not used to tag $K\mu 3$ and π^0 decay products are ignored for $\pi^+\pi^-\pi^0$.

Reconstruction of the Charged Modes

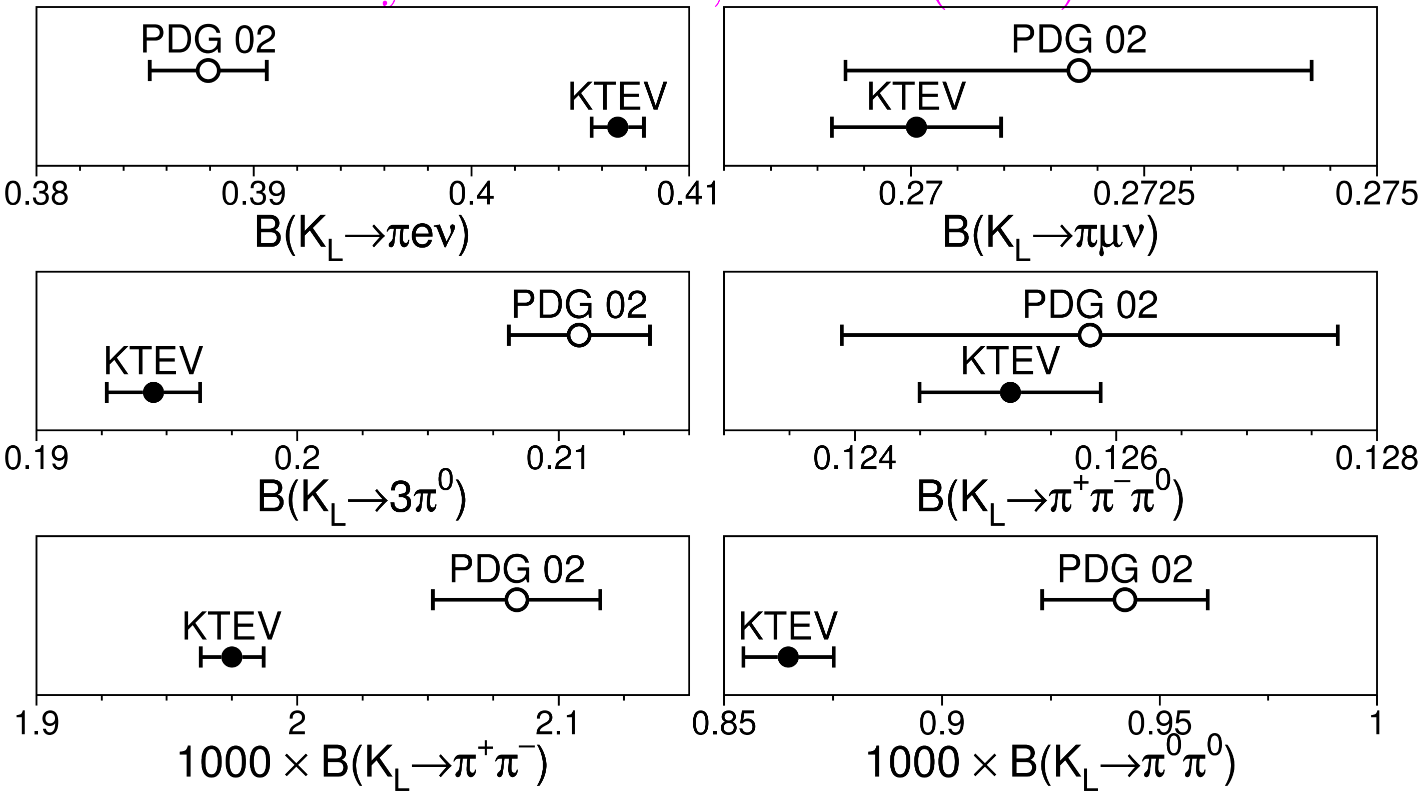


Different charged modes are distinguished from each other using CsI calorimeter energy response (left) and kinematic requirements (right).

The background for each charged mode is $\leq 0.1\%$.

KTeV results for K_L Branching Fractions

Phys. Rev. **D70**, 092006 (2004)

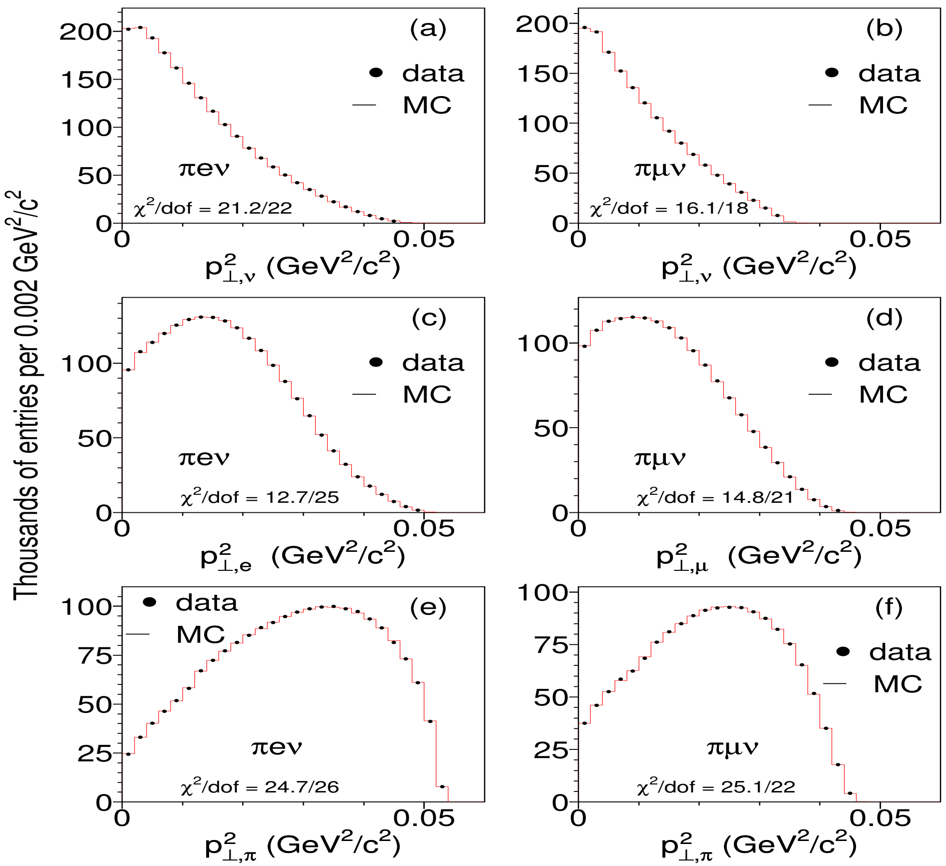


Large change compared to PDG for 4 out of 6 decay modes. In particular, $Ke3$ is about 5% higher. But $K\mu3$ is consistent with older values.

Measurement of semileptonic form factors

Boost invariant transverse-$t_\perp$ determined using $p_\perp$ of the particles:

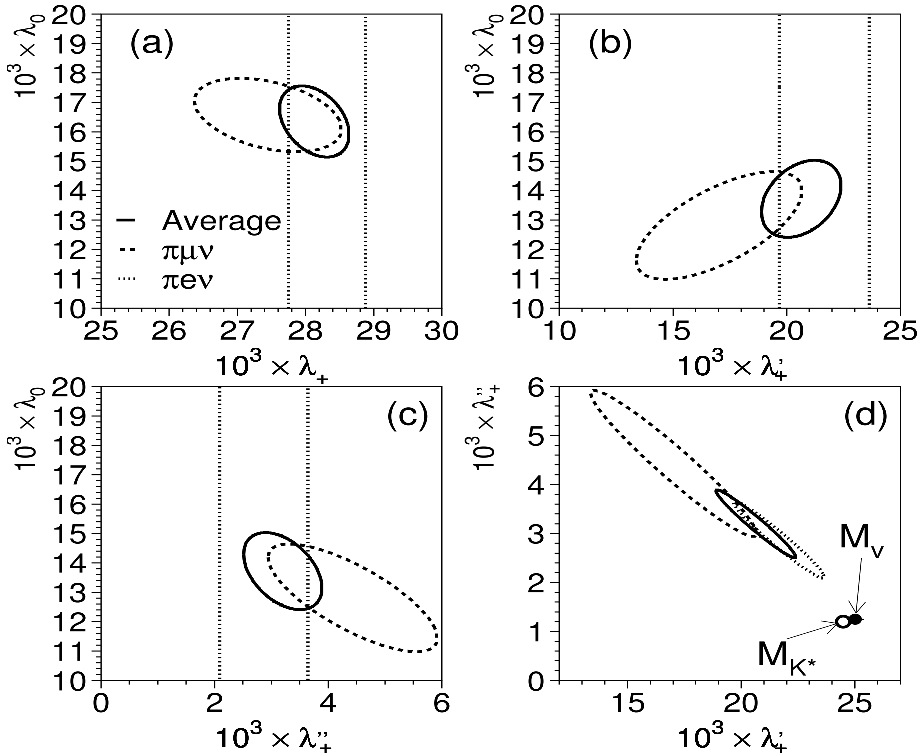
$$\begin{aligned} t_\perp^\ell &= M_\ell^2 + 2|p_{\perp,\nu}|\sqrt{p_{\perp,\ell}^2 + M_\ell^2} - 2\mathbf{p}_{\perp,\nu}\mathbf{p}_{\perp,\ell} \\ t_\perp^\pi &= M_K^2 + M_\pi^2 - 2M_K\sqrt{p_{\perp,\pi}^2 + M_\pi^2} \end{aligned} \tag{13}$$



$t_\perp$ reduces uncertainty from K_L momentum spectrum

Form factor results

Phys. Rev. **D70**, 092007 (2004)



KTeV result is consistent with ISTRA+ result for K^+

	λ'_+	λ''_+	λ_0 (for $\lambda_+ = 0.0277$)
	$\times 10^{-3}$		
KTeV	20.64 ± 1.75	3.20 ± 0.69	16.5 ± 1.1
ISTRA+	23.24 ± 1.55	1.68 ± 0.82	18.3 ± 1.1

Radiative Corrections for $K\ell 3$ decays

Two parts of radiative corrections:

$$\delta_{tot} = S_{EW}(1 + \delta_K^\ell) \qquad (14)$$

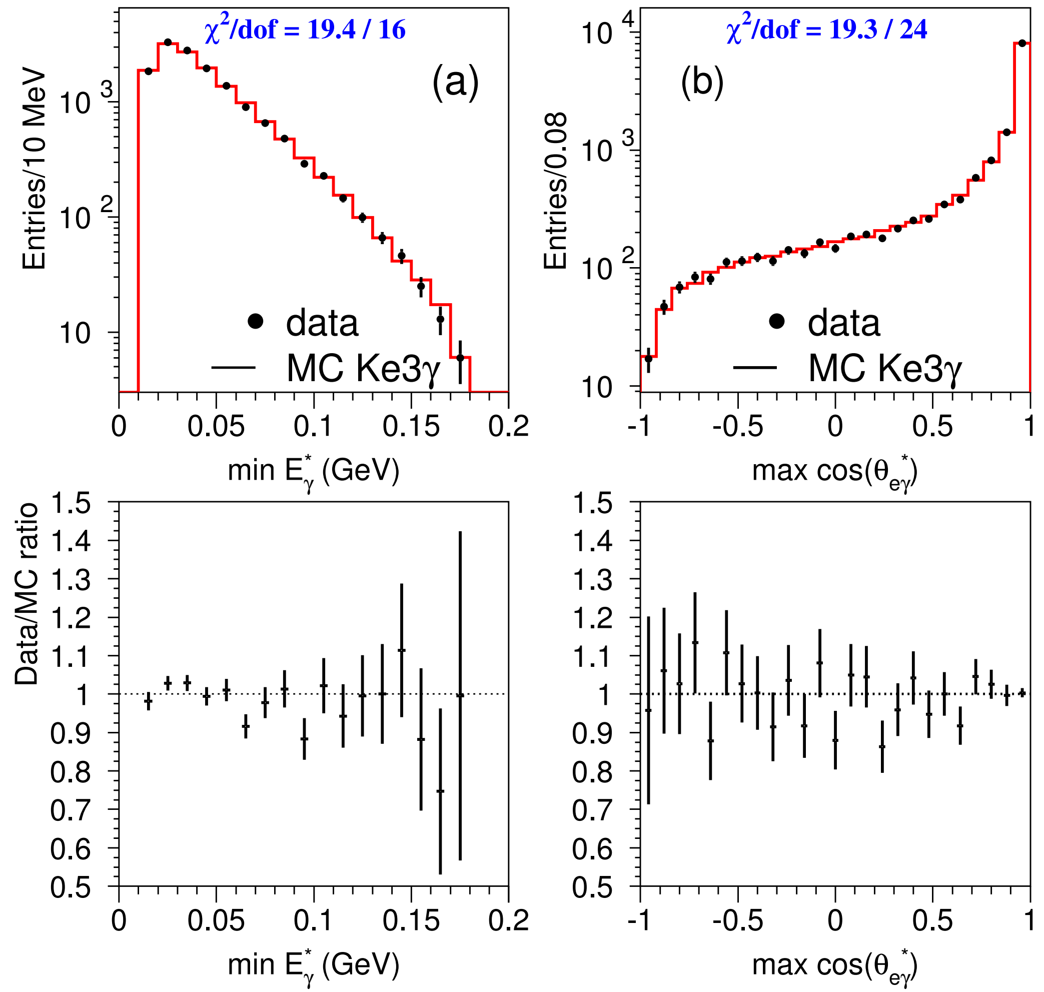
Universal short distance radiative corrections, $S_{EW} = 1.022$, calculated by Sirlin in 1981.

Mode dependent radiative corrections δ_K^ℓ:

- Originally calculated by Ginsberg in the late 1960s.
- New calculations for $K^0\ell 3$ and $K^\pm\ell 3$ using chiral QCD (Cirigliano et al, Bytev et al) and effective theory approach (Andre using **KLOR**) – for $K^0 e3$ about 0.5% lower than Ginsberg estimation
- The radiative corrections are included in MC simulation – new **KLOR** program developed by UofC student (T. Andre).

$\rightarrow$ $\delta_K^e = (1.3 \pm 0.3)\%$, $\delta_K^\mu = (1.9 \pm 0.3)\%$, the errors include the uncertainty arising from the change of the matching scale.

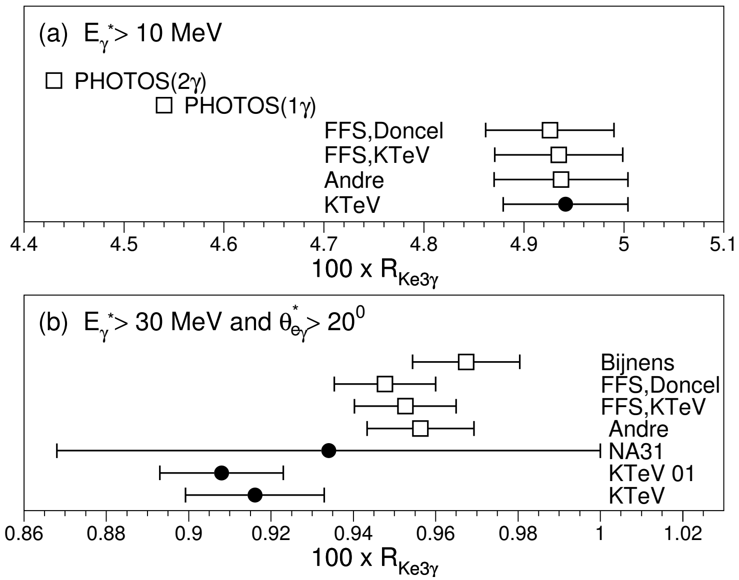
Measurement of $K\ell3\gamma$ branching fraction

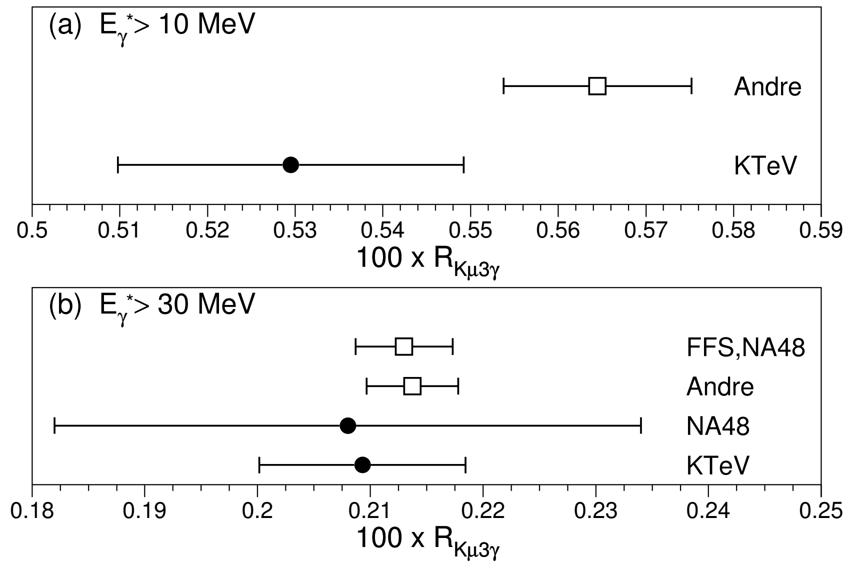


- Dedicated analysis with γ detected in the calorimeter
- **KLOR** describes kinematic distributions well.

$K\ell 3\gamma$ Results

Phys. Rev. **D71**, 012001 (2005)





- Extend measurement to lower $E_\gamma > 10$ MeV
- Estimate significant (for $Ke3$) second order correction using PHOTOS

KLOR prediction agrees with data, other theory estimates.

Crosscheck: Lepton universality

V_{us} measured with $Ke3$ and $K\mu3$ should be the same – lepton universality. More directly, the ratio of the Fermi coupling constants for electrons and muons must be the same:

$$\left(\frac{G_F^\mu}{G_F^e}\right)^2 = \left[\frac{\Gamma(K_L \to \pi^\pm \mu^\mp \nu)}{\Gamma(K_L \to \pi^\pm e^\mp \nu)}\right] \Big/ \left(\frac{1+\delta_K^\mu}{1+\delta_K^e} \cdot \frac{I_K^\mu}{I_K^e}\right) \qquad (15)$$

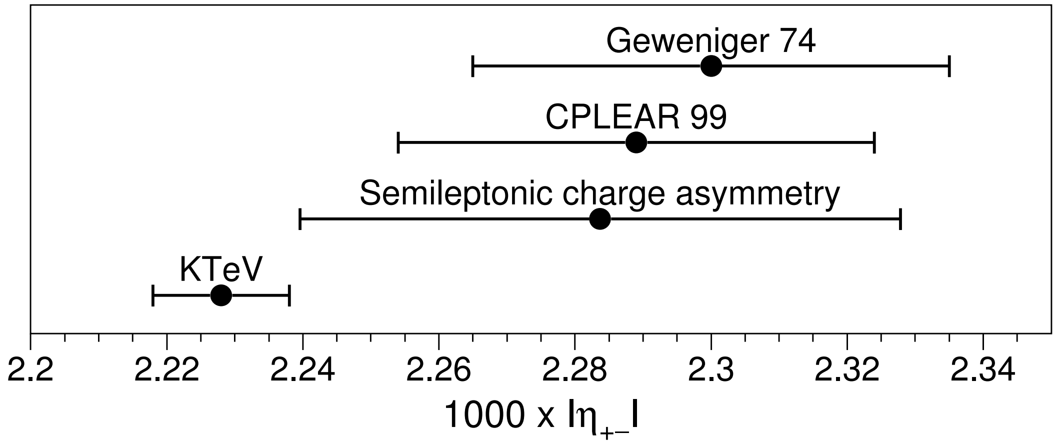
- Theoretical uncertainties in $f_+(0)$ cancel for this ratio
- "Matching scale" uncertainties for δ_K^ℓ are reduced: $(1+\delta_K^\mu)/(1+\delta_K^e) = 1.0058 \pm 0.0010$
- Uncertainties for the "rate" measurement of $\Gamma(K_L \to \pi^\pm \mu^\mp \nu)/\Gamma(K_L \to \pi^\pm e^\mp \nu) = 0.6640 \pm 0.0026$ differ vs the "shape" measurement of the form factors.
- Ratio of $I_K^\mu/I_K^e = 0.6622 \pm 0.0018$ has reduced dependence on the form factor parameterization.

$$(G_F^\mu/G_F^e)^2 = 0.9969 \pm 0.0048$$

Measurement η_{+-}

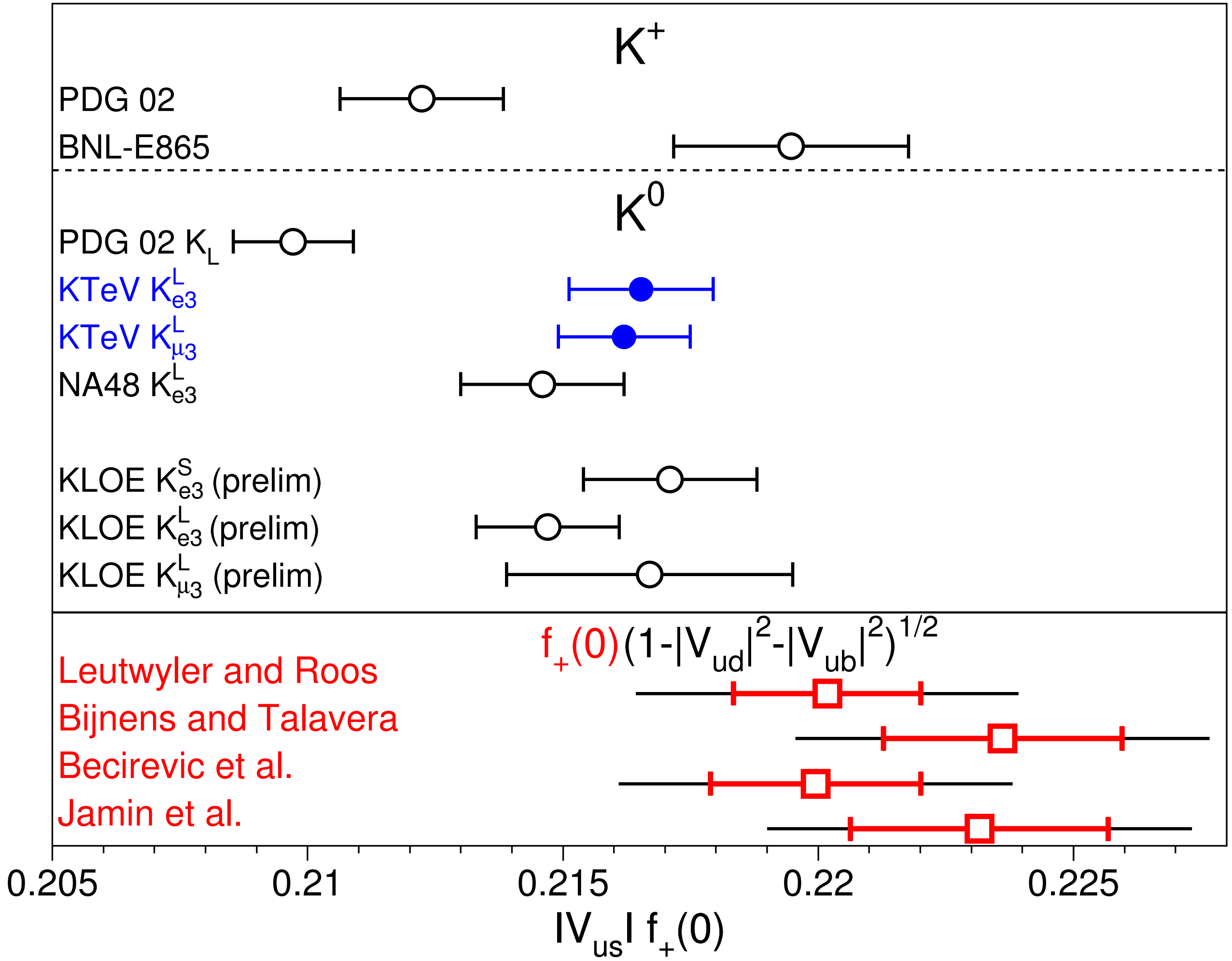
Using the measured $K_L \to \pi\pi$ branching fractions, external values of τ_S (KTeV, NA48) and $\tau_L = 5.15 \pm 0.04$ (PDG02), and correcting for small effects of $\Re(\epsilon'/\epsilon)$ and K_S semileptonic branching fraction one obtains $A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-) = \eta_{+-}$

$$\begin{aligned}\eta_{+-} &= \frac{\tau_S}{\tau_L}\frac{B_L(\pi^+\pi^-)+B_L(\pi^0\pi^0)\left[1+6\Re(\epsilon'/\epsilon)\right]}{1-B_S(Kl3)} \\ &= (2.228 \pm 0.010) \times 10^{-3}\end{aligned} \quad (16)$$



- Most of the error for KTeV is from external τ_L uncertainty
- Geweniger-74 and CPLEAR-99 are $K_L - K_S$ interference based measurements, depend on τ_S, corrected to new τ_S.

$|V_{us}| f_+(0)$ results



- Large deviation from old PDG values
- Reasonable agreement among recent results.

Extraction of $|V_{us}|$

For extraction of $|V_{us}|$, KTeV chooses to use Leutwyler and Roos value of $f_+(0) = 0.961 \pm 0.008$ (Z. Phys. **C25**, 91 (1984)), same as PDG. With this value,

$$|V_{us}| = 0.2252 \pm 0.008_{\mathrm{KTeV}} \pm 0.0023_{\mathrm{ext.}}$$

With this value for Cabibbo angle, the unitarity:

$$\delta = 1 - \left(|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2\right) = 0.0018 \pm 0.0019$$

is satisfied at 1σ level.

Conclusions

- Entire KTeV data set of $K_L \to \pi\pi ee$ events has been analyzed. The CP-violating asymmetry is $A = 13.7 \pm 2.1$.
- KTeV has measured the six largest K_L branching fractions. Large deviations from old PDG values are found for four of them.
- KTeV has determined $Kl3$ decay form factors. The measurement of the form factors and of the branching fractions are consistent with lepton universality.
- KTeV has performed a dedicated analysis of the radiative $Kl3\gamma$ decays. The data agrees well predictions of **KLOR** program.
- Using the measured branching fractions for $K\mu3$ and $Ke3$ and semileptonic form factors, as well as PDG values for τ_L and Leutwyler and Roos value for $f_+(0)$, KTeV determines new value of V_{us} which is consistent with unitarity at 1σ level.