Radiative K Decay Results from the KTeV Experiment

Robert S. Tschirhart
Fermilab

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The high flux of radiative kaon decays reconstructed with high precision enables:

1) High sensitivity for decays forbidden in the Standard Model.
2) Precision measurement of form-factors originating from physics beyond the Standard Model.
3) Important engineering data for characterizing background to physics at the sensitivity frontier.

"Medium Rare" Radiative Rare Decays Discussed Today

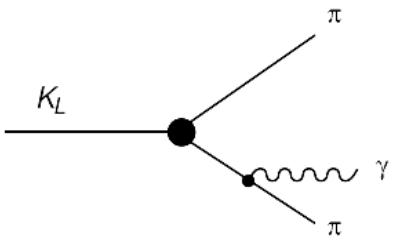
mode	Approx BR	Number of events
$K_L \to \pi^+\pi^-\gamma$	1×10^{-5}	112,000
$K_L \to \pi^+\pi^-\pi^0\gamma$	2×10^{-4}	5600
$K_L \to \pi^+\pi^-\pi^0 e^+e^-$	2×10^{-7}	132
$K_L \to e^+e^-\gamma$	1×10^{-5}	100,000
$K_L \to \pi^+e^-\nu e^+e^-$	1×10^{-5}	19,500

Experiment sensitivity: 10^{-8} --10^{-11}

Radiative Decay $K_L \to \pi^+\pi^-\gamma$

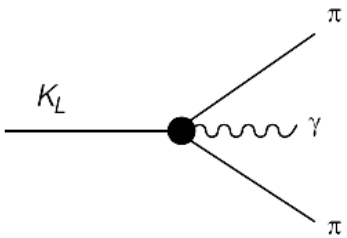
(John Shields and Michael Ronquest, University of Virginia)

internal bremsstrahlung



CP-violating

direct emission

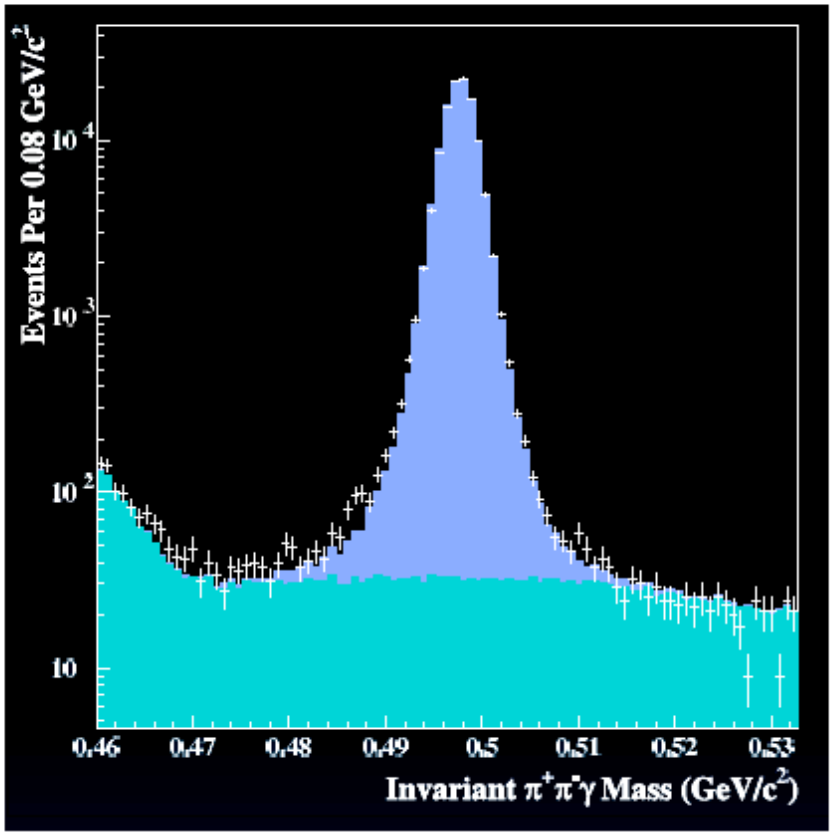


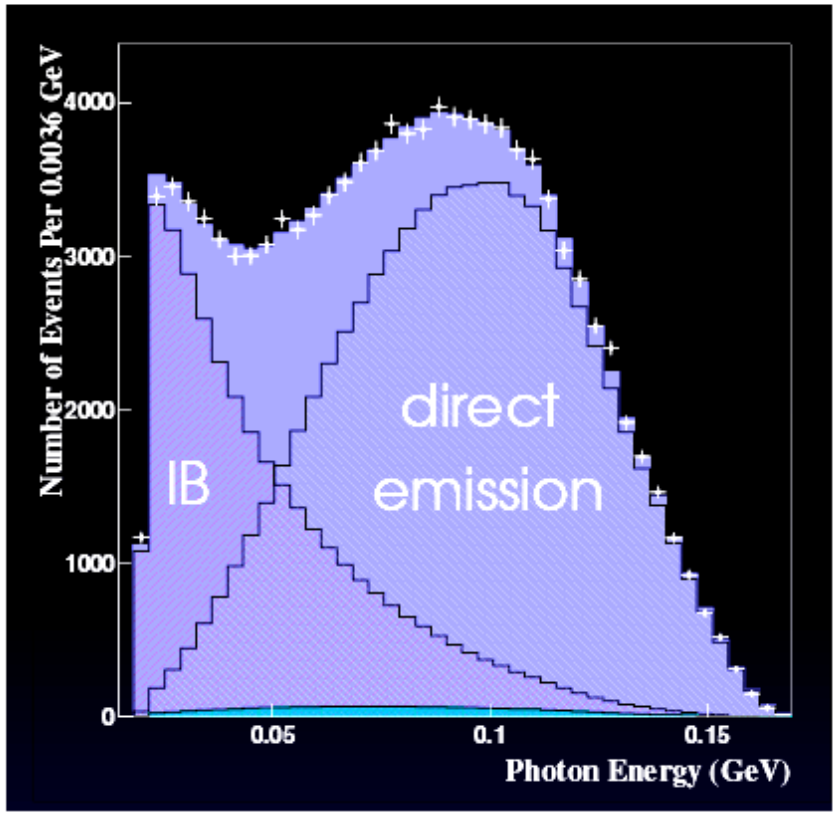
DE coupling requires energy dependence:

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

Direct emission can have M1,E1,M2,E2… multi-poles
E1 is CP violating.

1997 dataset of E832 (collected during ϵ'/ϵ data taking)
After all analysis cuts: 112.1×10^3 candidates including background of 671 ± 41 events.
Likelihood fit to full-differential decay amplitude.





KTeV Results for $K_L \to \pi^+\pi^-\gamma$

Form Factor parameters:

$$\frac{a_1}{a_2} = -0.738 \pm 0.007 \pm 0.018 \; (GeV^2)$$

$$\tilde{g}_{M1} = 1.198 \pm 0.035 \pm 0.086$$

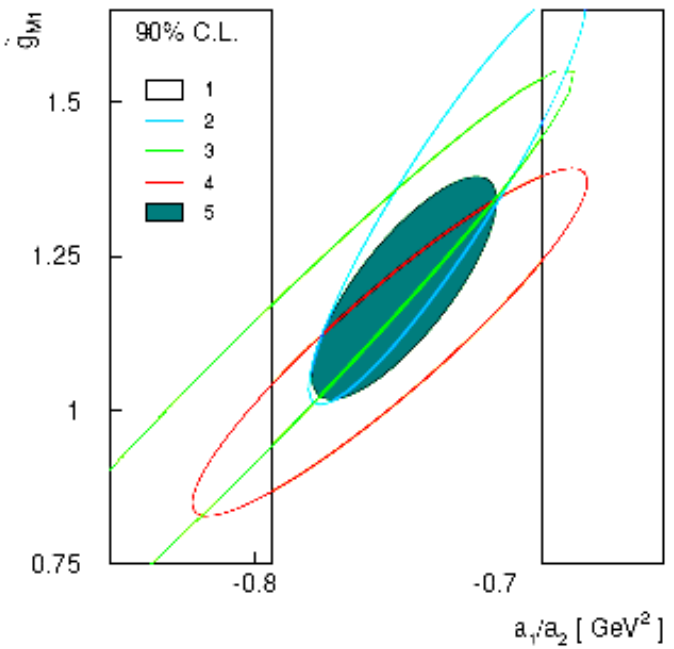
Decay rate for $E_\gamma > 20$ MeV:

$$\frac{DE}{DE + IB} = 0.689 \pm 0.021$$

CP violating E1 DE:

$$|g_{E1}| < 0.21 \; (90\% CL)$$

Figure: 90% contours for $\tilde{g}_{M1}$ vs a_1/a_2 for known experimental results:
1 - KTeV($\pi\pi\gamma$). PRL 86.761(2001)
2 - KTeV($\pi\pi ee$). PRL 84.408(2000)
3 - NA48($\pi\pi ee$). EPJ C30.33(2003)
4 - KTeV($\pi\pi ee$). PRL 96.101801(2006)
5 - KTeV($\pi\pi\gamma$). This Result, accepted to PRD

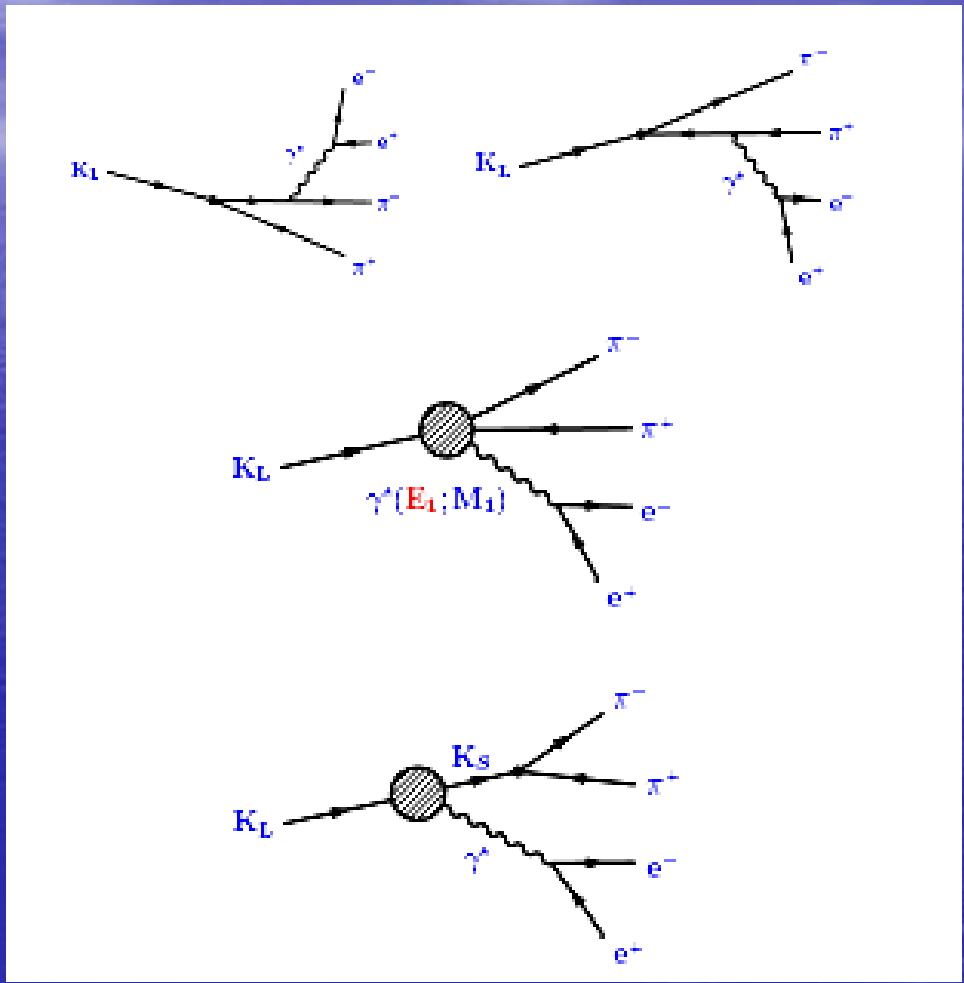


Can also use related decay $K_L \to \pi^+\pi^- e^+ e^-$

Has additional charge radius term

More sensitive to possible E1-term than $K_L \to \pi^+\pi^-\gamma$

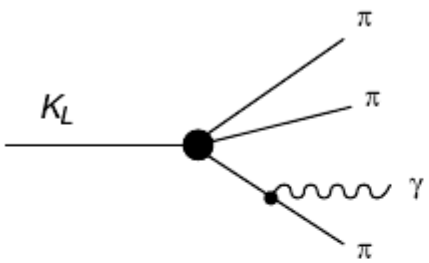
$|g_{E1}|/|g_{M1}| < 0.04$ (90% CL)



$K_L \to \pi^+\pi^-\pi^0\gamma$ and $K_L \to \pi^+\pi^-\pi^0 e^+e^-$

(Sasha Ledovskoy – University of Virginia)

internal bremsstrahlung

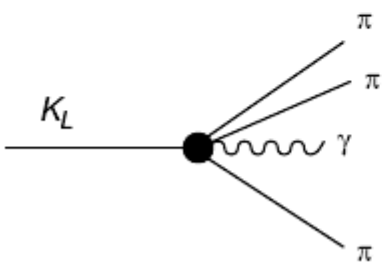


This decay is dominated by inner brem process

$$BR(E_\gamma > 10\,MeV) = (1.65 \pm 0.03) \times 10^{-4}$$

G. D'Ambrosio *et al*, Z. Phys. C **76**, 301 (1997)

direct emission



DE is estimated to be very small

$$BR\,|_{direct} = (8a_1 + a_2 - 10a_3)^2 \cdot 2 \cdot 10^{-10}$$

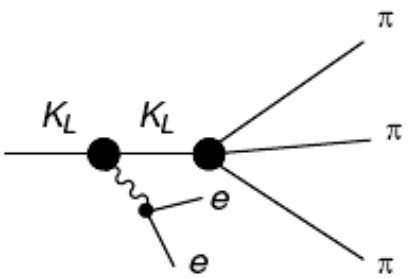
where $a_i = O(1)$ are unknown. G. Ecker *et al*, Nucl. Phys. B **413**, 321 (1994)

For $K_L \rightarrow \pi^+\pi^-\pi^0 e^+e^-$ there are no published theories

Inner Brem and DE

Same amplitude as in $K_L \rightarrow \pi^+\pi^-\pi^0\gamma$ with $\gamma^* \rightarrow e^+e^-$.

Charge radius

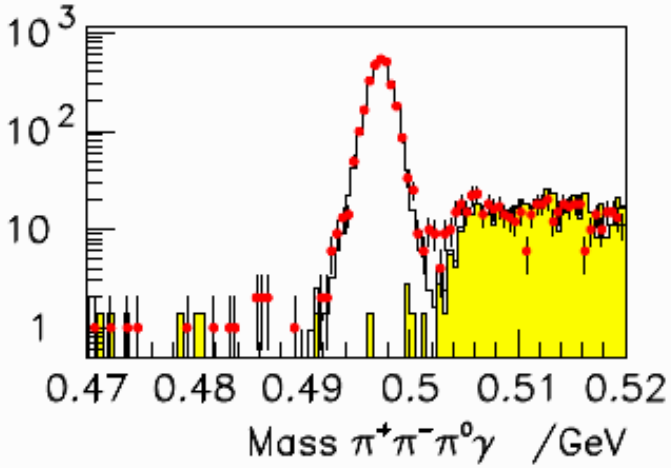


Similar to $K_L \rightarrow \pi^+\pi^-e^+e^-$.
Is it $K_L \rightarrow K_L\gamma^*$ or $K_L \rightarrow K_S\gamma^*$?

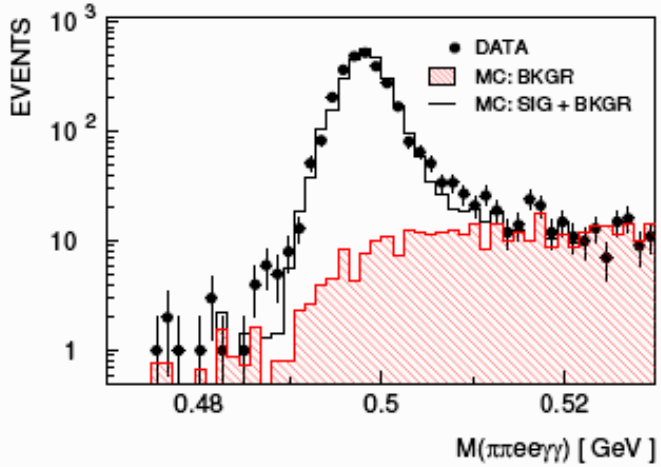
How one can measure IB, DE and CR amplitudes in $K_L \rightarrow \pi^+\pi^-\pi^0\gamma^{(*)}$ decays that have never been observed?

KTeV first observation of $K_L \to \pi^+\pi^-\pi^0\gamma$

E832: $\pi^0 \to \gamma\gamma$
2853 candidates



E799 (~40%): $\pi^0 \to e^+e^-\gamma$.
2847 candidates



KTeV Preliminary for $E_\gamma^{cm} > 10\ MeV$:

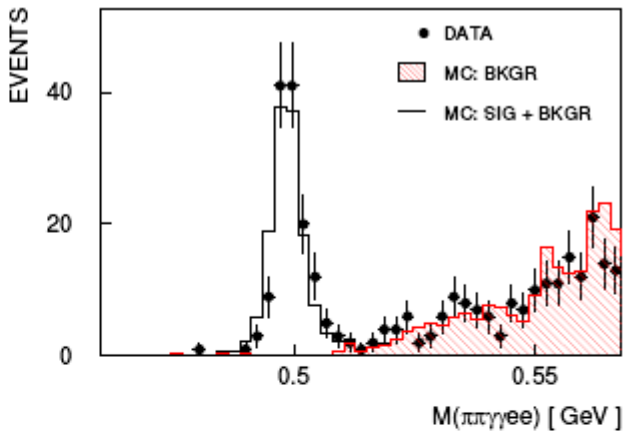
$$BR = (1.70 \pm 0.03_{stat} \pm 0.04_{syst} \pm 0.03_{norm}) \times 10^{-4}$$

Good agreement with SM calculations (ZP C76,301)

$$BR(K_L \to \pi^+\pi^-\pi^0\gamma, E_\gamma^{cm} > 10\ MeV) = (1.65 \pm 0.03) \times 10^{-4}$$

KTeV first observation of $K_L \to \pi^+\pi^-\pi^0 e^+e^-$

- E799 data,
- clean sample of 132 candidates
- estimated background level of 1.2 ± 0.9 evt
- Normalization mode is $K_L \to \pi^+\pi^-\pi^0_D$
- ~40% of KTeV data anayzed



KTeV Preliminary $E_{ee} > 20$ MeV:

$$BR = (1.60 \pm 0.18_{stat}) \times 10^{-7}$$

We will try to measure Direct Emission and Charge Radius amplitudes in near future.

$K_L \to e^+e^-\gamma$

(Mike Wilking – University of Colorado)

$K_L \to \mu^+\mu^-$ arises partly by a short distance coupling whose value yields a measurement of $|V_{td}|$

However it also has a long distance coupling related to $K_L \to \gamma^{(*)}\gamma^{(*)}$ which must be subtracted.

Two form factor models are usually considered.

2 parameter model of D'Ambrosio, Isidori and Portoles based on chiral perturbation theory.

Vector dominance inspired model of Bergstrom, Masso and Singer.

$$f_{BMS}(x) = \frac{1}{1 - x\frac{M_K^2}{M_\rho^2}} + \frac{C\ \alpha_{K^*}}{1 - x\frac{M_K^2}{M_{K^*}^2}} \left(\frac{4}{3} - \frac{1}{1 - x\frac{M_K^2}{M_\rho^2}} - \frac{1}{9}\frac{1}{1 - x\frac{M_K^2}{M_\omega^2}} - \frac{2}{9}\frac{1}{1 - x\frac{M_K^2}{M_\phi^2}} \right)$$

$x = (m_{ee}/m_K)2$

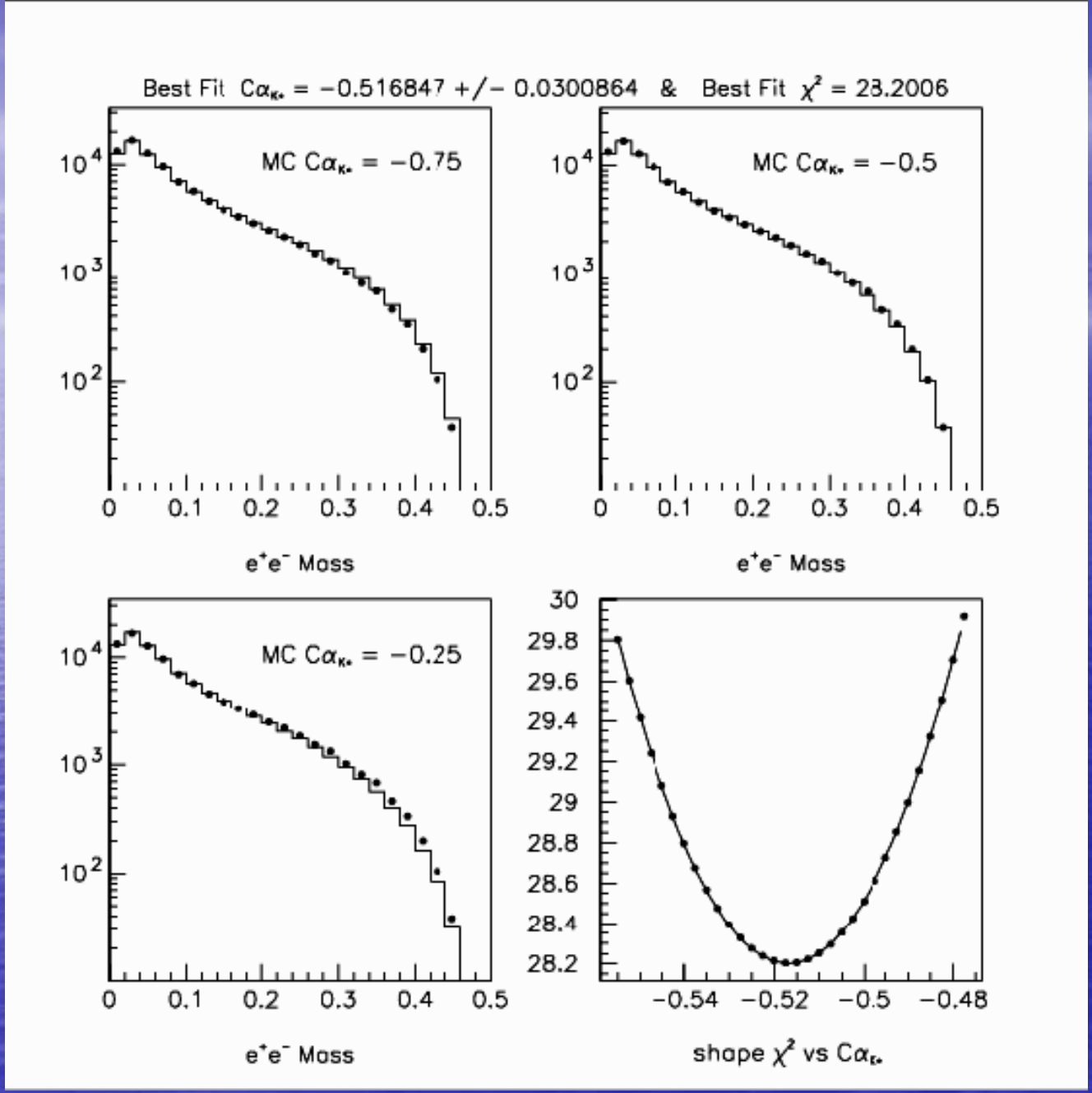
Experiments actually determine $C \cdot \alpha_K^*$ where C is:

$$C = (8\pi\alpha_{EM})^{1/2} G_{NL} f_K^* {}_{K\gamma} m_\rho^2 / (f_K^* f_\rho^2 A_{\gamma\gamma})$$

A number of experiments have reported values of α_K^* from various decay modes, but are inconsistent as to value of C as the parameters making up C have changed over time.

We report $C\alpha_K^*$ and compare it with $C\alpha_K^*$ from other experiments

Distribution of m_{ee} is quite sensitive to the form factor.

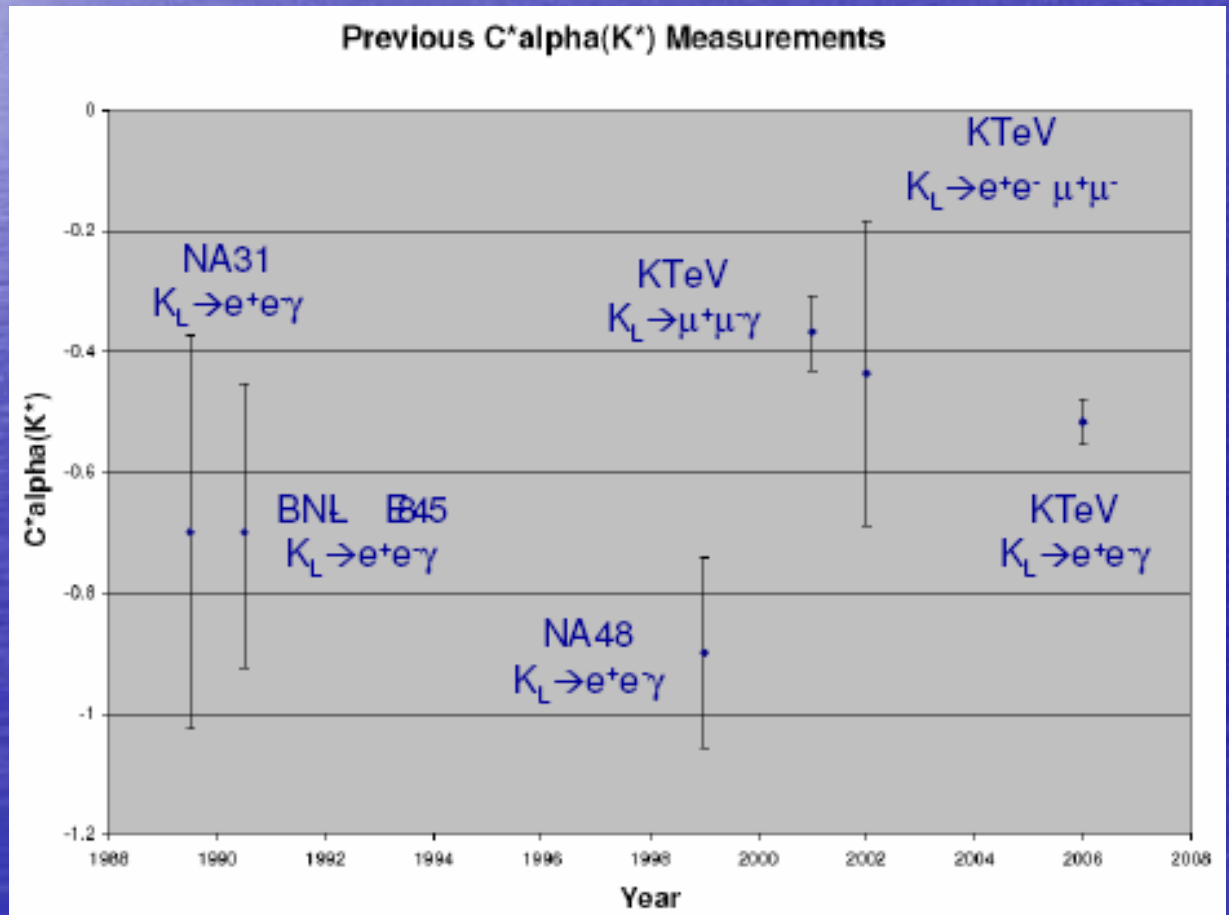

Best Fit $C\alpha_{K^*}$ = −0.516847 +/− 0.0300864 & Best Fit χ^2 = 23.2006
MC $C\alpha_{K^*}$ = −0.75
MC $C\alpha_{K^*}$ = −0.5
MC $C\alpha_{K^*}$ = −0.25
e^+e^- Mass
shape χ^2 vs $C\alpha_{K^*}$

Corrected preliminary KTeV $K_L \to e^+e^-\gamma$ Results

BR: (9.25 E0.03(stat) E 0.07(syst) E 0.26(ext syst)) x10^{-6}

$C\alpha_K^*$: -0.517 E 0.030(fit) E 0.022(syst)

α_{DIP} : -1.729 E 0.043(fit) E 0.028(syst)



$K_L \to \pi^+ e^- \nu e^+ e^-$ (commonly called Ke3ee)

(Katsushige Kotera – Osaka University)

Because of missing ν, backgrounds are harder to control.

Worst backgrounds are:

$K_L \to \pi^+ \pi^- \pi^o$ ($\pi^0 \to e^+ e^- \gamma$ or $e^+ e^- e^+ e^-$)

$K_L \to \pi^+ e^- \nu \pi^0$ ($\pi^0 \to e^+ e^- \gamma$)

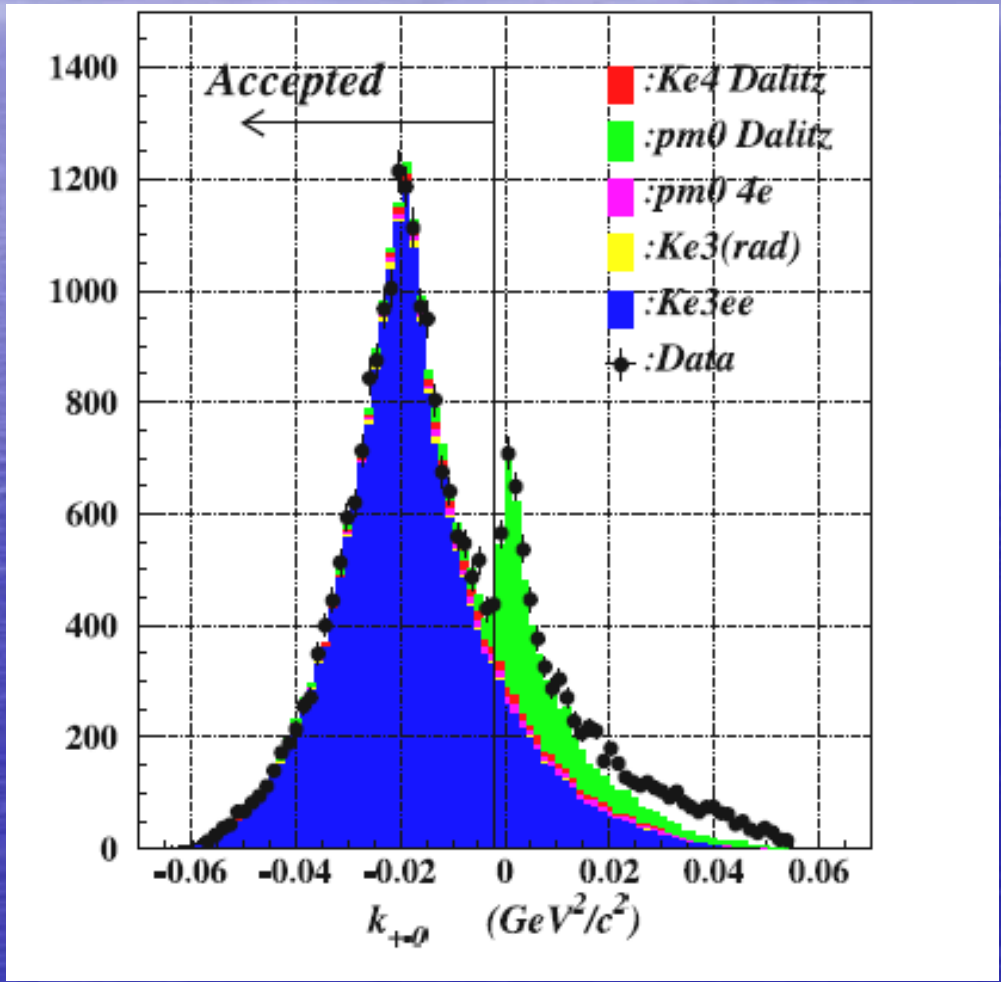
$K_L \to \pi^+ e^- \nu \gamma$ (γ converts in material)

Use full π/e ID power of CsI calorimeter and the TRD's

k_{+-0} is 4 momentum squared a π^0 from a Dalitz decay would have

Calculated assuming identified e from Ke3 is actually a π

signal is mostly < 0 $\pi^+\pi^-\pi^0(\pi^0 \rightarrow e^+e^-\gamma)$ background >0



Final sample 19466 candidates with background of ~5%

(this is based on about 25% of all E799 data)

Preliminary results:

$BR[K_L \rightarrow \pi^+ e^- \nu e^+ e^-;\ m_{e^+e^-} > 0.005\ GeV/c^2,\ E_{e^+e^-} > 0.03\ GeV]$

$= [1.281 \pm 0.010(stat) \pm 0.019(syst) \pm 0.035(ext\ syst)] \times 10^{-5}$

K.Tsuji (paper in preparation) has calculated in χPT the ratio:

$$R = \Gamma(Ke3ee,\ m_{ee} > 0.005\ GeV/c^2) / \Gamma(Ke3)$$

$R = 4.06 \times 10^{-5}$ at leading order

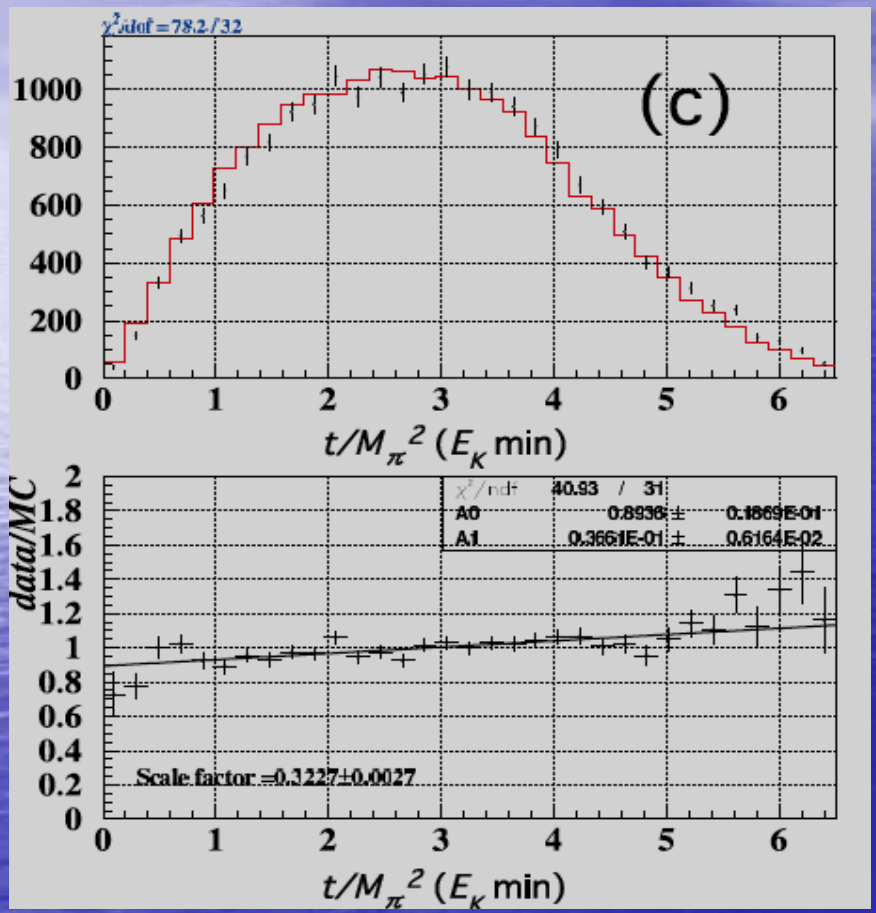
$R = 4.29 \times 10^{-5}$ at next to leading order (p^4)

Measured BR corresponds to $R = (4.54 \pm 0.15) \times 10^{-5}$

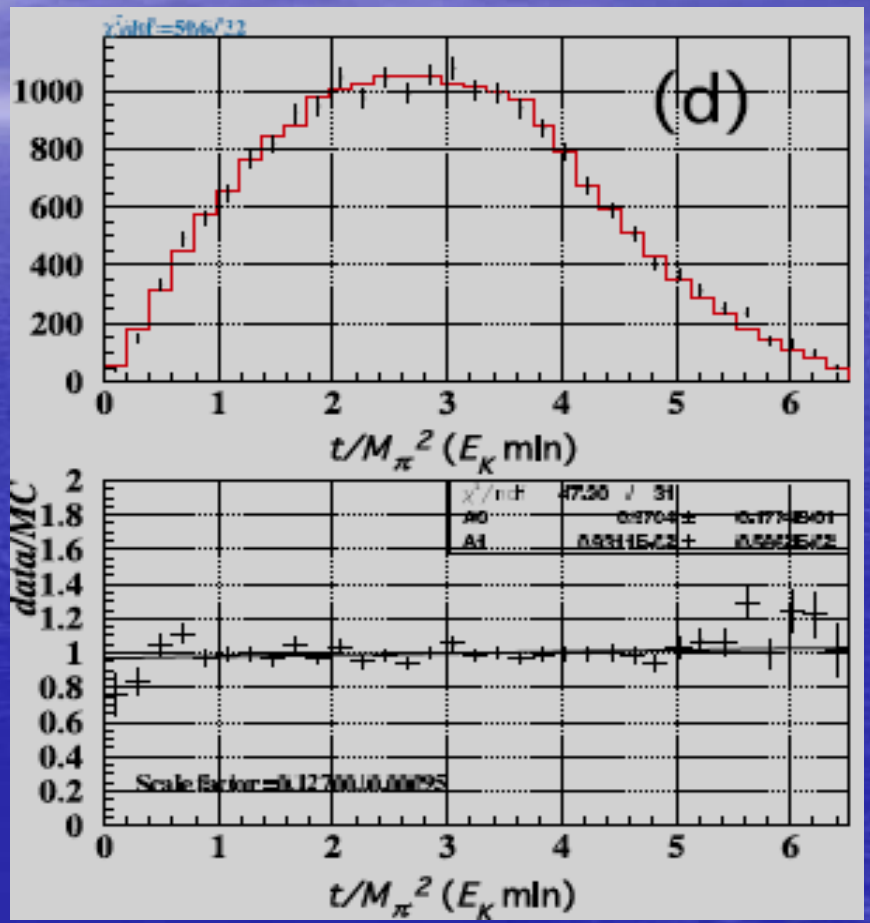
3.2σ from LO and 1.7σ from NLO

Chiral Perturbation Theory for $K_L \to \pi e \nu ee$

Leading order



Next to leading order



Summary of Recent KTeV Radiative Decays

$K_L \to \pi^+\pi^-\gamma^{(*)}$ Sensitive probe of CP, T-violation, SM still safe!

$K_L \to \pi^+\pi^-\pi^0\gamma^{(*)}$: New System observed, motivates Theory.

$K_L \to e^+e^-\gamma$: Form-factor characterized. Important engineering.

$K_L \to \pi^+e^-\nu e^+e^-$: Form factor well modelled. Hints of beyond Leading Order Chiral Perturbation effects.