Recent Results From KTeV

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- Updates of the $K_L \rightarrow \pi \pi ee$ 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 $K_L \rightarrow \pi \ell \nu \gamma$ decay branching fractions.
\[ K_L \rightarrow \pi\pi ee \text{ decay} \]

\begin{itemize}
  \item[a)] **Bremsstrahlung** CP violation (as in \( K_L \rightarrow \pi^+\pi^- \))
  \item[b)] **Direct emission.** CP conserving + possible CP violation.
  \hspace{1cm} \text{– higher } e^+e^- \text{ pair energy}
  \item[c)] **Kaon charge radius.** Present for virtual photons only
  \hspace{1cm} \text{– higher } e^+e^- \text{ pair invariant mass}
\end{itemize}

CP violation shows up as an angular asymmetry for the angle \( \phi \) between normals to \( \pi^+\pi^- \) and \( e^+e^- \) planes in kaon CM.
$K_L \to \pi\pi\ell\ell$ 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:

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

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

\[ \tilde{g}_{m1} = 1.11 \pm 0.12 \text{ stat} \pm 0.07 \text{ syst} \]
\[ a_1/a_2 = -0.744 \pm 0.022 \text{ stat} \pm 0.032 \text{ syst} \]

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

\[ \frac{|g_{E1}|}{|g_{M1}|} < 0.04 (90\% \text{CL}) \]
$K_L \rightarrow \pi\pi ee$ measurement of kaon charge radius

$$|g_{CR}| = 0.163 \pm 0.017 \text{ stat} \pm 0.023 \text{ syst}$$  \hspace{1cm} (4)

$|g_{CR}| = -\frac{1}{3} \langle R^2_K \rangle M_K^2$ where $\langle R^2_K \rangle$ is $K^0$ charge radius. Measurements before NA48 and KTeV are based on regeneration on free electrons.
$K_L \rightarrow \pi\pi ee$ measurement of CP violating asymmetry

\[ A = \frac{N_{\sin \phi \cos \phi > 0} - N_{\sin \phi \cos \phi < 0}}{N_{\sin \phi \cos \phi > 0} + N_{\sin \phi \cos \phi < 0}} \]  \quad (5)

\begin{align*}
A &= [13.7 \pm 1.4 \, \text{stat} \pm 1.5 \, \text{syst}] \\
\text{Predicted at } &\sim 14\% 
\end{align*}  \quad (6)
Measurement of $|V_{us}|$

Measure based on semileptonic $K_L$ decays:

$$\Gamma_{K\ell3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^\ell) \; |V_{us}|^2 \; f_+(0) I_K^\ell, \quad (7)$$

- Experimental input: Decay width ($\Gamma_{K\ell3}$), decay form factors (affect phase space integrals $I_K^\ell$)
- Theoretical input: $f_+(0)$, radiative corrections $S_{EW} (1 + \delta_K^\ell)$.

KTeV measures $B r_{K\ell3}$, $I_K^\ell$ and checks $\delta_K^\ell$ by measuring $\Gamma_{K\ell3\gamma, E_{\gamma} > 10}$ MeV
Measurement of $K_L$ branching fractions

KTeV can not tag the kaon → 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 $\tau_L$ to convert branching fractions into partial widths.

The five measured ratios are:

\begin{align*}
\Gamma_{K\mu3}/\Gamma_{Ke3} & \equiv \frac{\Gamma(K_L \to \pi^{\pm}\mu^{\mp}\nu)}{\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)} \quad (8) \\
\Gamma_{+-0}/\Gamma_{Ke3} & \equiv \frac{\Gamma(K_L \to \pi^{+}\pi^{-}\pi^{0})}{\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)} \quad (9) \\
\Gamma_{000}/\Gamma_{Ke3} & \equiv \frac{\Gamma(K_L \to \pi^{0}\pi^{0}\pi^{0})}{\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)} \quad (10) \\
\Gamma_{+-}/\Gamma_{Ke3} & \equiv \frac{\Gamma(K_L \to \pi^{+}\pi^{-})}{\Gamma(K_L \to \pi^{\pm}e^{\mp}\nu)} \quad (11) \\
\Gamma_{00}/\Gamma_{000} & \equiv \frac{\Gamma(K_L \to \pi^{0}\pi^{0})}{\Gamma(K_L \to \pi^{0}\pi^{0}\pi^{0})} \quad (12)
\end{align*}

The ratios are formed between charged (2-track), neutral (0-tracks) decay modes to cancel systematic uncertainties.
Acceptance is different for different modes but well described by MC.

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


Large change compared to PDG for 4 out of 6 decay modes. In particular, $K e 3$ is about 5% higher. But $K \mu 3$ is consistent with older values.
Measurement of semileptonic form factors

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

$$t^\ell_\perp = M^2_\ell + 2|p_\perp,\nu|\sqrt{p^2_{\perp,\ell} + M^2_\ell - 2p_\perp,\nu p_{\perp,\ell}}$$

$$t^\pi_\perp = M^2_K + M^2_\pi - 2M_K \sqrt{p^2_{\perp,\pi} + M^2_\pi}$$

$t_\perp$ reduces uncertainty from $K_L$ momentum spectrum
Form factor results


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

<table>
<thead>
<tr>
<th></th>
<th>$\lambda''_+$</th>
<th>$\lambda'_+$</th>
<th>$\lambda_0$ (for $\lambda_+ = 0.0277$)</th>
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<tbody>
<tr>
<td></td>
<td>$\times 10^{-3}$</td>
<td>$\times 10^{-3}$</td>
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<tr>
<td>KTeV</td>
<td>20.64 ± 1.75</td>
<td>3.20 ± 0.69</td>
<td>16.5 ± 1.1</td>
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<tr>
<td>ISTRA+</td>
<td>23.24 ± 1.55</td>
<td>1.68 ± 0.82</td>
<td>18.3 ± 1.1</td>
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Radiative Corrections for $K\ell 3$ decays

Two parts of radiative corrections:

$$\delta_{tot} = S_{EW}(1 + \delta_K)$$

(14)

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

Mode dependent radiative corrections $\delta_K$:

- 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 $K^0 e 3$ about 0.5% lower than Ginsberg estimation
- The radiative corrections are included in MC simulation – new KLOR program developed by UofC student (T. Andre).

$$\rightarrow \delta^e_K = (1.3 \pm 0.3)\%, \quad \delta^\mu_K = (1.9 \pm 0.3)\%,$$

the errors include the uncertainty arising from the change of the matching scale.
Measurement of $K\ell 3\gamma$ branching fraction

- Dedicated analysis with $\gamma$ detected in the calorimeter
- **KLORE** describes kinematic distributions well.
**$K\ell 3\gamma$ Results**


- 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:

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

- Theoretical uncertainties in $f_+(0)$ cancel for this ratio
- “Matching scale” uncertainties for $\delta_K^\mu$ are reduced:
  \hspace{1cm} (1 + \delta_K^\mu)/(1 + \delta_K^e) = 1.0058 \pm 0.0010
- Uncertainties for the “rate” measurement of
  \Gamma(K_L \rightarrow \pi^\pm \mu^{\mp} \nu)/\Gamma(K_L \rightarrow \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.

$$\left(\frac{G_F^\mu}{G_F^e}\right)^2 = 0.9969 \pm 0.0048$$
Measurement $\eta_{+-}$

Using the measured $K_L \to \pi \pi$ branching fractions, external values of $\tau_S$ (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 $A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-) = \eta_{+-}$

$$\eta_{+-} = \frac{\tau_S}{\tau_L} \frac{B_L(\pi^+\pi^-) + B_L(\pi^0\pi^0)[1 + 6\Re(\epsilon'/\epsilon)]}{1 - B_S(K^0\ell\bar{\nu})} = (2.228 \pm 0.010) \times 10^{-3}$$

Most of the error for KTeV is from external $\tau_L$ uncertainty

Gweniger-74 and CPLEAR-99 are $K_L - K_S$ interference based measurements, depend on $\tau_S$, corrected to new $\tau_S$. 
- Large deviation from old PDG values
- Reasonable agreement among recent results.
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,

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

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 $1\sigma$ level.
Conclusions

- Entire KTeV data set of $K_L \rightarrow \pi\pi ee$ 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 KLOp program.

- Using the measured branching fractions for $K\mu3$ and $Ke3$ and semileptonic form factors, as well as PDG values for $\tau_L$ and Leutwyler and Roos value for $f_+(0)$, KTeV determines new value of $V_{us}$ which is consistent with unitarity at 1σ level.