

# Recent Results from KTeV

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## Outline

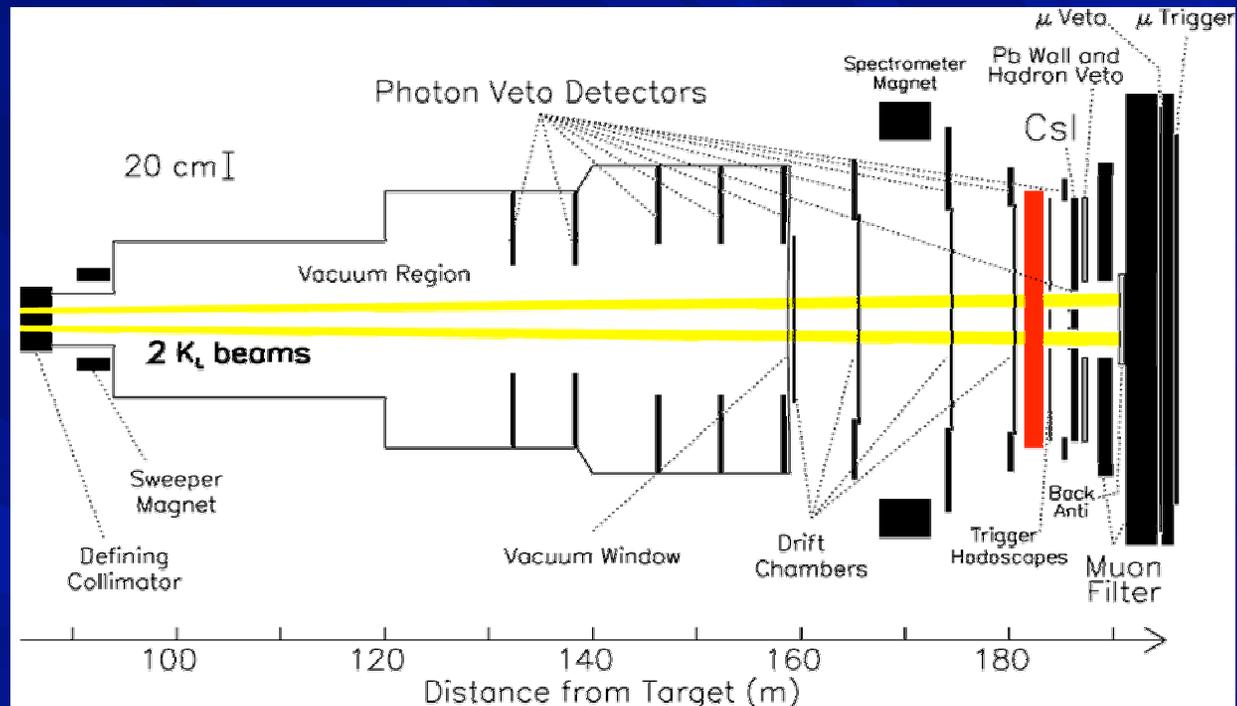
- The KTeV experiment
- $K_L \rightarrow \pi^+ \pi^- \gamma$
- $K_L \rightarrow \pi^0 \pi^0 \gamma$
- $K_L \rightarrow \pi^\pm e^\mp \nu e^+ e^-$
- $\pi^0 \rightarrow e^+ e^-$
- $K_L \rightarrow e^+ e^- \gamma$

# KTeV Institutions

University of Arizona  
University of California at Los Angeles  
Universidade Estadual de Campinas  
University of Chicago  
University of Colorado  
Elmhurst College  
Fermilab  
Osaka University  
Rice University  
Universidade de Sao Paulo  
University of Virginia  
University of Wisconsin

# The KTeV Detector

- The KTeV detector was used by two Fermilab experiments
  - E799: rare decays
  - E832:  $\text{Re}(\epsilon'/\epsilon)$
- Two beams of neutral kaons
- 60m vacuum decay region

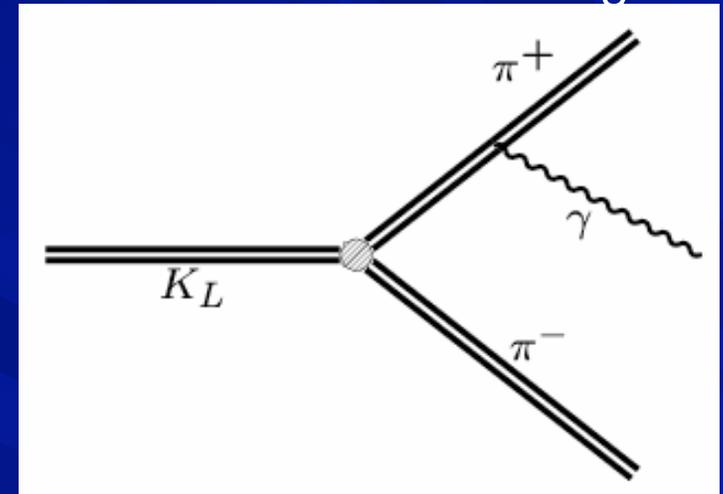


- A momentum spectrometer consisting of 4 drift chambers and an analysis magnet:  $\sigma(P)/P = 0.38\% (+) 0.016\% * P(\text{GeV}/c)$
- A transition radiation detector (TRD) for  $e/\pi$  separation (E799 only)
- 3100 crystal CsI calorimeter:  $\sigma(E)/E = 0.45\% (+) 2\%/\sqrt{E(\text{GeV})}$
- A muon filter consisting of alternating layers of steel and scintillator

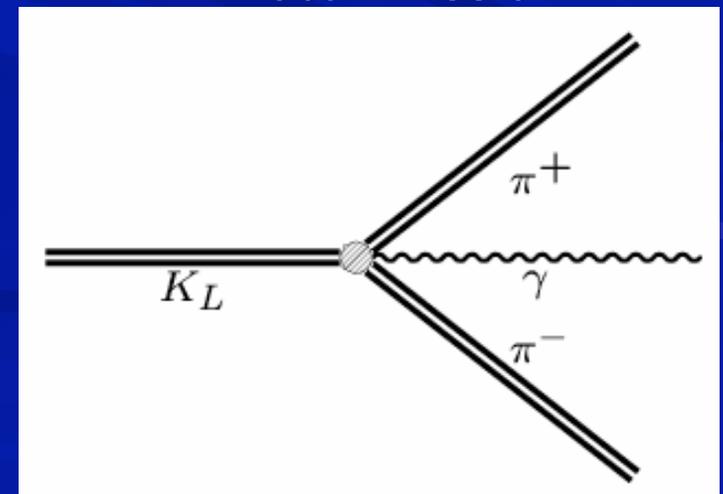
# The Decay $K_L \rightarrow \pi^+ \pi^- \gamma$

- composed of 2 processes
  - Inner Bremsstrahlung from CP violating decay  $K_L \rightarrow \pi^+ \pi^-$
  - Direct emission from the  $K_L \pi^+ \pi^-$  vertex
    - CP conserving M1 term (dominant)
    - CP violating E1 term (suppressed)
  - Interference between IB and E1 type DE

Inner Bremsstrahlung

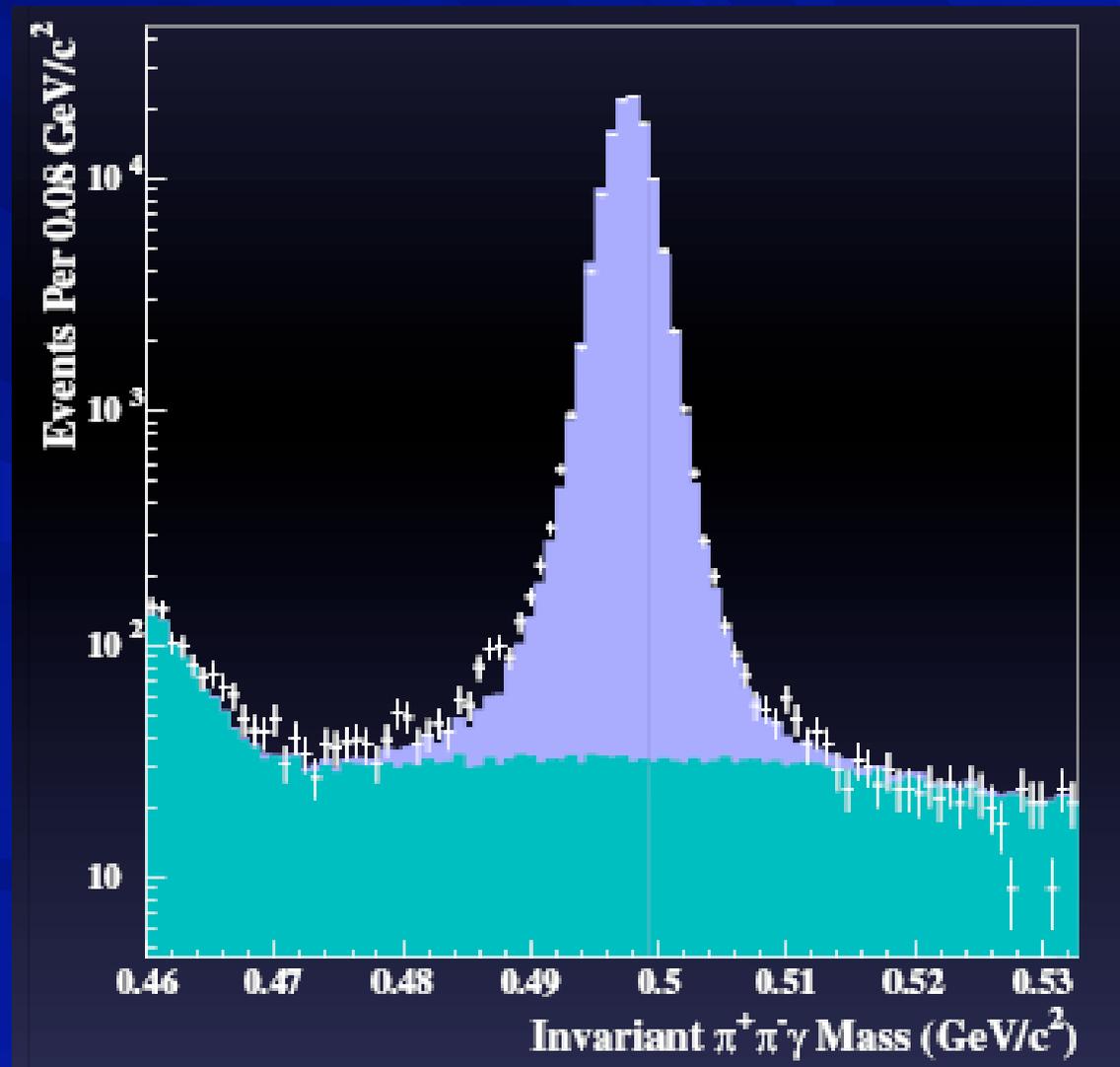


Direct Emission



# $K_L \rightarrow \pi^+ \pi^- \gamma$ Event Sample

- 111.4k signal events
- 0.6% background
  - mostly  $K_L \rightarrow \pi^\pm e^\mp \nu$  with an accidental  $\gamma$
  - some  $K_L \rightarrow \pi^+ \pi^- \pi^0$  ( $\pi^0 \rightarrow \gamma\gamma$ ) with a missing  $\gamma$



# $K_L \rightarrow \pi^+ \pi^- \gamma$ Likelihood Fit

- We fit for the 3 parameters in the DE decay amplitudes shown below

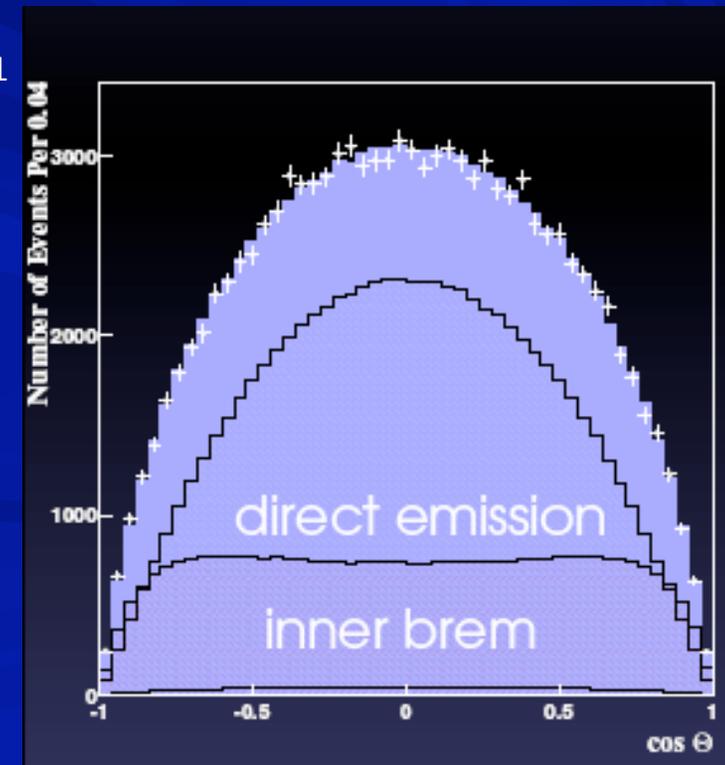
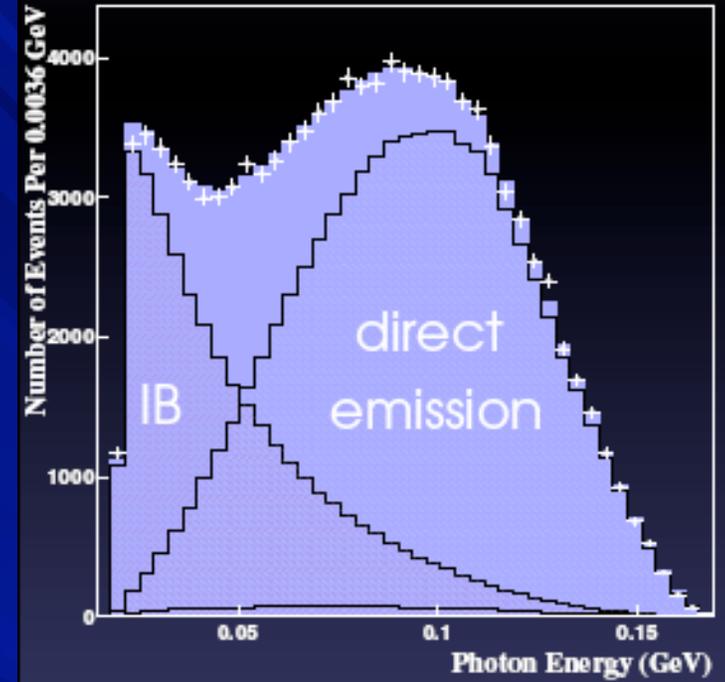
$$E_{IB}(K_L) = \left( 4 \frac{M_K^2}{E_\gamma^2} \right) \frac{\eta_{+-} e^{i\delta_0}}{1 - \beta^2 \cos^2(\theta)}$$

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

$$E_{DE}(K_L) = g_{E1} e^{i(\delta_1 + \phi_\epsilon)}$$

- A 2D likelihood fit is performed using  $\pi^0 \rightarrow \gamma$ :

- $E_\gamma$  in the  $K_L$  rest frame
- $\cos(\theta_{\gamma, \pi^+})$  in the  $\pi^+ \pi^-$  rest frame



# Preliminary $K_L \rightarrow \pi^+ \pi^- \gamma$ Results

- Measured values for M1 direct emission (CP conserving):
  - $g_{M1} = 1.198 \pm 0.035(\text{stat}) \pm 0.086(\text{syst})$
  - $a_1/a_2 = -0.738 \pm 0.007(\text{stat}) \pm 0.018(\text{syst})$
  - these results are the most precise to date
- Upper limit on E1 direction emission (CP violating)
  - $g_{E1} < 0.21$  (90% confidence)
- Direct emission fraction
  - $DE/(DE+IB) = 0.689 \pm 0.021$  ( $E_\gamma > 20$  MeV)

# The Decay $K_L \rightarrow \pi^0 \pi^0 \gamma$

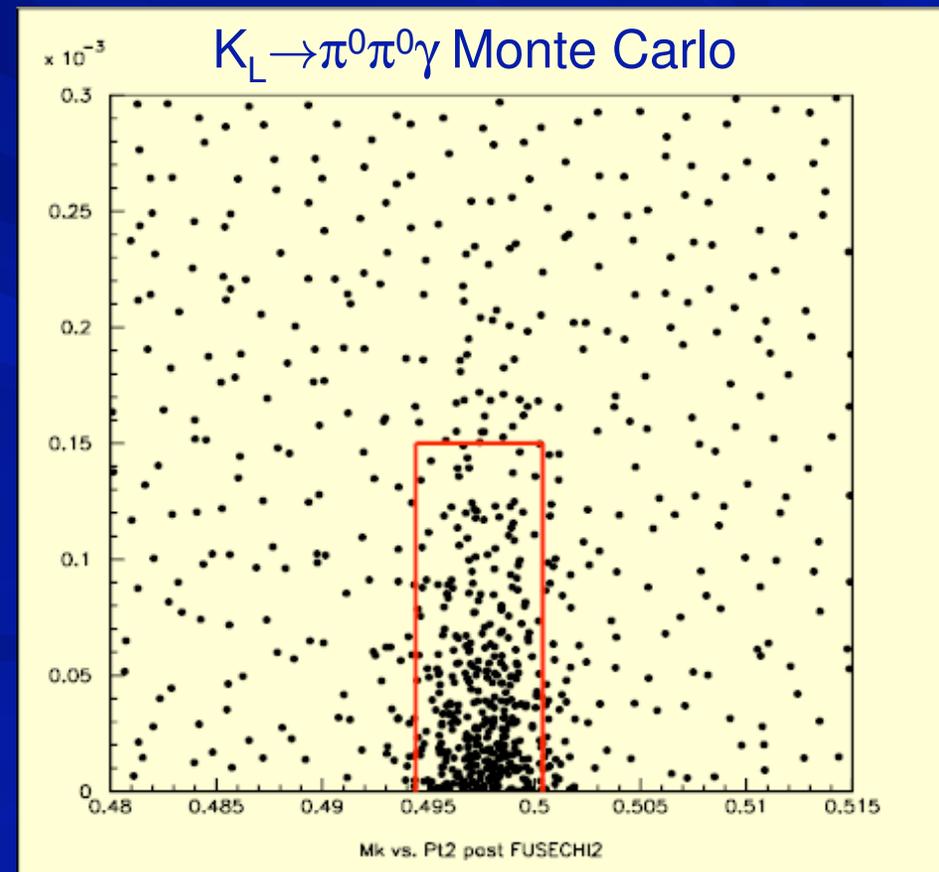
- This decay can only proceed via direct emission from the  $K_L \pi^0 \pi^0$  vertex
- Since the two pions in this decay are identical, the lowest contributing multipole moment is  $L=2$ 
  - E2 direct emission is CP conserving
  - M2 direct emission is CP violating
- The decay amplitude vanishes to  $O(p^4)$  in chiral perturbation theory
  - probe of  $O(p^6)$  chiral perturbation theory
- Estimated Branching Ratio:
  - Based on  $\pi^+ \pi^- \gamma$  branching ratio:  $1 \cdot 10^{-8}$
  - From chiral perturbation theory:  $7 \cdot 10^{-11}$
- current upper limit:  $5.6 \cdot 10^{-6}$  (from NA31)

# $K_L \rightarrow \pi^0 \pi^0 \gamma$ Event Selection

- Require  $K_L \rightarrow \pi^0 \pi^0_D \gamma$  ( $\pi^0 \rightarrow \gamma \gamma$ ,  $\pi^0_D \rightarrow e^+ e^- \gamma$ ) due to sensitive charged trigger
- Large background due to  $K_L \rightarrow \pi^0 \pi^0 \pi^0_D$  with a missing  $\gamma$
- 80% of signal Monte Carlo lies within the signal region
  - $|M_K - M_{e^+e^-}| < 0.003 \text{ GeV}/c^2$
  - $p_t^2 < 0.00015 \text{ GeV}^2/c^2$   
( $p_t$  = momentum transverse to the kaon direction)
- This was a blind analysis

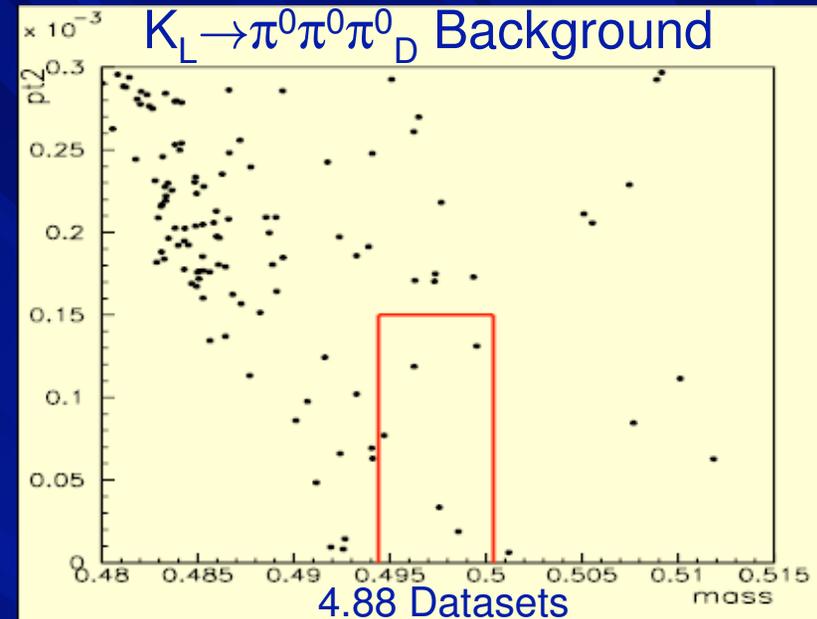
$p_t^2$  vs  $M_K$  for  $K_L \rightarrow \pi^0 \pi^0 \gamma$  Monte Carlo.

The signal box is shown in red

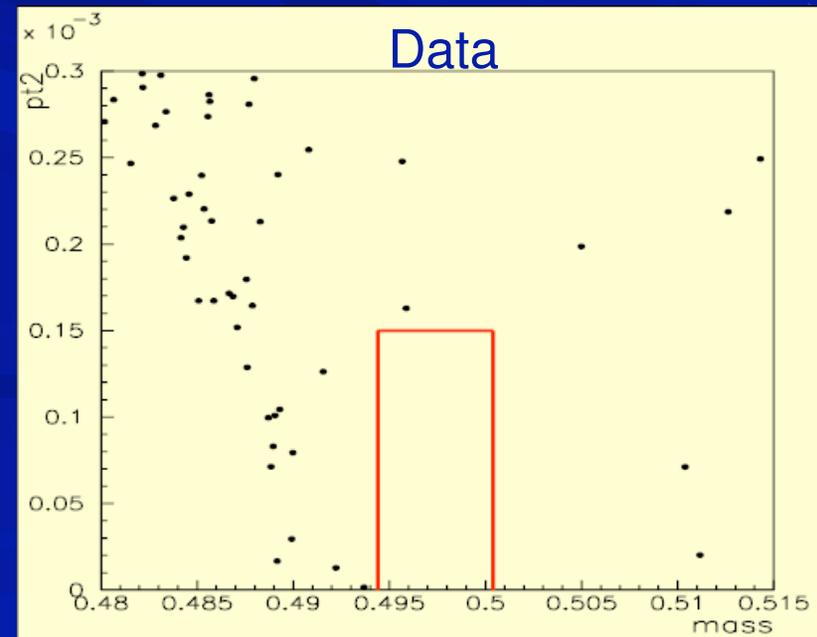


# Preliminary $K_L \rightarrow \pi^0 \pi^0 \gamma$ Results

- This result is from 40% of the total data set ( $N_K = 2.4 \cdot 10^{11}$ )
- expected background of  $1.66 \pm 0.59$  events
- $BR(K_L \rightarrow \pi^0 \pi^0 \gamma) < 2.52 \cdot 10^{-7}$  (at 90% confidence)
- Factor of 22 improvement on NA31 result
- Work is continuing on the full data set



After opening the box, no signal events were found



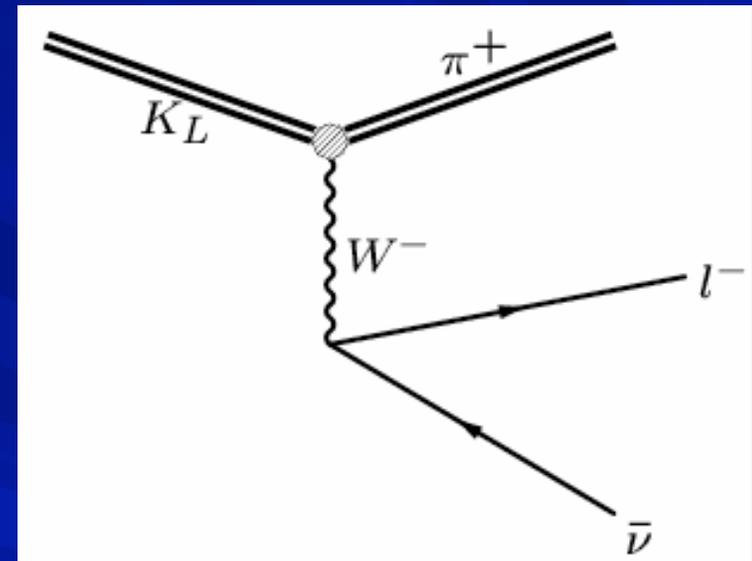
# The Decay $K_L \rightarrow \pi^\pm e^\mp \nu e^+ e^-$

- The CKM matrix element  $V_{us}$  can be extracted from  $K_L \rightarrow \pi^\pm e^\mp \nu$  decays via:

$$\Gamma_{Kl3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW} (1 + \delta_K^l) C^2 |V_{us}|^2 f_+^2(0) I_K^l$$

- The uncertainty in the K- $\pi$ -W vertex parameters is currently larger than the experimental uncertainty in  $\Gamma_{Kl3}$
- The DE  $K_L \rightarrow \pi^\pm e^\mp \nu \gamma$  decay is sensitive to the structure of the K- $\pi$ -W vertex
- Unfortunately,  $K_L \rightarrow \pi^\pm e^\mp \nu \gamma$  is dominated by IB
- $K_L \rightarrow \pi^\pm e^\mp \nu \gamma$  with a virtual  $\gamma$  has an enhancement in the DE/IB ratio, and is therefore a more sensitive probe of the K- $\pi$ -W vertex

$K_L \rightarrow \pi^+ l^- \nu$  Diagram

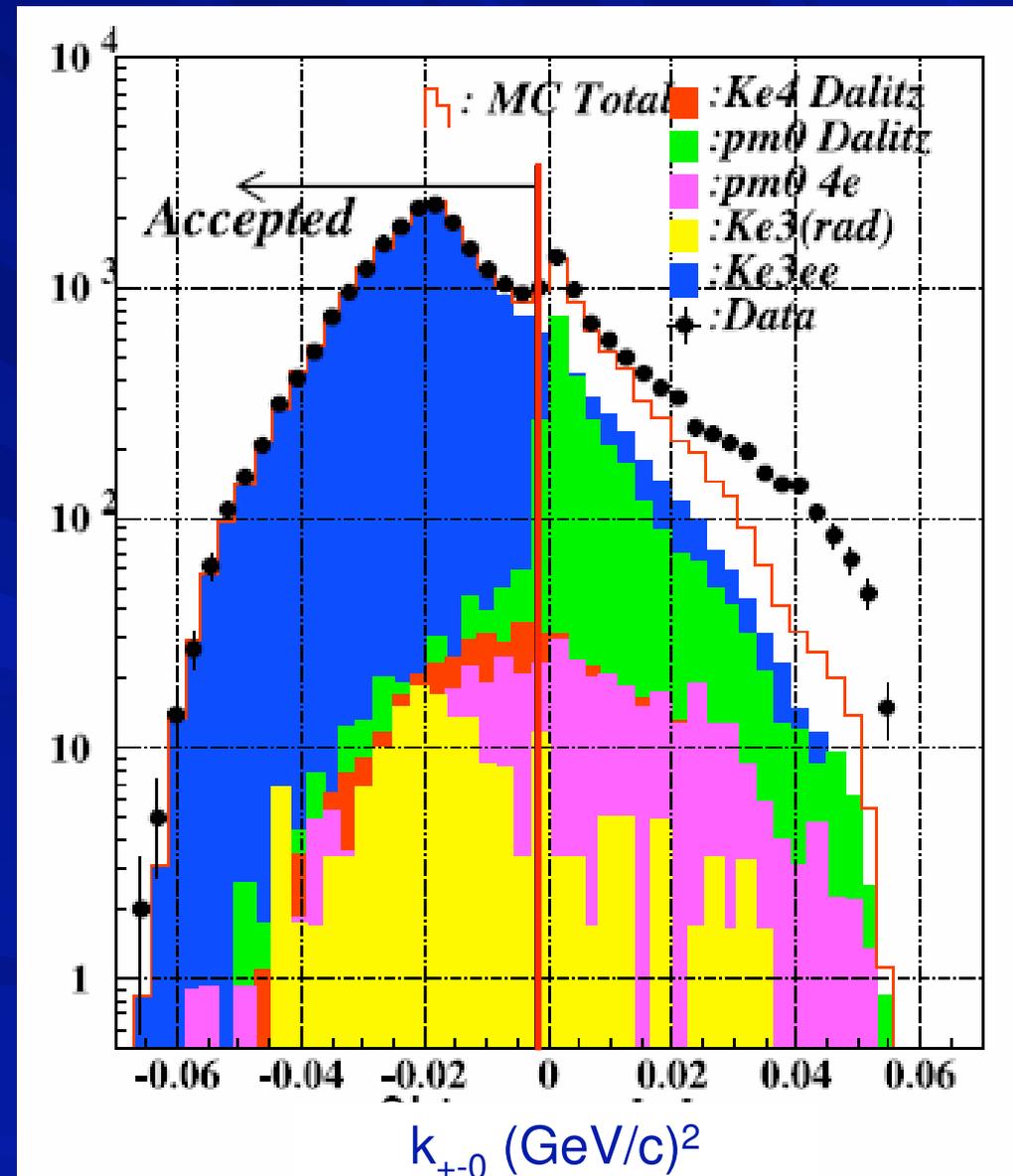


- For now, only the preliminary branching ratio result for  $K_L \rightarrow \pi^\pm e^\mp \nu e^+ e^-$  will be presented

# $K_L \rightarrow \pi^\pm e^\mp \nu e^+ e^-$ Reconstruction

- The main background is from  $K_L \rightarrow \pi^+ \pi^- \pi^0_D$  ( $\pi^0_D \rightarrow e^+ e^- \gamma$ ) with a missing  $\gamma$
- This background is greatly reduced by cutting on the variable  $k_{+-0}$ .
- $k_{+-0}$  is the square of the longitudinal momentum of the missing  $\pi^0$  in the frame where:

$$\bar{p}_K \cdot \bar{p}_{\pi\pi} = 0$$





# The Decay $\pi^0 \rightarrow e^+e^-$

- $\pi^0 \rightarrow e^+e^-$  proceeds through a loop process at lowest order
- The contribution from on-shell photons sets a unitary bound on the rate:

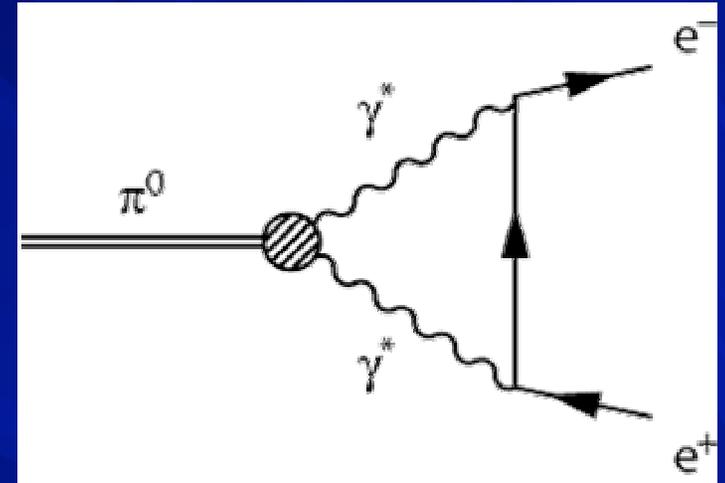
- $\Gamma(\pi^0 \rightarrow e^+e^-) / \Gamma(\pi^0 \rightarrow \gamma\gamma) \geq 4.75 * 10^{-8}$

- vector meson dominance (VMD) models predict a branching ratio of

- $BR(\pi^0 \rightarrow e^+e^-) = 6.2-6.4 * 10^{-8}$

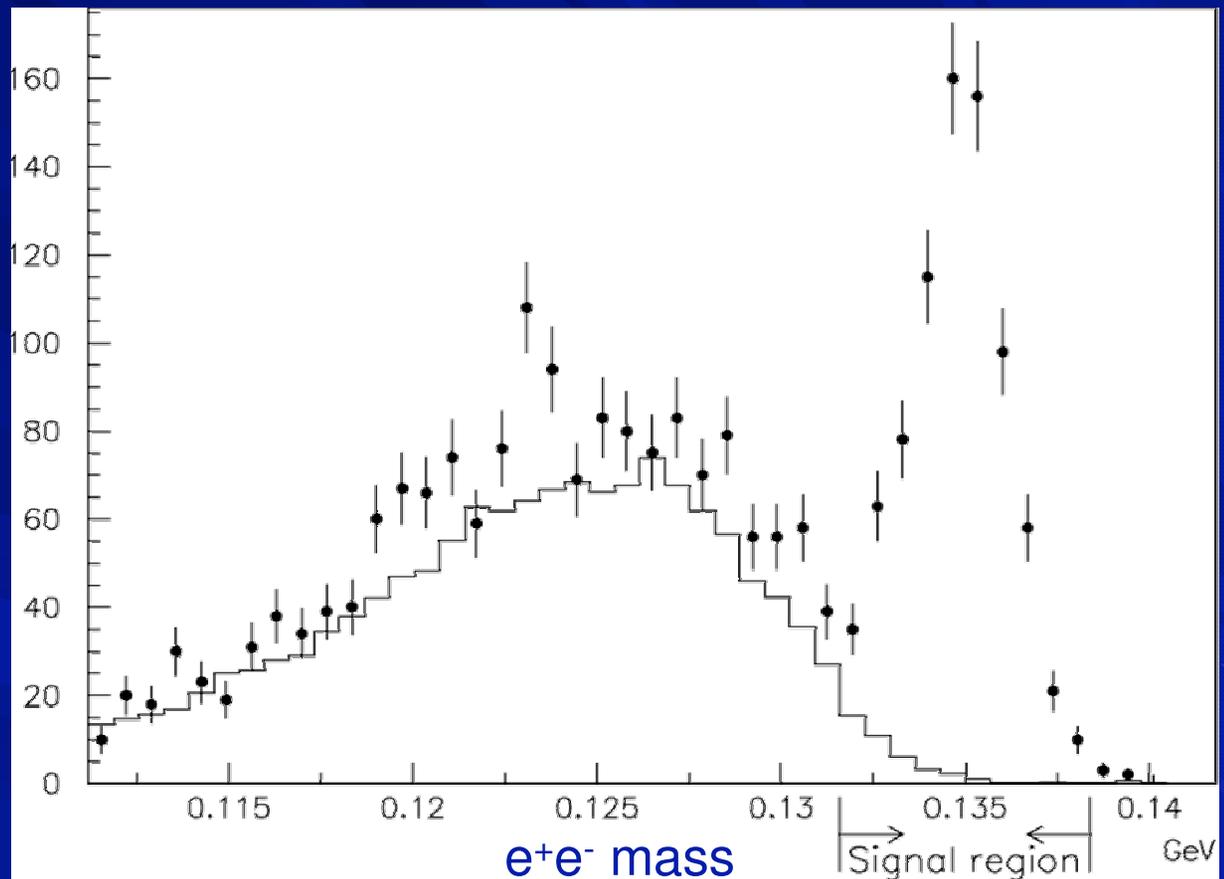
- Predictions from chiral perturbation theory have a range of

- $BR(\pi^0 \rightarrow e^+e^-) = 6.4-8.3 * 10^{-8}$



# $\pi^0 \rightarrow e^+e^-$ Event Sample

- A comparison between data (dots) and background MC (histogram) is shown
- The main background is from  $\pi^0 \rightarrow e^+e^- \gamma$  decays with a missing  $\gamma$



- There are 714 events in the signal region with a background of  $39.9 \pm 12.3$  events
- The main systematic uncertainty comes from the mismatch between the data and the background MC

# Preliminary $\pi^0 \rightarrow e^+e^-$ Results

$$\frac{BR(\pi^0 \rightarrow e^+e^-, x > 0.95)}{BR(\pi^0 \rightarrow e^+e^-\gamma, x > 0.232)} = (1.721 \pm 0.068(stat) \pm 0.036(syst)) * 10^{-4}$$

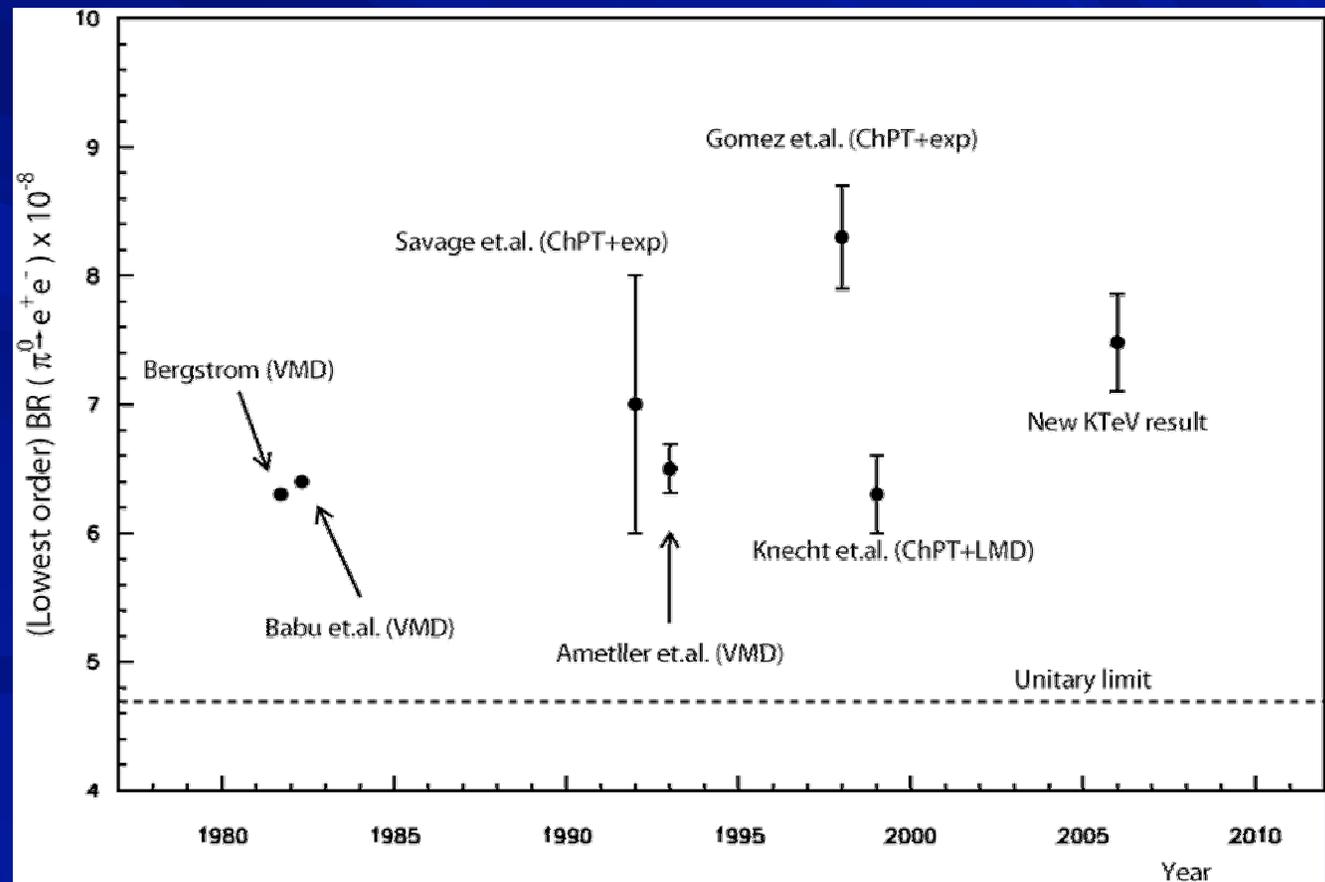
■ Using the Dalitz spectrum and branching ratio, we find:

$$BR(\pi^0 \rightarrow e^+e^-, x > 0.95) = (6.56 \pm 0.26(stat) \pm 0.23(sys)) * 10^{-8}$$

■ The systematic error now includes:

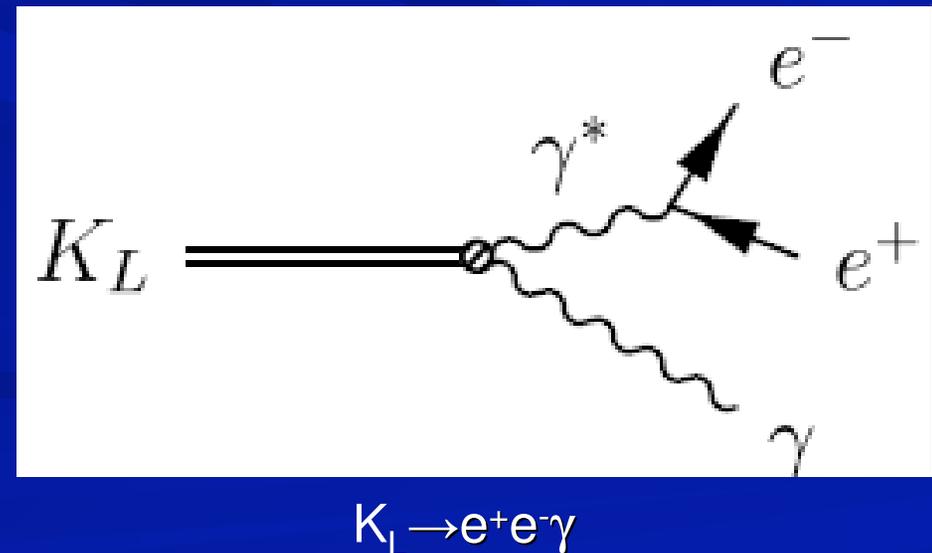
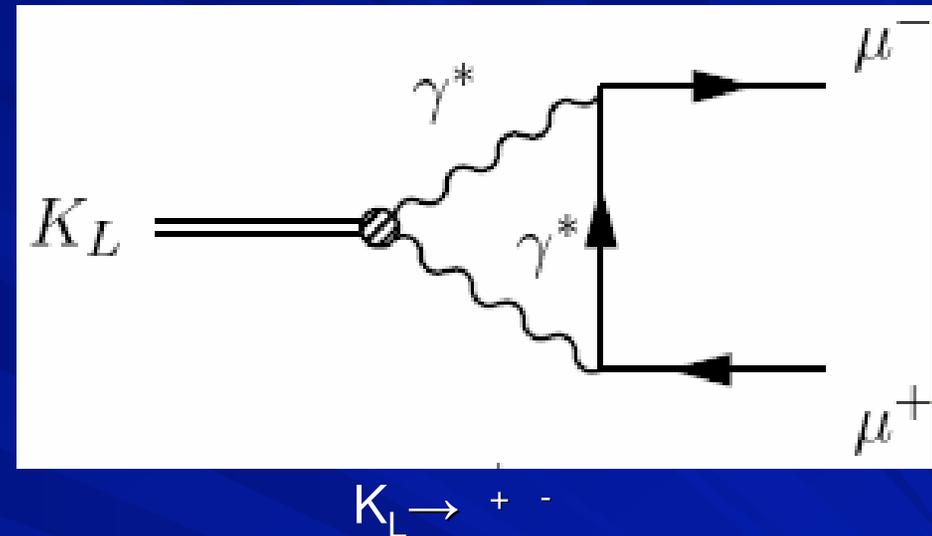
- 2.7% Dalitz branching ratio uncertainty
- 0.5%  $\pi^0$  slope parameter uncertainty

■ The plots shows a comparison between the tree level rate and various theory calculations



# The Decay $K_L \rightarrow e^+e^-\gamma$

- The decay  $K_L \rightarrow + -$  contains short-distance contributions from which one can extract  $|V_{td}|$ .
- Long-distance contributions (from the  $K_L \rightarrow \gamma^* \gamma^*$  vertex) must first be subtracted
- The  $K_L \rightarrow + -$  rate is dominated by these QED contributions, so a precise understanding of the  $K_L \rightarrow \gamma^* \gamma^*$  vertex is required
- The  $K_L \rightarrow \gamma^* \gamma^*$  vertex can be probed by various double and single Dalitz decays such as  $K_L \rightarrow e^+e^-\gamma$



# $K_L \gamma^* \gamma$ Form Factor

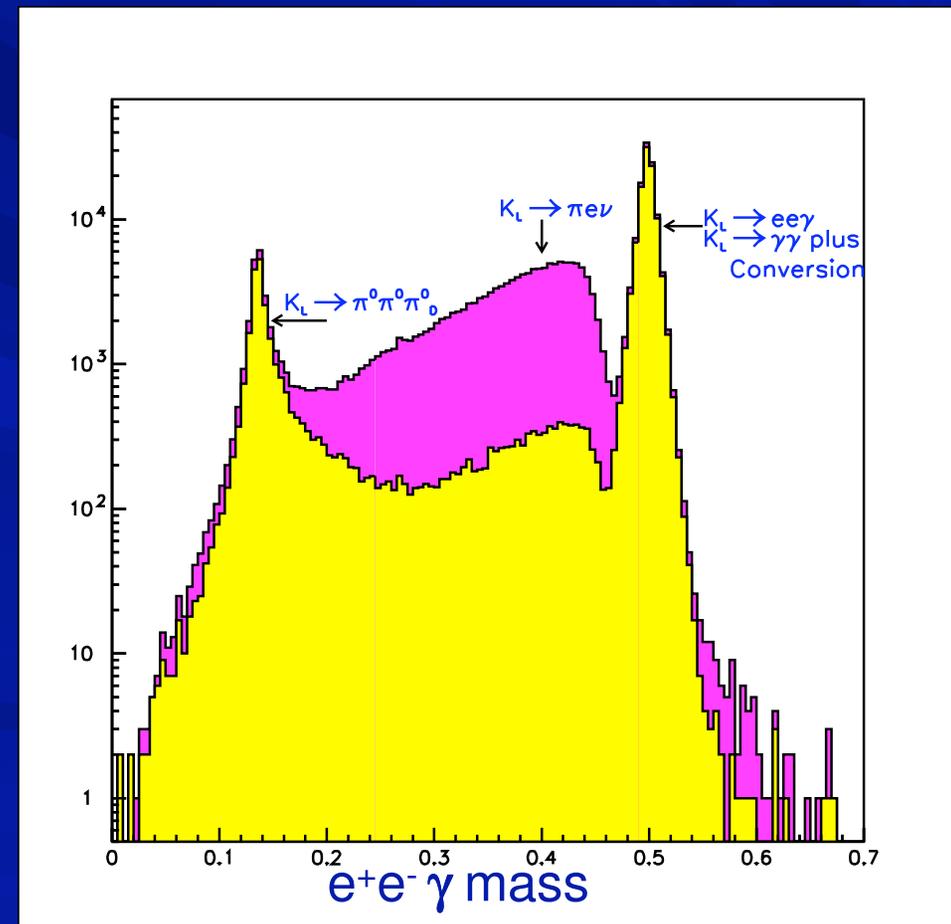
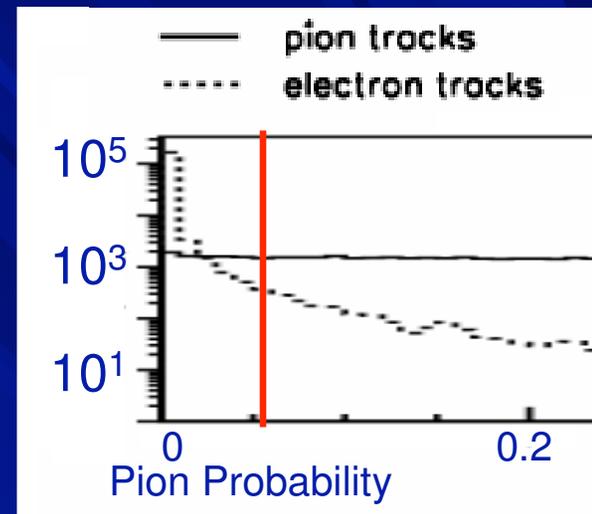
- Two form factor models were considered
  - D'Ambrosio, Isidori, and Portoles (DIP) for which  $\alpha_{\text{DIP}}$  is extracted
  - Bergstrom, Masso, and Singer (BMS) for which  $\alpha_{K^*}$  is extracted
- Previous fits for  $\alpha_{\text{DIP}}$  have been straightforward, but there has been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

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

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

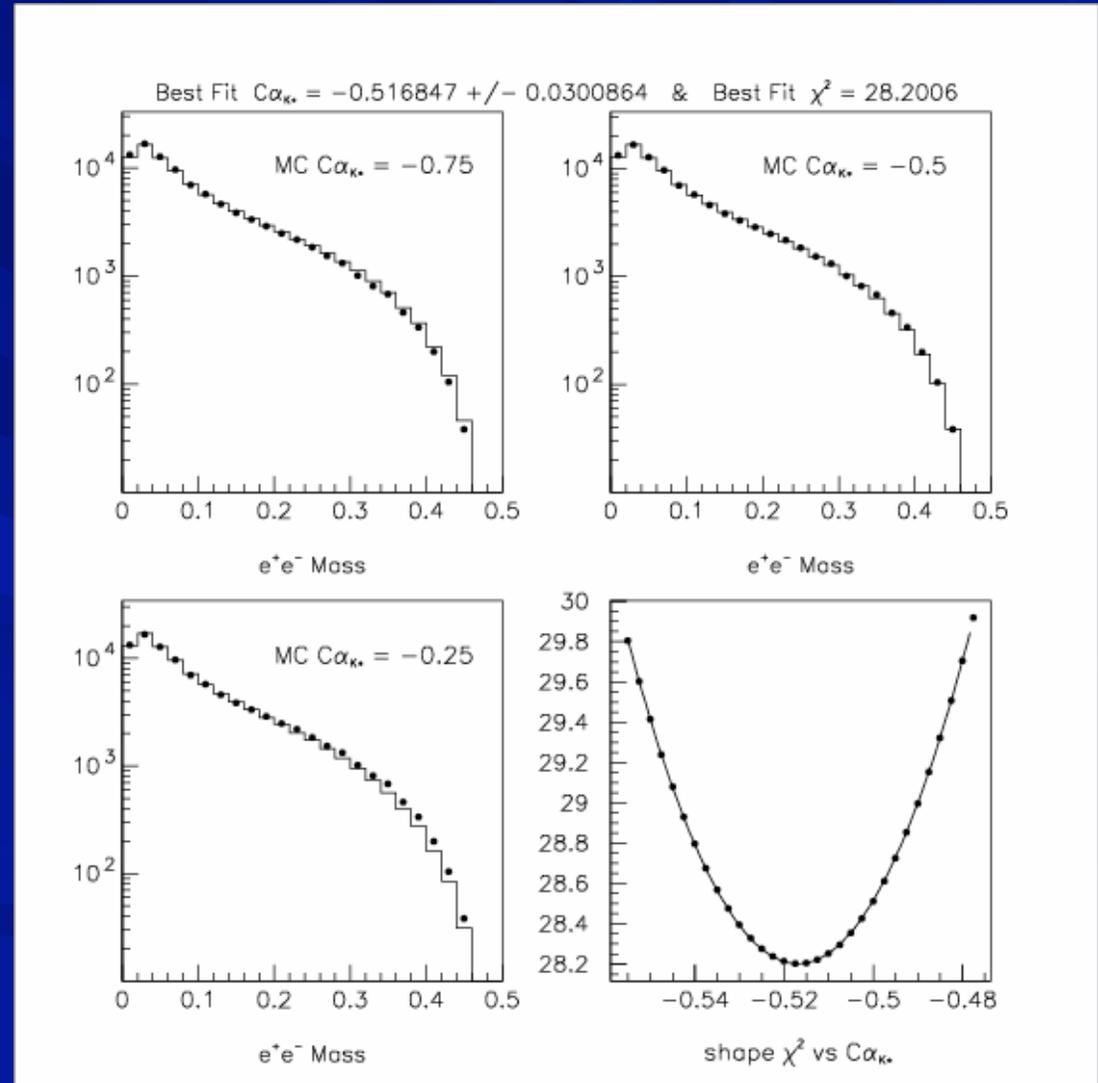
# $K_L \rightarrow e^+e^-\gamma$ Event Selection

- The main background is  $K_L \rightarrow \pi^\pm e^\mp \nu$  with an accidental  $\gamma$  where the  $\pi^\pm$  is misidentified as an  $e^\pm$
- Using the  $\pi/e$  separation provided by the TRD, this background is greatly reduced



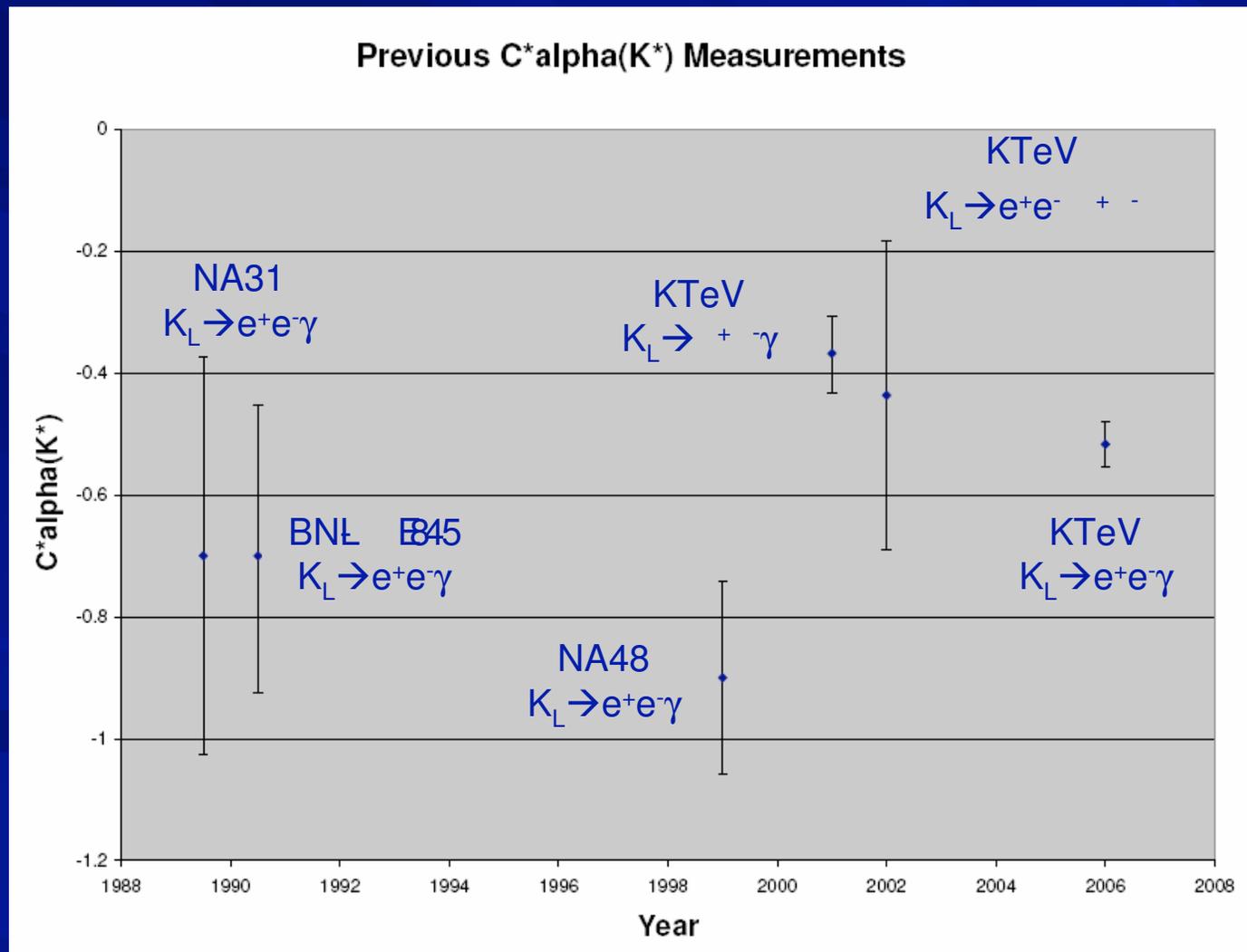
# $K_L \rightarrow e^+e^-\gamma$ Form Factor Measurement

- The shape of the  $e^+e^-$  mass is very sensitive to the form factor
- A bin-by-bin shape- $\chi^2$  fit is performed between the data and sets of Monte Carlo with differing values of each  $\alpha$
- The plot shows three data / Monte Carlo  $e^+e^-$  mass comparisons and the shape- $\chi^2$  vs  $\alpha_{K^*}$  fit



# Corrected Preliminary $K_L \rightarrow e^+e^-\gamma$ Results

- $\text{BR}(K_L \rightarrow e^+e^-\gamma) = (9.25 \pm 0.03(\text{stat}) \pm 0.07(\text{syst}) \pm 0.26(\text{ext syst})) \cdot 10^{-6}$
- $C\alpha_{K^*} = -0.517 \pm 0.030(\text{fit}) \pm 0.022(\text{syst})$
- $\alpha_{\text{DIP}} = -1.729 \pm 0.043(\text{fit}) \pm 0.028(\text{syst})$



# Summary

## ■ Preliminary $K_L \rightarrow \pi^+ \pi^- \gamma$ Results

- $g_{M1} = 1.198 \pm 0.035(\text{stat}) \pm 0.086(\text{syst})$
- $a_1/a_2 = -0.738 \pm 0.007(\text{stat}) \pm 0.018(\text{syst})$
- $g_{E1} < 0.21$  (90% confidence)

## ■ Preliminary $K_L \rightarrow \pi^0 \pi^0 \gamma$ Results

- $\text{BR}(K_L \rightarrow \pi^0 \pi^0 \gamma) < 2.52 \cdot 10^{-7}$  (90% confidence)

## ■ Preliminary $K_L \rightarrow \pi^\pm e^\mp \nu e^+ e^-$ Results

- $\text{BR}(K_L \rightarrow \pi^\pm e^\mp \nu e^+ e^-, M_{e^+ e^-} > 5 \text{MeV}/c^2)$   
 $= (1.606 \pm 0.012(\text{stat})^{+0.026}_{-0.016}(\text{syst}) \pm 0.045(\text{ext syst})) \cdot 10^{-5}$

## ■ Preliminary $\pi^0 \rightarrow e^+ e^-$ Results

- $\text{BR}(\pi^0 \rightarrow e^+ e^-) = (6.56 \pm 0.26(\text{stat}) \pm 0.23(\text{syst})) \cdot 10^{-8}$

## ■ Corrected Preliminary $K_L \rightarrow e^+ e^- \gamma$ Results

- $\text{BR}(K_L \rightarrow e^+ e^- \gamma)$   
 $= (9.25 \pm 0.03(\text{stat}) \pm 0.07(\text{syst}) \pm 0.26(\text{ext syst})) \cdot 10^{-6}$
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