Rare Radiative Kaon Decay Results from KTeV

Arizona, UCLA, UCSD, Campinas, Chicago,
Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers,
Sao Paolo, Virginia, Wisconsin

Beach 2006

Lancaster University

Hogan Nguyen

Fermilab

Even though the K_L is charge neutral, it can couple directly to photons due to its non-point-like internal structure.

The following KTeV results probe the K_L and π^0 internal structure

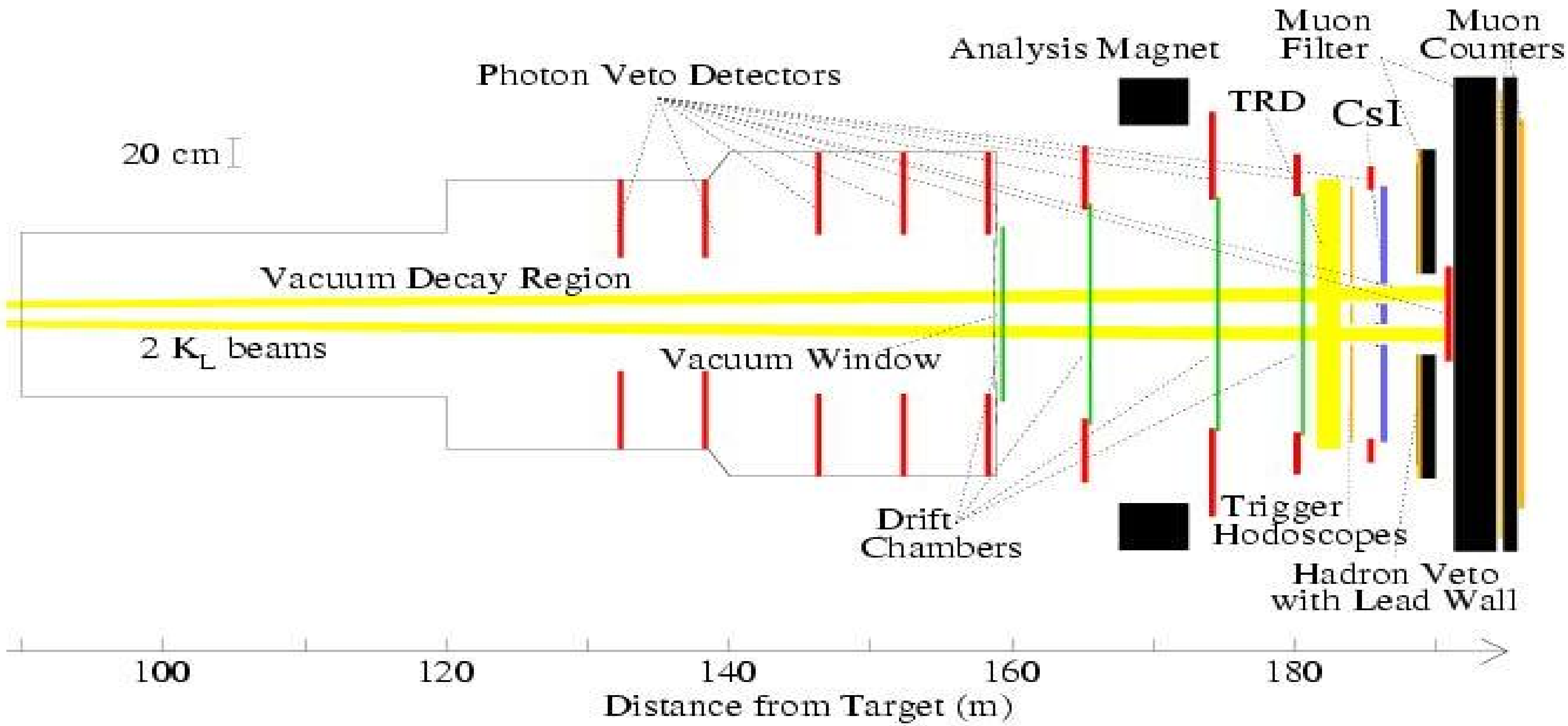
$K_L \to \pi^+\pi^-\gamma$

$K_L \to \pi^0\pi^0\gamma$

$K_L \to \pi^{\pm}e^{\mp}\nu\gamma^*$ $\quad \gamma^* \to ee$

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

$\pi^0 \to e^+e^-$



Large acceptance for nearly all neutral kaon decays

Spectrometer: $\delta(P)/P = 0.38\% + 0.16\% P(\mathrm{GeV})$

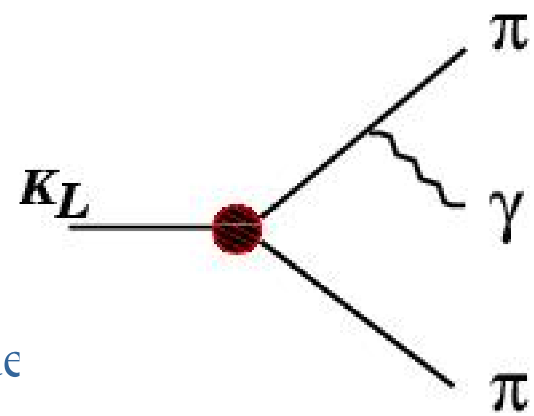
CsI calorimeter: $\delta(E)/E = 0.45\% + 2\%/\sqrt{E}$ (GeV)

Transition Radiation Detector for additional particle-ID resolving power

Ran in 1997 and 1999 at Fermilab, with an exposure of $\sim 10^{12}$ K_L decays in the fiducial volume

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

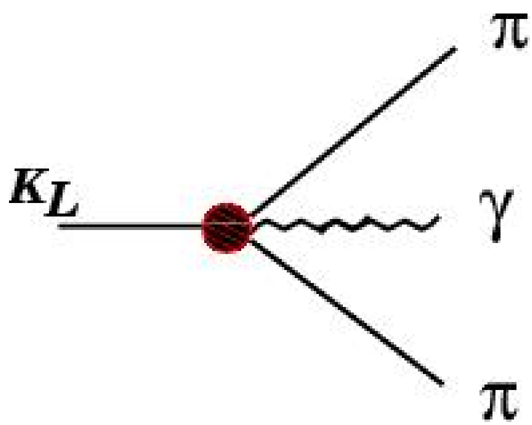
This decay proceeds in two competing processes:



Inner Brems (IB) –*CP violating*, E1 photon

Direct Emission (DE) –*CP conserving* but suppressed due to M1 photon emission.

DE could have an E1 photon, which would be *CP violating*.



E1 photon: $J_\gamma = 1$, $P = -1$

M1 photon: $J_\gamma = 1$, $P = +1$

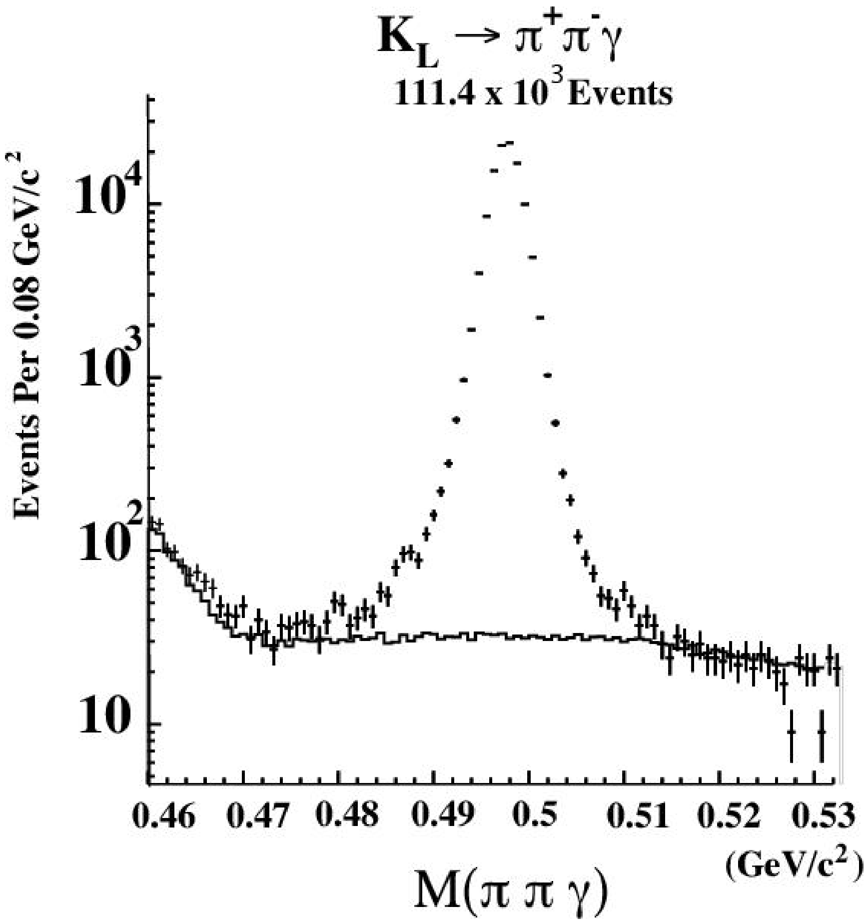
E1 photons from IB or DE can quantum mechanically interfere

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

This result uses the full KTeV data set.

Primary backgrounds are $K_{\mu3}$ and K_{e3} with accidental photons.

These and other backgrounds well under control.



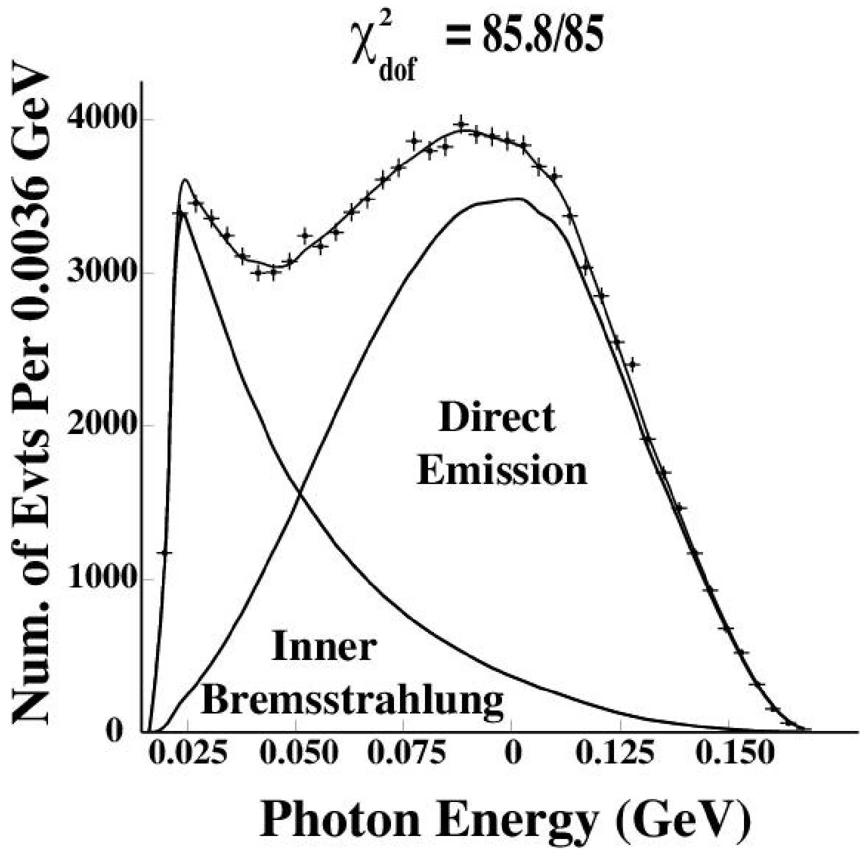
$K_L \rightarrow \pi^+ \pi^- \gamma$

IB process has a softer photon and is suppressed due to CP violation

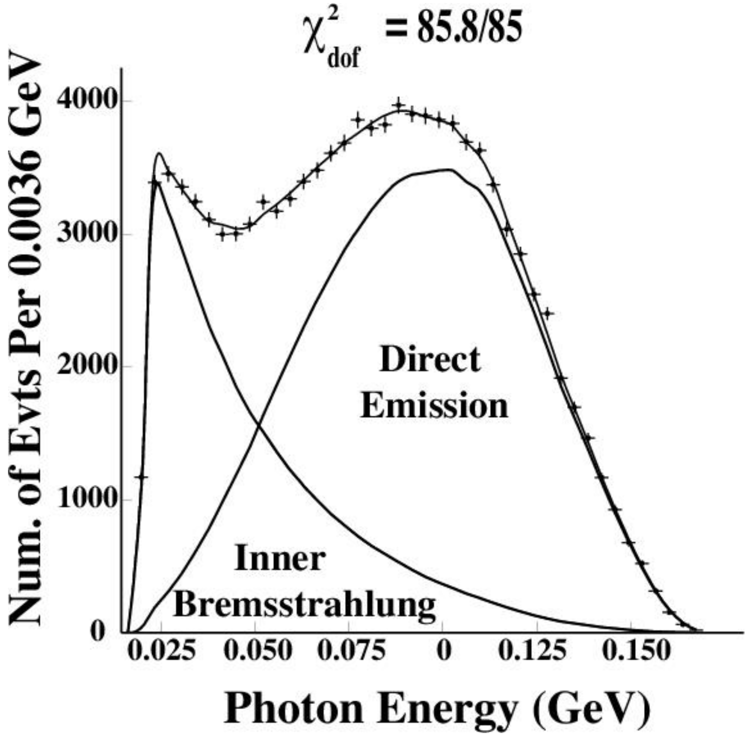
DE process has a harder photon, is CP conserving, but is suppressed due to the M1 photon emission.

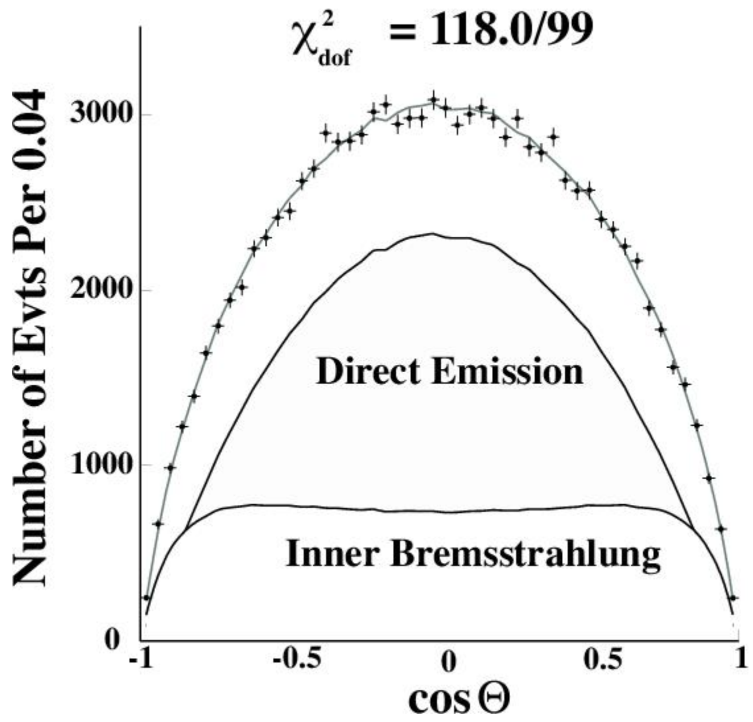
As a result of this competition, the two processes contribute about equally!

DE/(DE+IB)=0.689 ±0.021



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





A maximum likelihood fit is done to the E_γ and cosθ distributions.

θ is the angle between the γ and the π^+ in the ππ CM.

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

Amplitudes from Chiral PT:

$$|M1_{DE}| = |g_{M1}|\,\left(1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_\gamma}\right)e^{i\delta_1}$$

$$E1_{DE} = |g_{E1}|\,e^{i\delta_1}$$

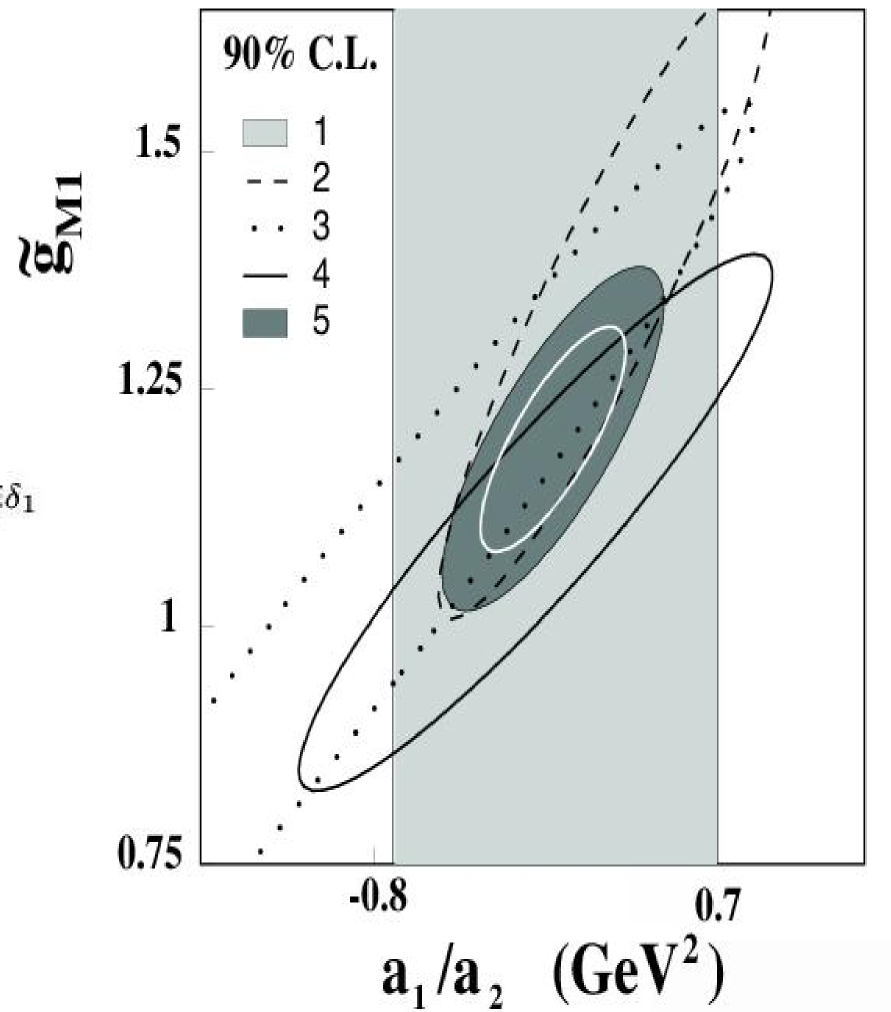
We fit for g_{M1}, a_1/a_2 and g_{E1}.

We do not see evidence for g_{E1}

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

$g_{M1} = 1.198 \pm 0.035 \pm 0.086$

$a_1/a_2 = -0.738 \pm 0.007 \pm 0.018$ (GeV/c^2)



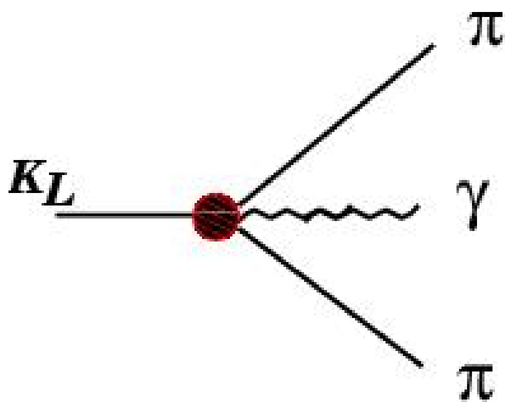
5 is this result (90%CL)

2,3,4 from ππee

$K_L \to \pi^0\pi^0\gamma$

Neutral analog of $K_L \to \pi^+\pi^-\gamma$, so no Inner Brems.

Never observed, we have a preliminary result giving the best limit.



Because the two πs are identical bosons they have L=2. Thus only higher multipoles contribute:

M2—CP violating

E2—CP conserving

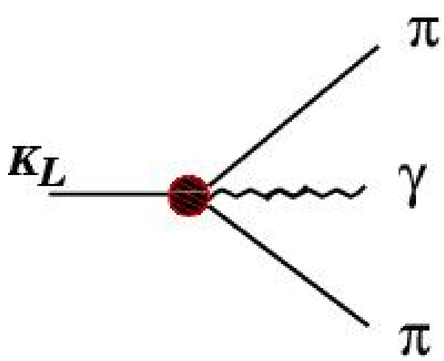
$K_L \to \pi^0 \pi^0 \gamma$

This decay amplitude vanishes to O(p4) ChPT, so this decay probes O(p6) ChPT.

Estimates on the BR include:

from $K_L \to \pi^+\pi^-\gamma$, ~ 1×10^{-8}

from ChPT, ~ 7×10^{-11}



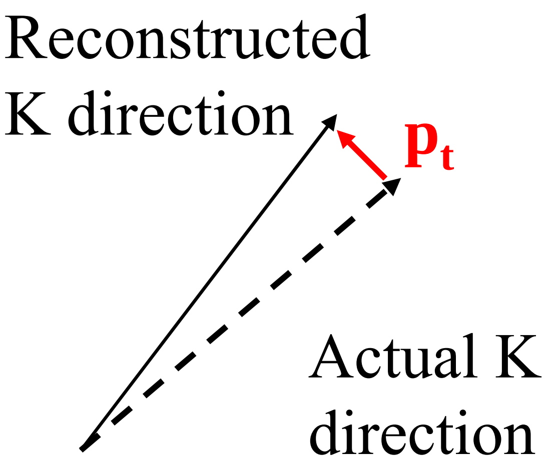
Current best upper limit is 5.6×10^{-6} from NA31

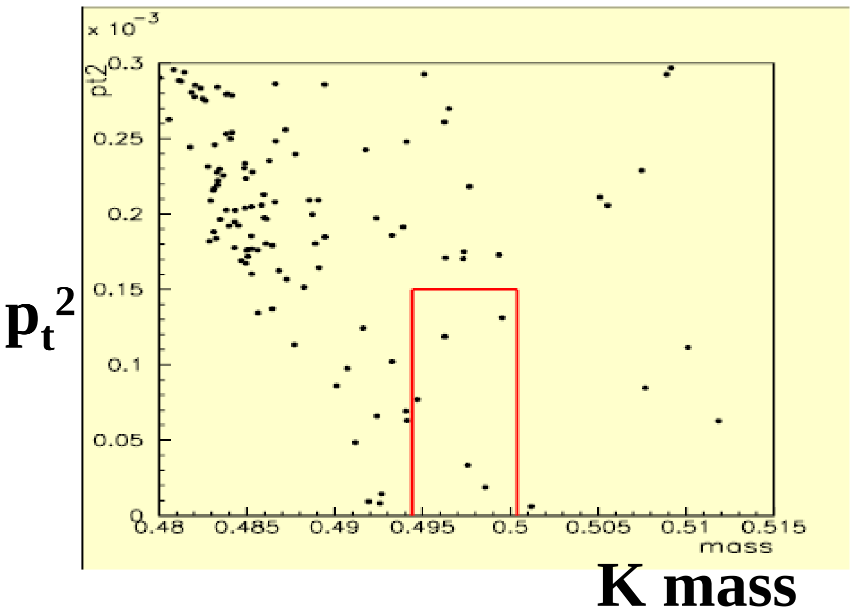
KTeV search required one π^0 Dalitz decay, $\pi^0 \to ee\gamma$

Dominant background is $K_L \to \pi^0\pi^0\,\pi^0_D$

$K_L \to \pi^0 \pi^0 \gamma$

Define a signal box in K mass vs p_t^2. For a well-reconstructed K, p_t is close to 0.





P_t^2 vs K mass for $K \to \pi^0 \pi^0 \pi^0{}_D$ background Monte Carlo (4.88 times data flux).

$K_L \to \pi^0\pi^0\gamma$

Expected background is

1.7 ±0.6 events.

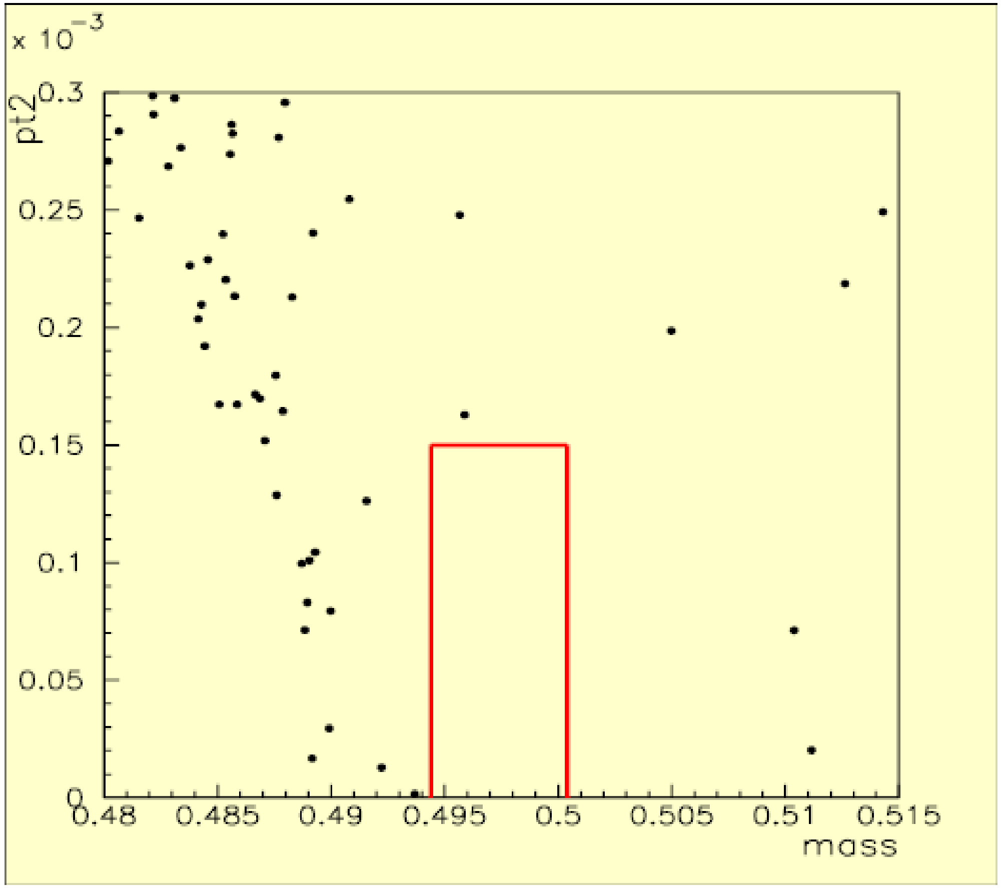
The signal box is empty, giving a preliminary limit

$BR(K_L \to \pi^0\pi^0\gamma) < 2.5 \times 10^{-7}$

Based on 40% of the data.

Full dataset under analysis.

p_t^2



K mass

$K_L \to \pi^{\pm} e^{\mp} \nu \gamma^{*}$ $\gamma^{*} \to ee$

Semileptonic decays controlled by V_{us}

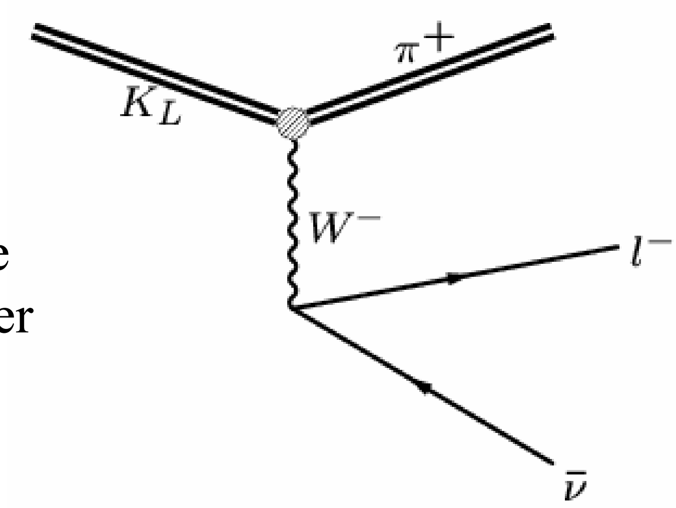
Uncertainties remain in the form factors

Direct Emission $K_L \to \pi^{\pm} e^{\mp} \nu \gamma$ is sensitive to the form factor, but the decay is dominated by Inner Brems

If the photon is virtual, DE has a larger contribution

We have a preliminary measurement of the BR for

$K_L \to \pi^{\pm} e^{\mp} \nu \gamma^{*}$ with $\gamma^{*} \to ee$



$K_L \to \pi^{\pm} e^{\mp} \nu \gamma^{*}$ $\gamma^{*} \to ee$

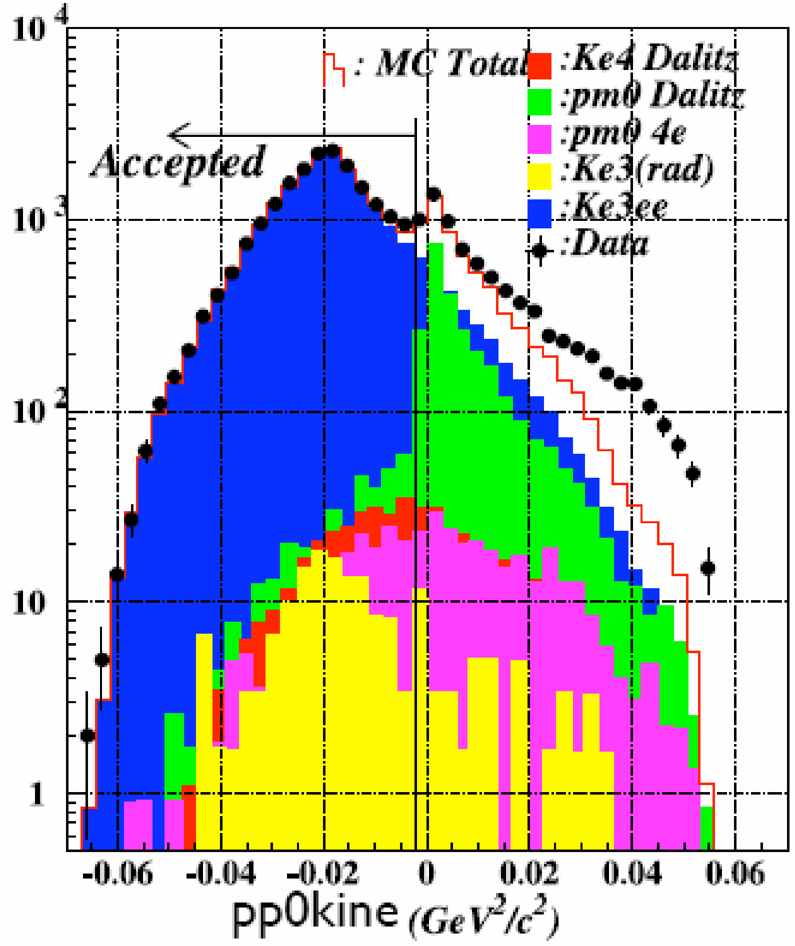
Dominant background is $K_L \to \pi^+\pi^-\pi^0_D$ with one lost photon and π/e misID

To control this background, assume the charged tracks are are πs and calculate the square of the longitudinal momentum of the π^0 in a frame where $p_K \perp p_{\pi\pi}$

For $K_L \to \pi^+\pi^-\pi^0$ decays, this quantity is positive.

For the signal, this quantity can have an unphysical negative value.

A cut on this quantity eliminates most of the background.



$K_L \to \pi^{\pm} e^{\mp} \nu \gamma^{*} \;\; \gamma^{*} \to ee$

19466 signal event candidates observed with a background of about 5%.

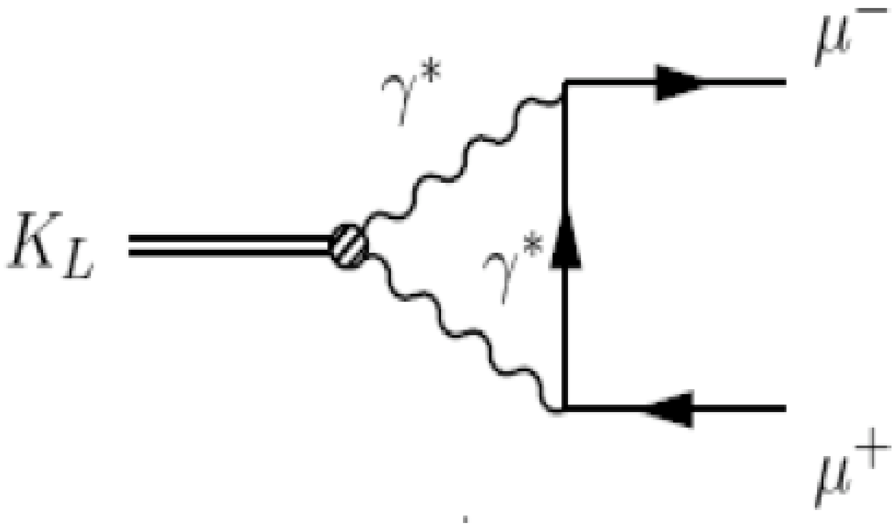
Normalization mode is $K_L \to \pi^+ \pi^- \pi^0_D$

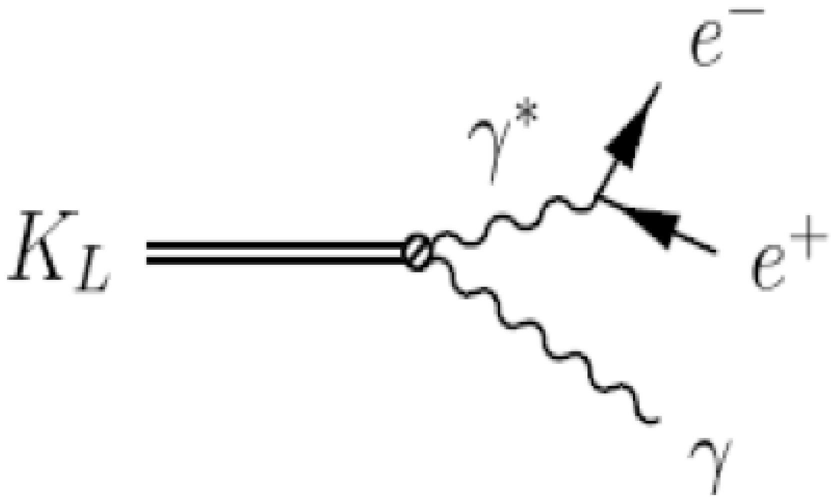
Preliminary BR($K_L \to \pi^{\pm} e^{\mp} \nu ee$, $M_{ee} > 5$ MeV/c^2) =

$[1.606 \pm 0.012 \mathit{(stat)}\ ^{+0.026}_{-0.016}\ \mathit{(sys)} \pm 0.045\ \mathit{(ext\ sys)}\ ] \times 10^{-5}$

First observation of this mode.

$K_L \to ee\gamma$ Form Factor Measurement





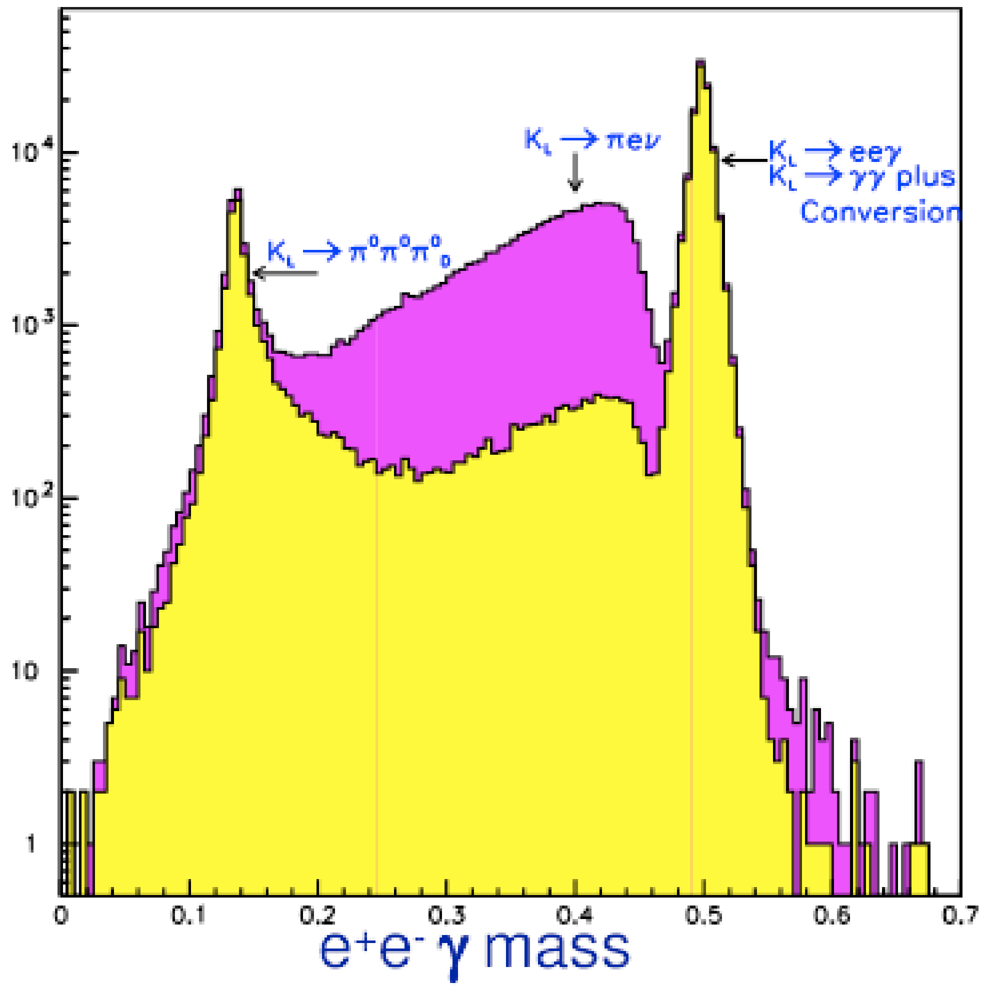
$K_L \to \mu\mu$ has both short and long distance contributions.

The long distance contribution is controlled by $K_L \to \gamma^*\gamma^*$, which must be subtracted from $K_L \to \mu\mu$ in order to extract the interesting CKM parameters (eg. V_{td})

The $K_L \to ee\gamma$ form factor tells us something about $K_L \to \gamma^*\gamma^*$

Main background is $K_L \to \pi e\nu$
With an accidental γ
And a π misidentified as an e

Greatly reduced by using the transition Radiation Detector for e/π separation.



M_{ee} distribution is sensitive to the form-factor.

We fit M_{ee} to two different form-factor models:

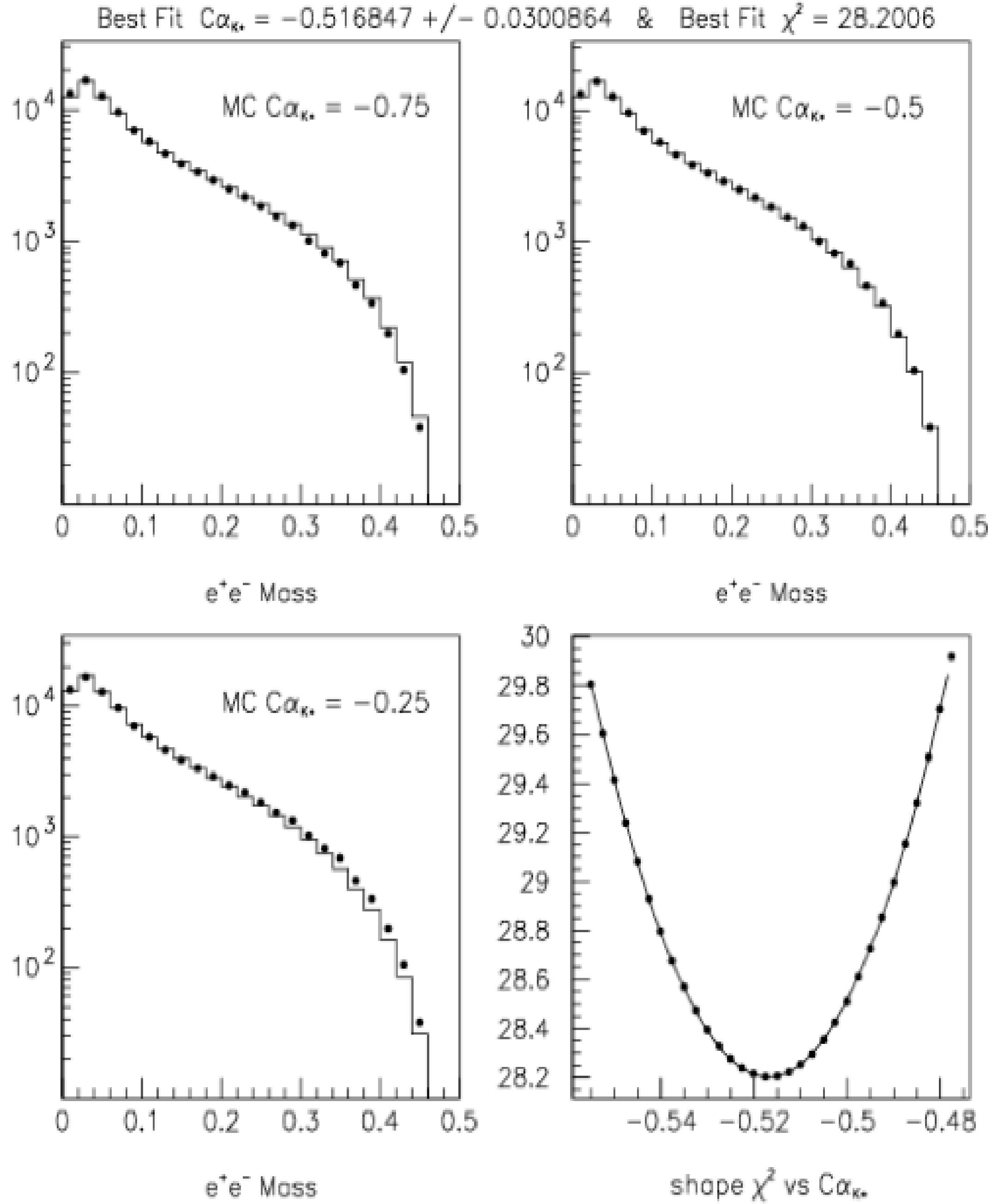
(1) D'Ambrosio, Isidori, Portoles

α_{DIP}

(2) Bergstrom, Masso, Singer

$C\alpha_{K*}$

We fit for $C\alpha_{K*}$ instead of α_{K*} to avoid possible confusion on the value of C (see backup slide).

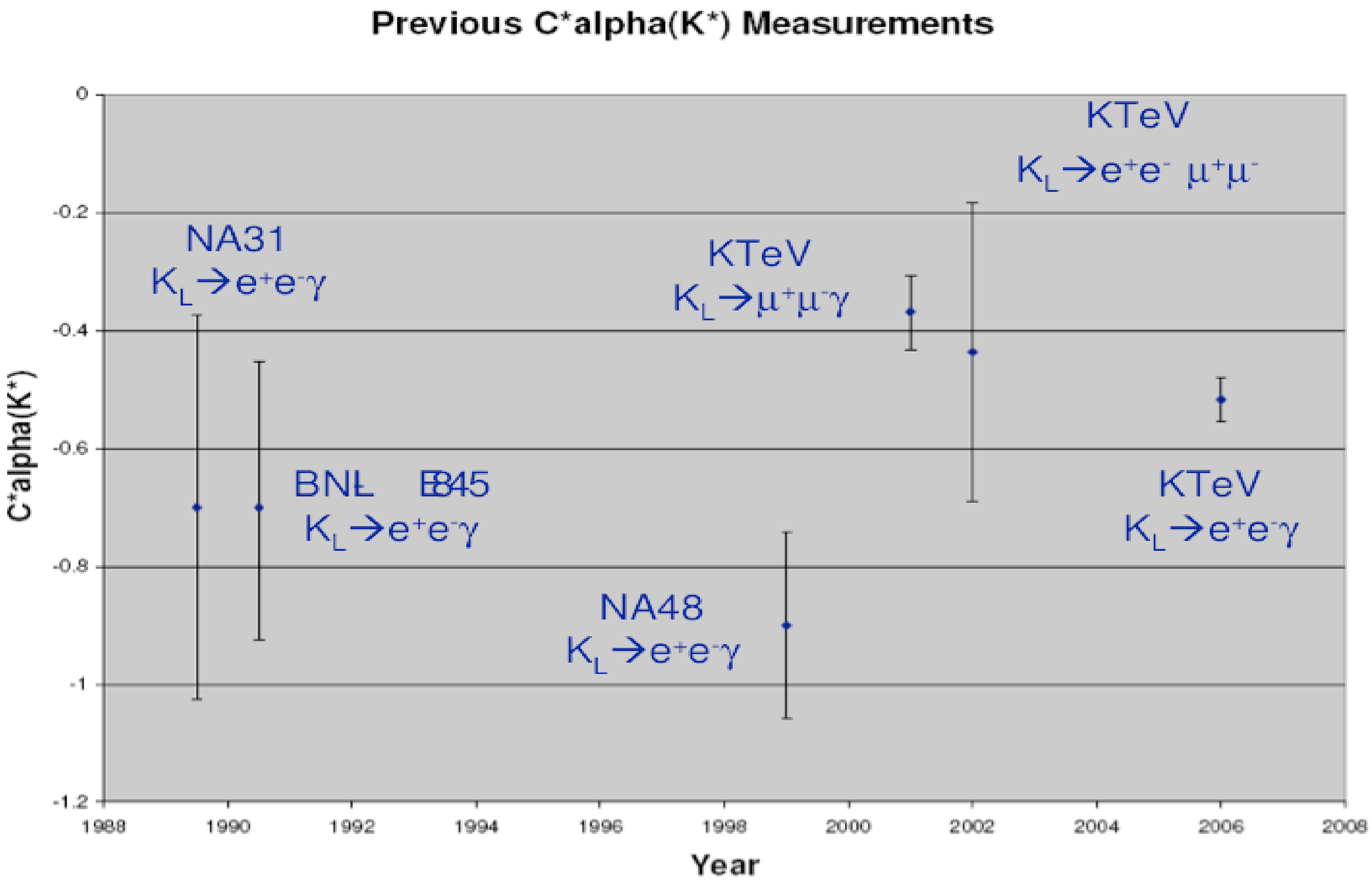


Fit Results

$$BR(K_L \to ee\gamma) \times 10^6 = 9.25 \pm 0.03_{stat} \pm 0.07_{sys} \pm 0.23_{\text{external sys}}$$

$$C\alpha_{K*} = -0.517 \pm 0.030_{fit} \pm 0.022_{sys} \qquad \text{(BMS model)}$$

$$\alpha_{DIP} = -1.729 \pm 0.043_{fit} \pm 0.028_{sys} \qquad \text{(DIP model)}$$

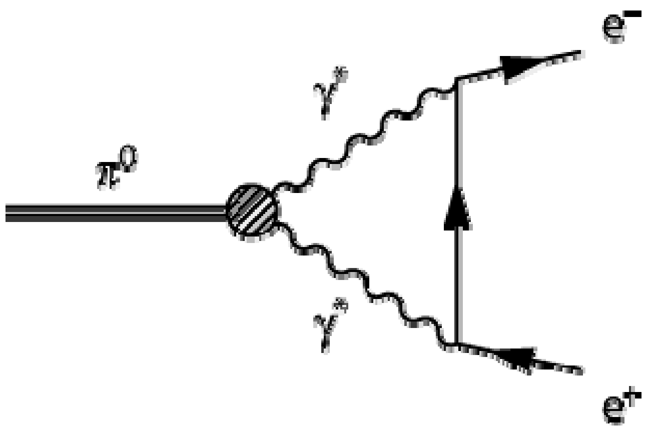


$K \to \pi^0 \pi^0 \pi^0$, $\pi^0 \to ee$

Drell calculated the contribution from on-shell photons in 1959. That contribution is the "unitary bound", or lower limit:

$\Gamma(\pi^0 \to ee)/\Gamma(\pi^0 \to \gamma\gamma) > 4.75 \times 10^{-8}$

Here we present a result from the full KTeV dataset.



$K \rightarrow \pi^0 \pi^0 \pi^0 \quad \pi^0 \rightarrow ee$

714 events in the signal region

expected background of
39.9 ±12.3 events.

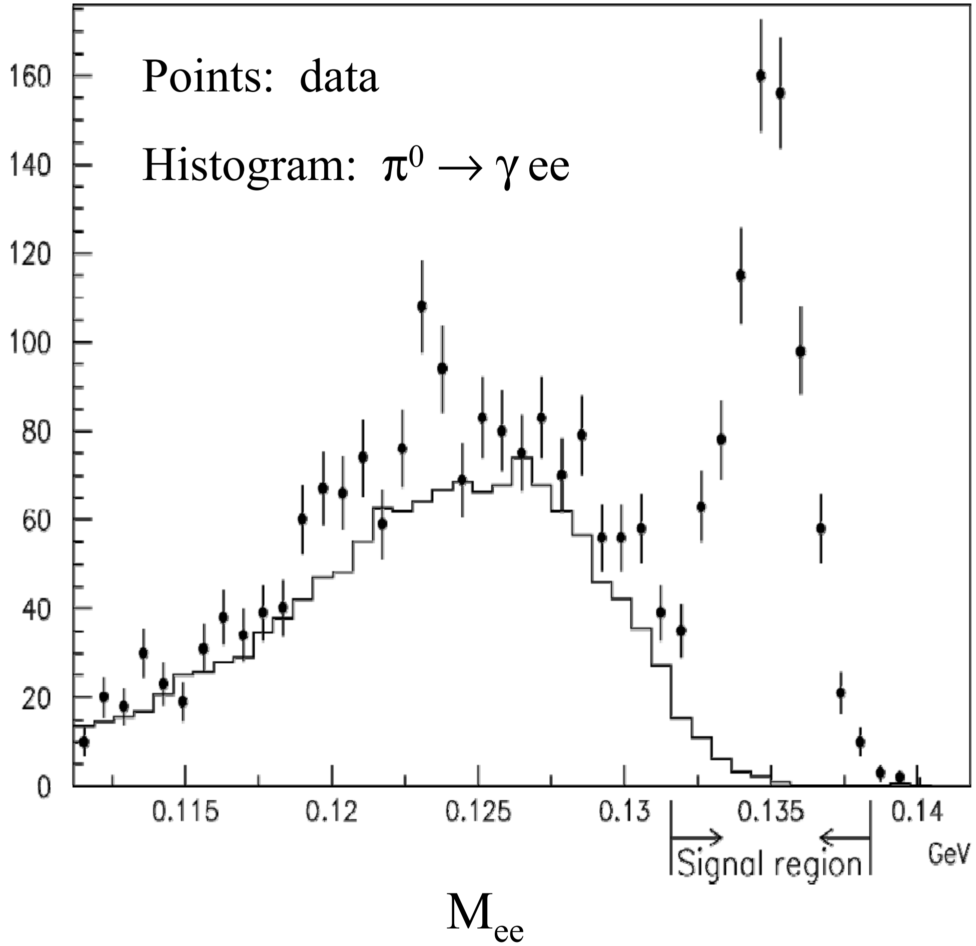
Preliminary

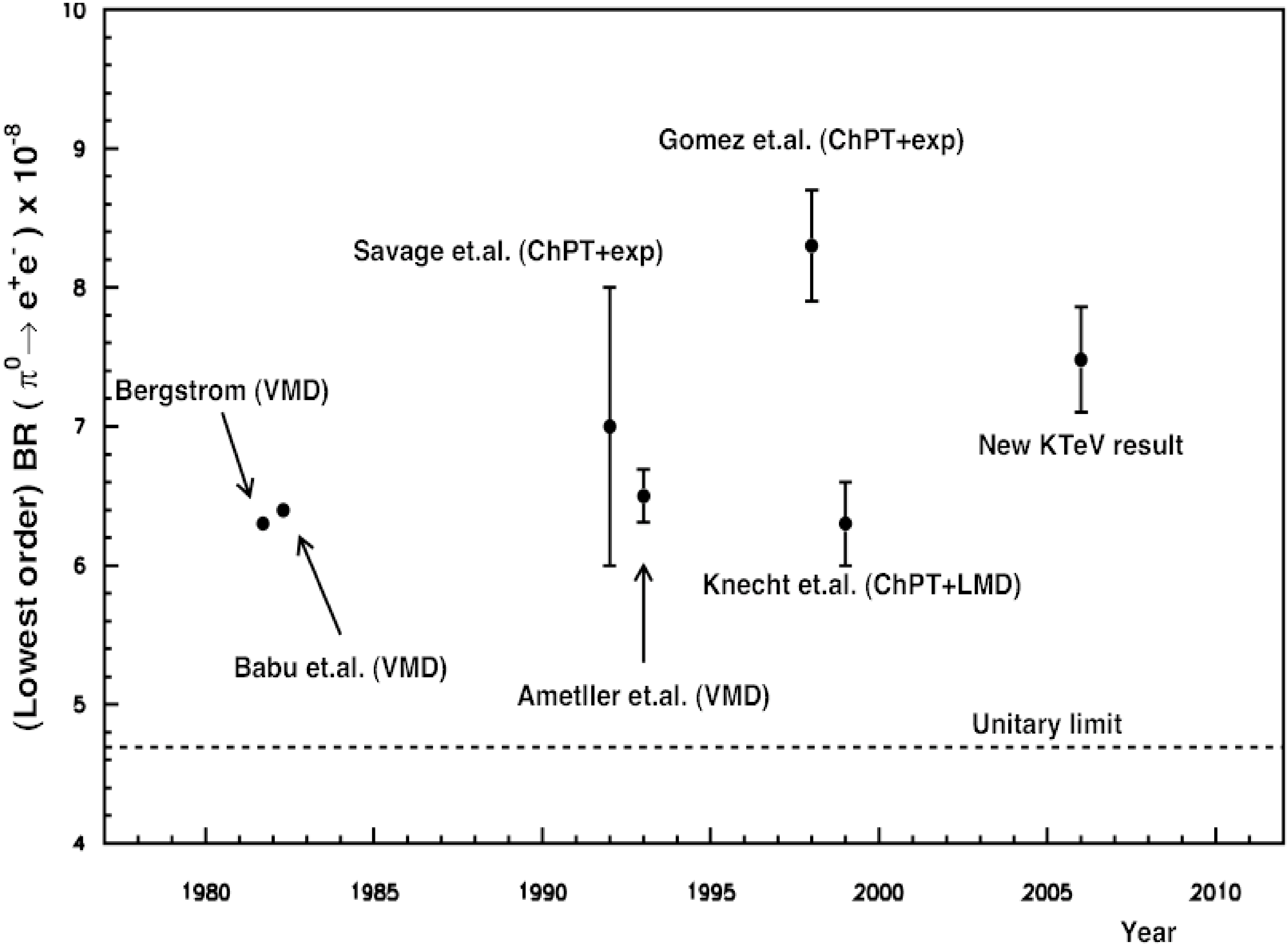
$BR(\pi^0 \rightarrow ee, (M_{ee}/M_\pi)^2 > 0.95) =$

$6.56 \pm 0.026 \pm 0.023 \times 10^{-8}$

Corrected to tree level, this result is 7σ above the unitarity limit.

Result falls between VMD and ChPT expectations.




(Lowest order) BR ($\pi^0 \rightarrow e^+e^-$) x 10^{-8}
10
9
8
7
6
5
4
1980
1985
1990
1995
2000
2005
2010
Year
Gomez et.al. (ChPT+exp)
Savage et.al. (ChPT+exp)
Bergstrom (VMD)
New KTeV result
Babu et.al. (VMD)
Knecht et.al. (ChPT+LMD)
Ametller et.al. (VMD)
Unitary limit

Summary

Large data sets and superb detectors allow precision measurements of many K decay modes.

Preliminary BR and form factor measurements

$K_L \to \pi^+\pi^-\gamma$ (result submitted to PRL in March 06)

$K_L \to \pi^0\pi^0\gamma$

$K_L \to \pi^\pm e^\mp \nu \gamma^*$

$K_L \to ee\gamma$ Form Factor Measurement

$\pi^0 \to e^+e^-$

$K_L\gamma^*\gamma$ Form Factor

- Two form factor models were considered
  - D'Ambrosio, Isidori, and Portoles (DIP) for which α_{DIP} is extracted
  - Bergstrom, Masso, and Singer (BMS) for which α_{K^*} is extracted
- Previous fits for α_{DIP} have been straightforward, but there has been some confusion in measuring α_{K^*}
- The parameter α_{K^*} is proportional to a physical constant labeled C in the BMS formula

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

- $C = (8\pi\alpha_{EM})^{1/2} G_{NL} f_{K^*K\gamma} m^2_{\rho} / (f_{K^*} f^2_{\rho} A_{\gamma\gamma})$
- It is not clear that the appropriate values for C were used in the past, and the value of C changes as the input parameters change
- To avoid this difficulty, in this analysis, we fit for $C\alpha_{K^*}$