Recent Results from KTeV

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for the KTeV Collaboration

- $K_L \rightarrow \pi^0\mu^+\mu^-$
- $\Xi^0 \rightarrow \Sigma^+\mu^-\nu$
- $|V_{us}|$ and related measurements

Phys Rev Lett **93**, 181802 (2004)
Phys Rev **D70**, 092005 (2004)
Phys Rev **D80**, 092007 (2004)
Phys Rev **D71**, 012001 (2005)

$K_L \to \pi^0\mu^+\mu^-$

$|K_L\rangle \approx |K_{ODD}\rangle + \varepsilon|K_{EVEN}\rangle$

Background from radiative muonic Dalitz decay of the kaon, $K_L \to \mu^+\mu^-\gamma\gamma$

$Br(K_L \to \mu^+\mu^-\gamma\gamma,\ m_{\gamma\gamma} > 1\ MeV) =$

$(10.4\ ^{+7.5}_{-5.9}\ {}_{STAT} \pm 0.7_{SYS}) \times 10^{-9}$

Phys.Rev.D62:112001(2000)

Indirect CPV

$\to \pi^0\gamma^* \to \pi^0\ell^+\ell^-$

$$Br(K_L \to \pi^0\ell^+\ell^-) = |\varepsilon|^2 \frac{\tau_L}{\tau_S} Br(K_S \to \pi^0\ell^+\ell^-)$$

Direct CPV

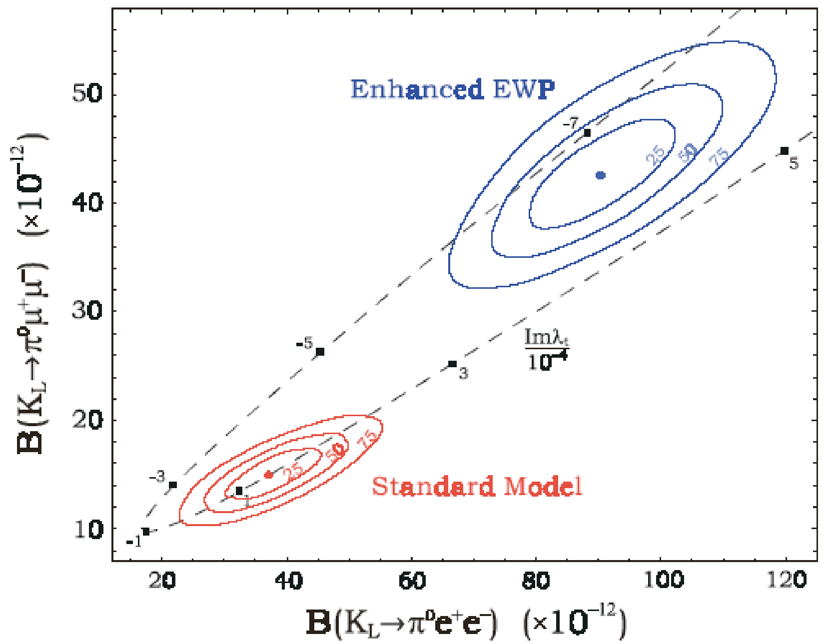
$\to$ $\pi^0\gamma^*$, $\pi^0 Z^*$, $\pi^0 W^{+*}W^{-*}$ $\to \pi^0\ell^+\ell^-$

$\to \pi^0\gamma^*\gamma^* \to \pi^0\ell^+\ell^-$ CPC

Theoretical:

Isidori, Smith & Unterdorfer, Eur.Phys.J.C36:57-66(2004)

Combo of $\pi^0\mu^+\mu^-$ & $\pi^0 e^+ e^-$ valuable in elucidating new physics



Experimental:

Park, et.al. (HyperCP), Phys.Rev.Lett. 94,021801 (2005)

- $Br(\Sigma^+\to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4}\,_{STAT} \pm 5.5_{SYST})\ \mathrm{x}10^{-8}$ (3 events)
- Expectation is ~ 0.1 $\mathrm{x}10^{-8}$
- All 3 events at the same mass: 214.3 ±0.5 MeV; C.L. for this in S.M. is 0.8%

May **indicate a new neutral intermediate state, P^0**

KTeV's existing limit on $\pi^0\mu^+\mu^-$ helps constrain P^0

$Br(\Sigma^+ \to p\mu^+\mu^-)$ is too small for P^0 to likely be a hadron - it is closer to the sort of rate typical of EM interactions

$(J)^P$ conservation limits a pointlike P^0 to $(J)^P = 0^-$ or 1^- ; but if P^0 is 1^- it will contribute to $K_L \to \pi^0\mu^+\mu^-$

From HyperCP's $Br(\Sigma^+ \to pP^0)$, PDG lifetimes for Σ^+, K_L and our limit $Br(K_L \to \pi^0\mu^+\mu^-) < 3.8 \times 10^{-10}$ Phys.Rev.Lett. **84**,5279(2000)

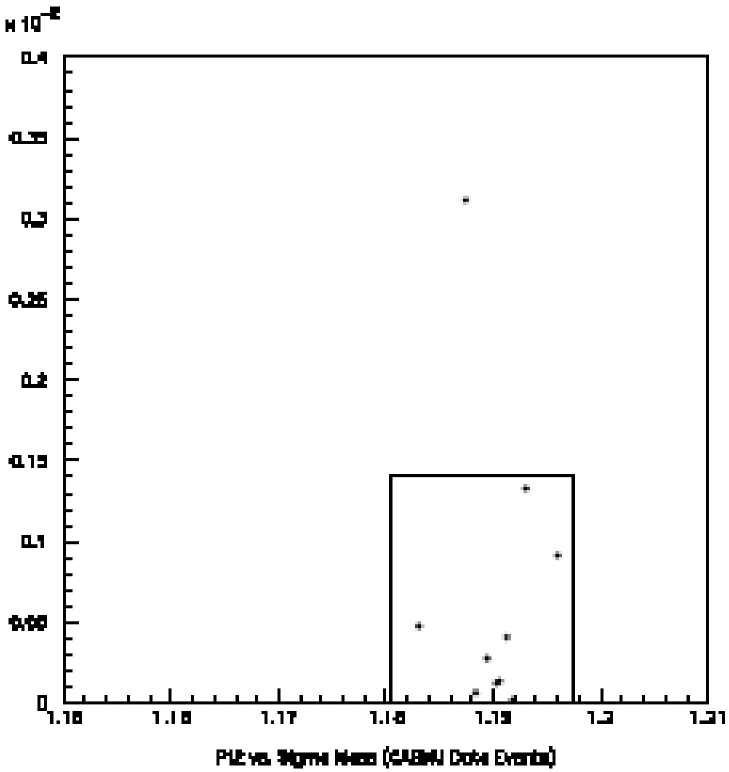
$$\Gamma(\Sigma^+ \to pP^0) \sim 2.5 \times 10^{-19}\ MeV$$

$$\Gamma(K_L \to \pi^0\mu^+\mu^-) < 4.8 \times 10^{-24}\ MeV$$

Rules out P^0 is $J = 1^-$ hypothesis

New limit on $Br(K_L \to \pi^0\mu^+\mu^-)$ from full KTeV dataset in progress

Observation of $\Xi^0 \rightarrow \Sigma^+ \mu^- \nu$



Normalized to $\Xi^0 \rightarrow \Lambda \pi^0$, $\Lambda \rightarrow p \pi^-$

With 9 events from '99 dataset, no background events seen in wrong sign, or in 10x MC sample -

Preliminary Result

$$\mathbf{BR}_{\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_\mu} = (4.3 \pm 1.4) \times 10^{-6}$$

$$\textbf{Theoretical Prediction: } 2.3 \times 10^{-6}$$

$|V_{us}|$ *etc.*

Long standing issue: 1st row unitarity $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1$

BNL E865 (May 2003) found a higher value for $Br(K^+ \to \pi^0 e^+ \nu)$ consistent with unitarity but giving $|V_{us}|$ ~2.7σ above existing $Br(K_L \to \pi^\pm e^\pm \nu)$ value.

@ ~2.2 σ level

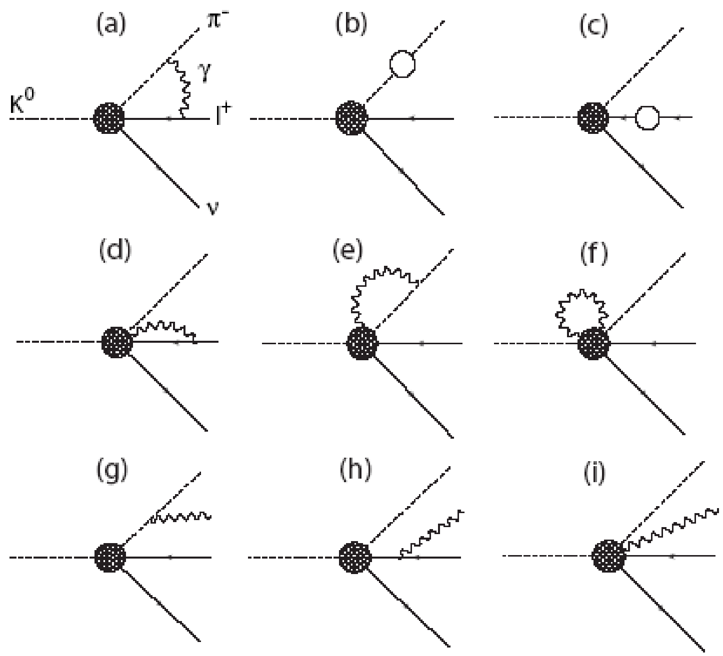
$$\Gamma_{\ell 3} = \frac{Br\left(K_L \to \pi^\pm \ell^\mp \nu\right)}{\tau_L} = \left(\frac{G_F^2\ m_K^5}{384\,\pi^3}\right) S_{EW}\, f_+^2(t=0)\,\left(1+\delta_\ell\right)\,|V_{us}|^2 \int \hat{f}^2$$

S_{EW}	Short range EW & QCD corrections - same for e,μ
$f_+(0)$	Form factor at $t = (P_\ell + P_\nu)^2 = 0$; we use 0.961 ±0.008 [Leutwyler & Roos, 1984]
δ_ℓ	Long range (mode-dependent) radiative corrections
$\int \hat{f}^2$	Integral over phase space of form factor squared

Step 1: Radiative corrections

$$\Gamma_{\ell 3} = \frac{Br\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\right)}{\tau_L} = \left(\frac{G_F^2\, m_K^5}{384\,\pi^3}\right) S_{EW}\, f_+^2(t=0)\,(1+\delta_\ell)\,|V_{us}|^2 \int \hat{f}^{\,2}$$

T.Andre, hep-ph/0406006



Take

$$\left\langle \pi^-(p_\pi)\middle|\bar{s}_L\gamma^\alpha u_L\middle|K^0(p_K)\right\rangle =$$
$$f_+(t)\left[p_K + p_\pi\right] + f_-(t)\left[p_K - p_\pi\right]$$

Evaluate with linear, quadratic and pole model form factors f

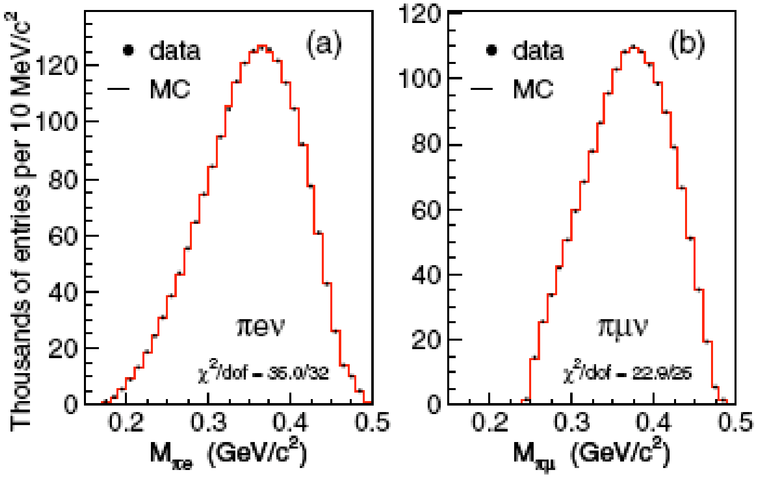
Step 2: Form factors

$$\Gamma_{\ell 3} = \frac{Br\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\right)}{\tau_L} = \left(\frac{G_F^2\, m_K^5}{384\,\pi^3}\right) S_{EW}\, f_+^2(t=0)\,\left(1+\delta_\ell\right)\left|V_{us}\right|^2 \int \hat{f}^{\,2}$$

We parameterize with $f_+(t)$ and $f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$

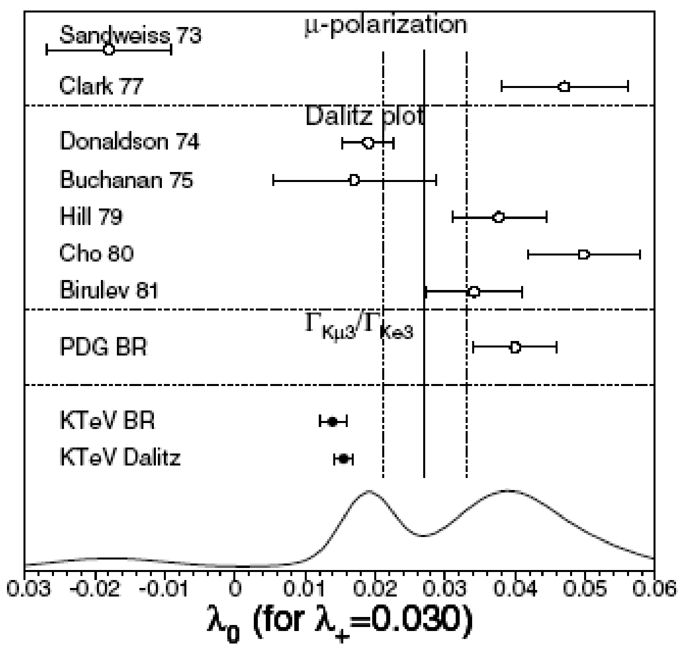
f_i expanded in powers of $t\,/\,m_\pi^2$; coefficients are λ_i

- Since p_K is not known, there is a two-fold reconstruction ambiguity due to unseen ν
- We use $t_\perp^{\ell} = (P'_\ell + P'_\nu)^2$ or $t_\perp^{\pi} = (P'_K - P'_\pi)^2$ -Basically, t evaluated without longitudinal coordinates to momenta. Costs ~15% of statistical power
- Some fits also use $m_{\ell\pi}$



	K_{e3}	$K_{\mu 3}$
	Linear model x10^{-3}	
λ_+	28.32±0.57	27.45±1.08
λ_0	-	16.57±1.25
	Quadratic model x10^{-3}	
λ_+'	21.67±1.99	17.03±3.65
λ_+''	2.87±0.87	4.43±1.49
λ_0	-	12.81±1.83

Pole model fits also reported…



Linear model λ_+ values consistent with PDG values.

Quadratic term significant at 4σ level
Lowers phase space integral by ~1%.

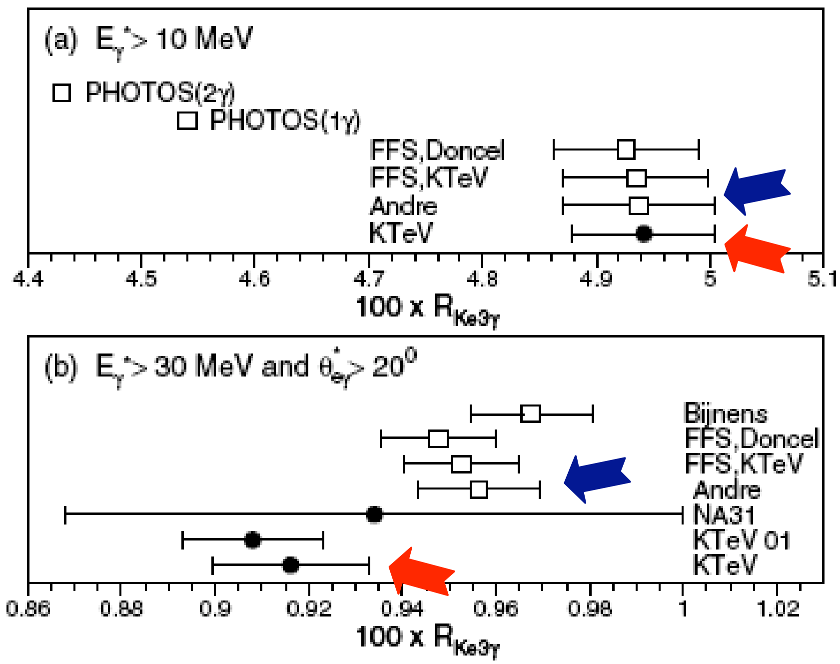
Step 3: Check steps 1&2 with $K_L \to \pi \ell \nu \gamma$

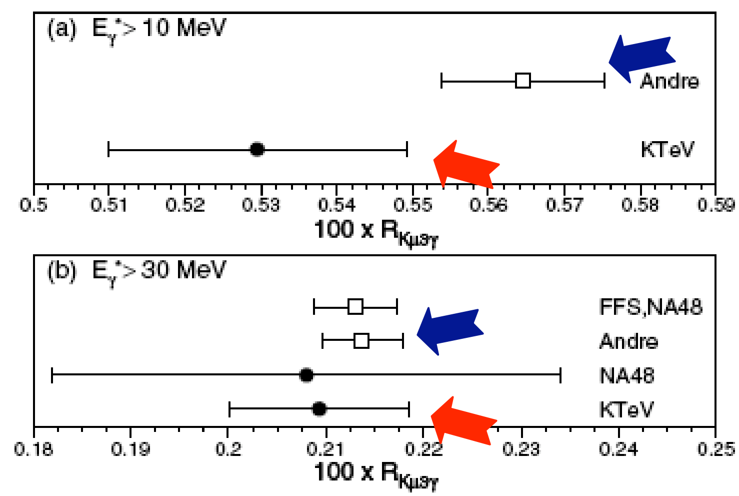
$$R_{K\gamma 3\gamma} \equiv \frac{\Gamma\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\gamma;\ E_{\gamma}^{*} > 10\,MeV\right)}{\Gamma\left(K_L \to \pi^{\pm}\ell^{\mp}\nu + n\gamma\right)}$$

Acceptance corrections for 2nd γ via PHOTOS ~1.8% for K_{e3}

Andre's prediction

KTeV's measurement





Step 4: Get the branching ratio

$$\Gamma_{\ell 3} = \frac{Br\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\right)}{\tau_L} = \left(\frac{G_F^2\, m_K^5}{384\,\pi^3}\right) S_{EW}\, f_+^2(t=0)\,(1+\delta_\ell)\,\left|V_{us}\right|^2 \int \hat{f}^{\,2}$$

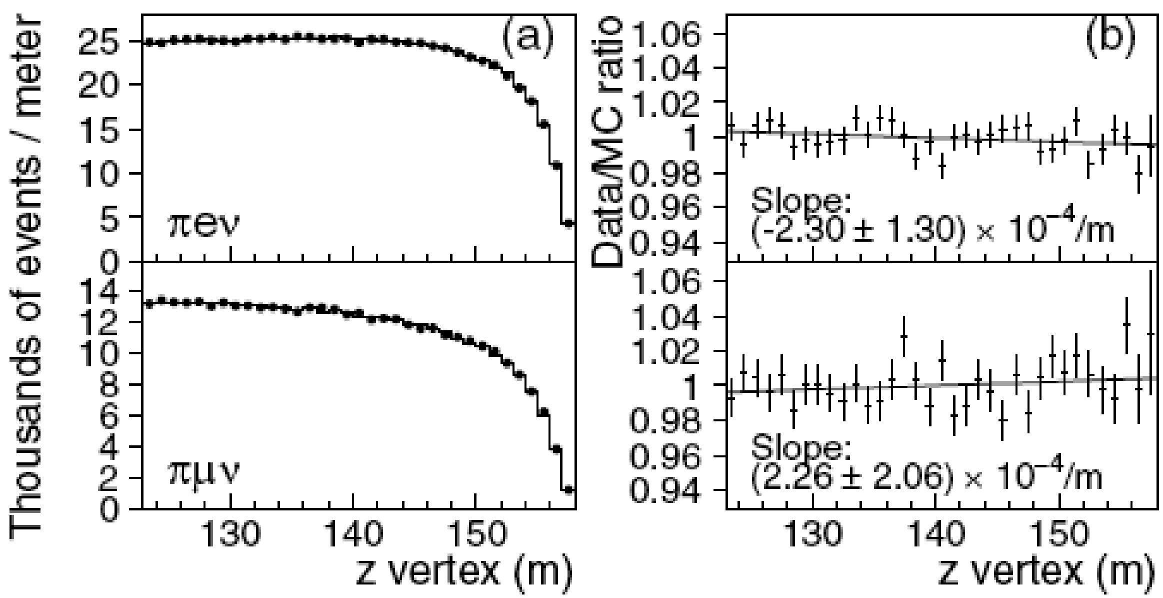
Ordinarily, would measure something like $\Gamma\left(K_L \to \pi^{\pm}\ell^{\mp}\nu\right)/\Gamma\left(K_L \to nice\right)$ where the "$nice$" mode has high statistics, a well-known rate, and is similar to $K_{\ell 3}$ in the detector. Sadly, there is no "$nice$" mode.

Measure these 5 ratios, use Σ = 1 constraint to get Br

$\Gamma_{K\mu 3}/\Gamma_{Ke3}$ $\quad$ $\Gamma_{+-0}/\Gamma_{Ke3}$ $\quad$ $\Gamma_{000}/\Gamma_{Ke3}$

Γ_{+-}/Γ_{Ke3} $\quad$ Γ_{000}/Γ_{00}

- Except for $\Gamma_{000}/\Gamma_{Ke3}$, all ratios have final similar states
- Except for Γ_{00}/Γ_{000}, all ratios in same trigger; this analysis similar to the ε'/ε neutral mode analysis



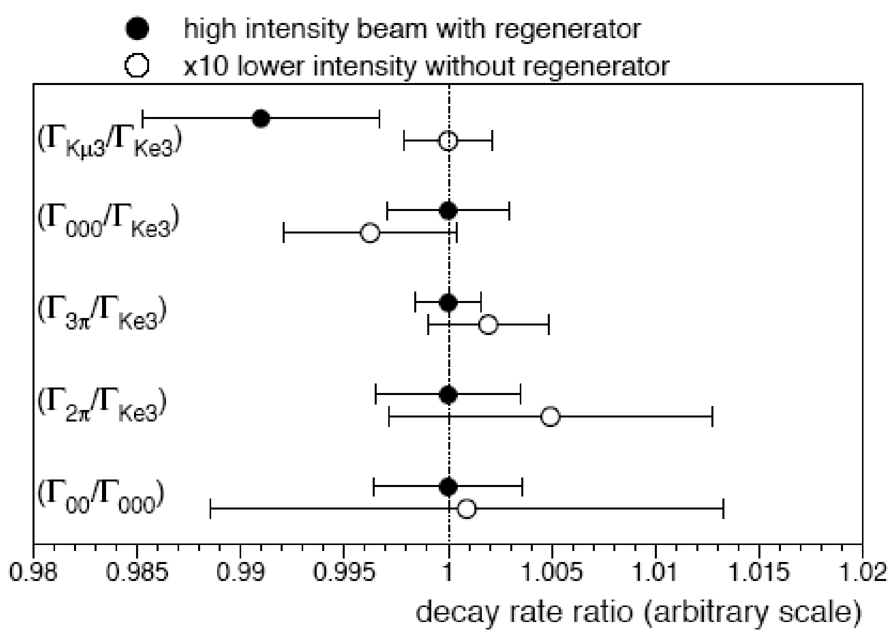
- $K\rightarrow\pi\mu\nu$ ratios without/with μ ID agree to $(0.08 \pm 0.02_{stat})$%
- $K\rightarrow\pi^+\pi^-\pi^0$ ratios without/with $\pi^0\rightarrow\gamma\gamma$ reconstruction in CsI -factor ~4 change in acceptance- agree to $(0.03 \pm 0.28_{stat})$%

More Cross-checks

Using lepton universality, $$\frac{\Gamma_{K\mu 3}}{\Gamma_{Ke3}} = \frac{1+\delta_\mu}{1+\delta_e} \bullet \frac{\int \hat{f}_\mu}{\int \hat{f}_e}$$

Taking δ_ℓ from our radiative correction algorithm, phase-space integrals from our form factor measurements $\Gamma_{K\mu3} / \Gamma_{Ke3} = 0.6660 \pm 0.0019$

And from the direct measurement, $\Gamma_{K\mu3} / \Gamma_{Ke3} = 0.6640 \pm 0.0014 \pm 0.0022$



From measured ratios to $|V_{us}|$

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

$Br(K_{e3}) = 0.4067 \pm 0.0011$
$Br(K_{\mu3}) = 0.2701 \pm 0.0009$

Using $\tau_K = 51.5 \pm 0.4\ ns$

$\Gamma(K_{e3}) = (7.897 \pm 0.065) \times 10^6\ s^{-1}$
$\Gamma(K_{\mu3}) = (5.244 \pm 0.044) \times 10^6\ s^{-1}$

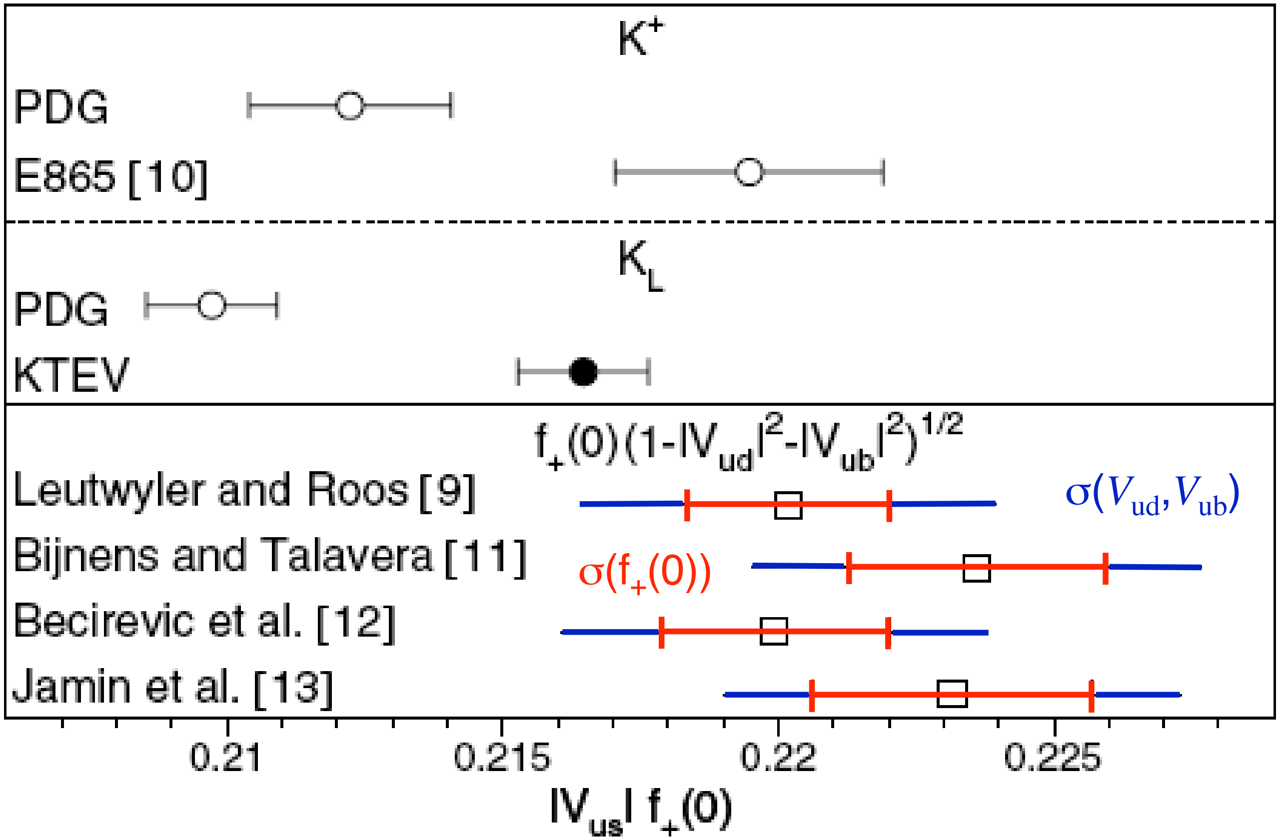
K_{e3}: $|V_{us}| = 0.2253 \pm 0.0023$

$K_{\mu3}$: $|V_{us}| = 0.2250 \pm 0.0023$

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

Γ ratios, form factors

$f_+(0)$, τ_K, rad corrs



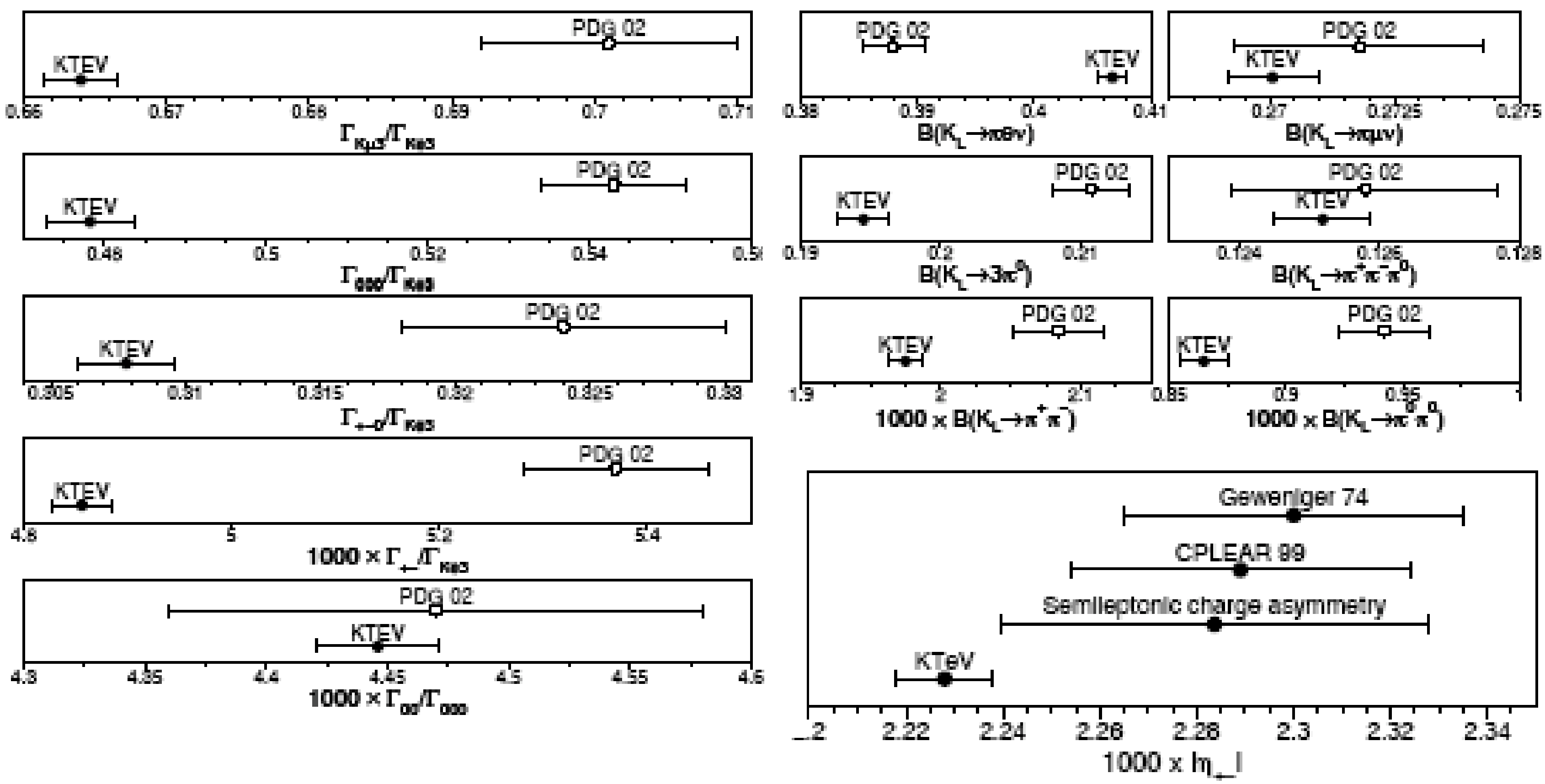
Compared to PDG-02, $Br(K_{e3})$ is ~5% (6σ!) higher; $Br(K_{\mu3})$ not much changed. Phase space integrals are lower by 1.7% and 4.2% in e and μ modes, including the ~1% shift from quadratic term

Conclusions

- HyperCP's anolomy in $\Sigma^+ \to p\mu^+\mu^-$ is not due to a $(J)^P$ conserving vector boson
- Final KTeV result on $Br(K_L \to \pi^0\mu^+\mu^-)$ on its way -also, watch for $K_L \to e^+e^-\gamma$, $K_L \to \pi^+\pi^-e^+e^-$ form factors and branching ratio
- Preliminary results on $\Xi^0 \to \Sigma^+\mu^-\nu$ shown

- We have new and very precise results on major branching ratios, partial widths, $|\eta_{+-}|$, form factors, radiative semileptonic decays, and $|V_{us}|$ in the K_L system. They show a great deal of internal consistency and solve the CKM 1st-row unitarity problem.

Spares

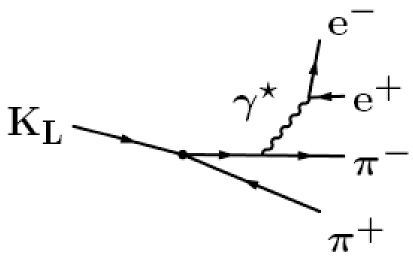

PDG 02
KTEV
0.66
0.67
0.68
0.69
0.7
0.71
PDG 02
KTEV
0.38
0.39
0.4
0.41
PDG 02
KTEV
0.27
0.2725
0.275
PDG 02
KTEV
0.48
0.5
0.52
0.54
PDG 02
KTEV
0.19
0.2
0.21
PDG 02
KTEV
0.124
0.126
0.128
PDG 02
KTEV
0.305
0.31
0.315
0.32
0.325
0.33
PDG 02
KTEV
1.9
2
2.1
PDG 02
KTEV
0.85
0.9
0.95
PDG 02
KTEV
4.8
5
5.2
5.4
PDG 02
KTEV
4.3
4.35
4.4
4.45
4.5
4.55
4.6
Gewenlger 74
CPLEAR 99
Semileptonic charge asymmetry
KTeV
2.22
2.24
2.26
2.28
2.3
2.32
2.34
1000 x |η+-|

PDG 2002:

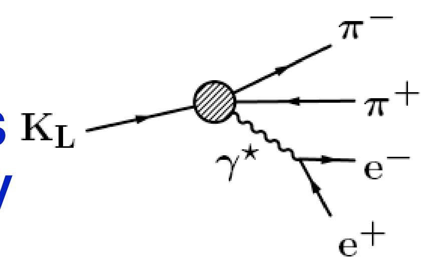
$\Gamma(\pi^{\pm} e^{\mp} \nu_e)$ Γ_1

VALUE (10^6 s^{-1})	EVTS	DOCUMENT ID		TECN	COMMENT
7.50±0.08 OUR FIT Error includes scale factor of 1.1.					
7.7 ±0.5 OUR AVERAGE					
7.81±0.56	620	CHAN	71	HBC	
$7.52^{+0.85}_{-0.72}$		AUBERT	65	HLBC	$\Delta S = \Delta Q$, CP assumed

$K_L \rightarrow \pi^+\pi^- e^+e^-$



Interference between IB and DE amplitudes gives observable CPV



From 5241 candidates (background of 185 ±14) in full dataset:

$$\tilde{g}_{M1} = 1.11 \pm 0.12(stat) \pm 0.07(syst)$$

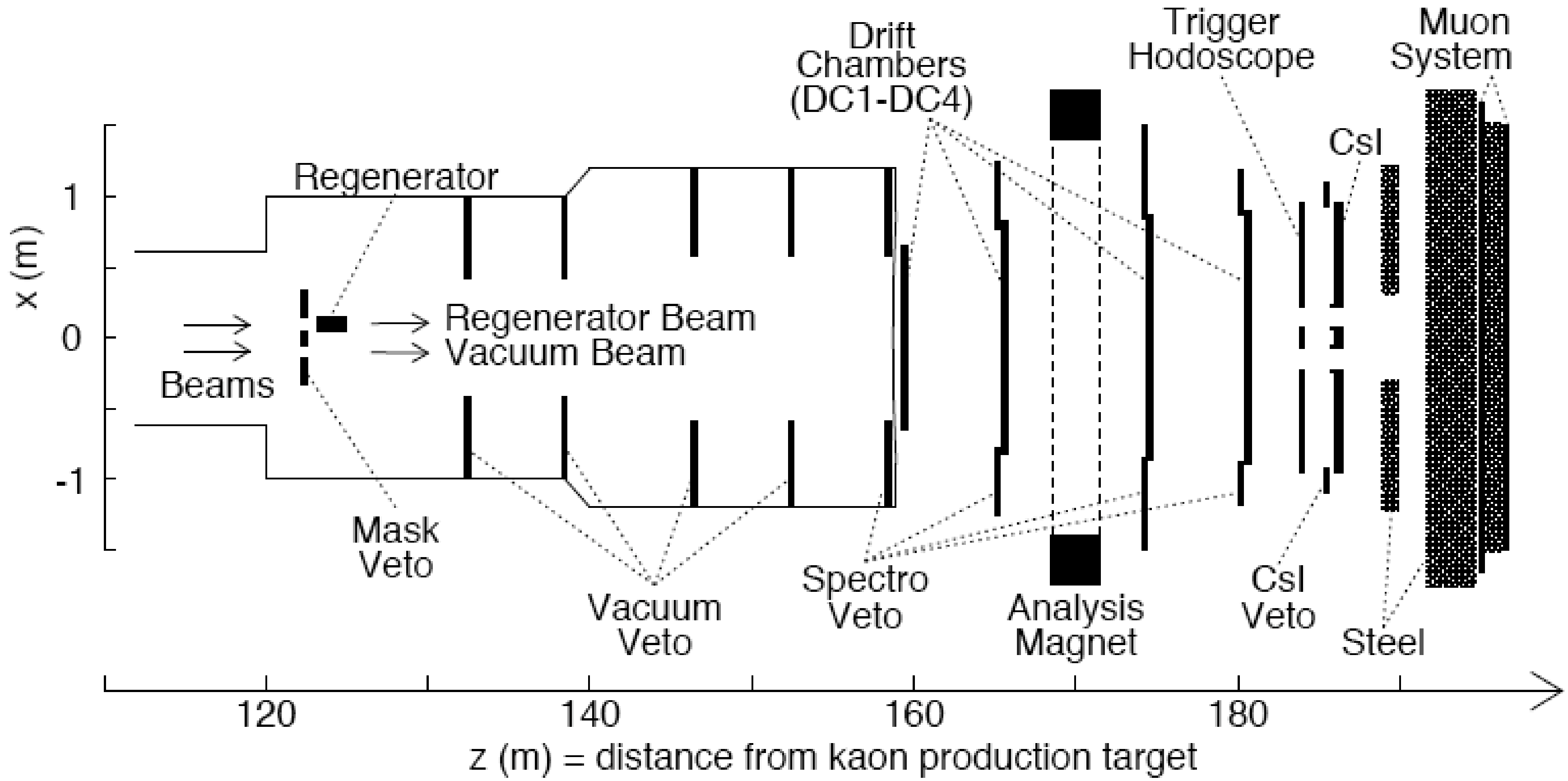
$$\frac{a_1}{a_2} = [-0.744 \pm 0.022(stat) \pm 0.032(syst)] \ (GeV)^2$$

$$|g_{CR}| = 0.163 \pm 0.017(stat) \pm 0.023(syst)$$

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

Preliminary Results

KTeV detector (E832)



$\sigma(p)/p \sim [\ 1.7 \oplus (p/14\text{GeV})\ ] \times 10^{-3}$ 0.043 X_0 = 0.021 Λ_0 upstream of CsI

$\sigma(E)/E \sim [\ 4 \oplus 20/\sqrt{E}\ ] \times 10^{-3}$ π punchthrough = $(1.0 \pm 0.1) \times 10^{-4}\ p$(GeV)