Recent Results from KTeV

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Outline

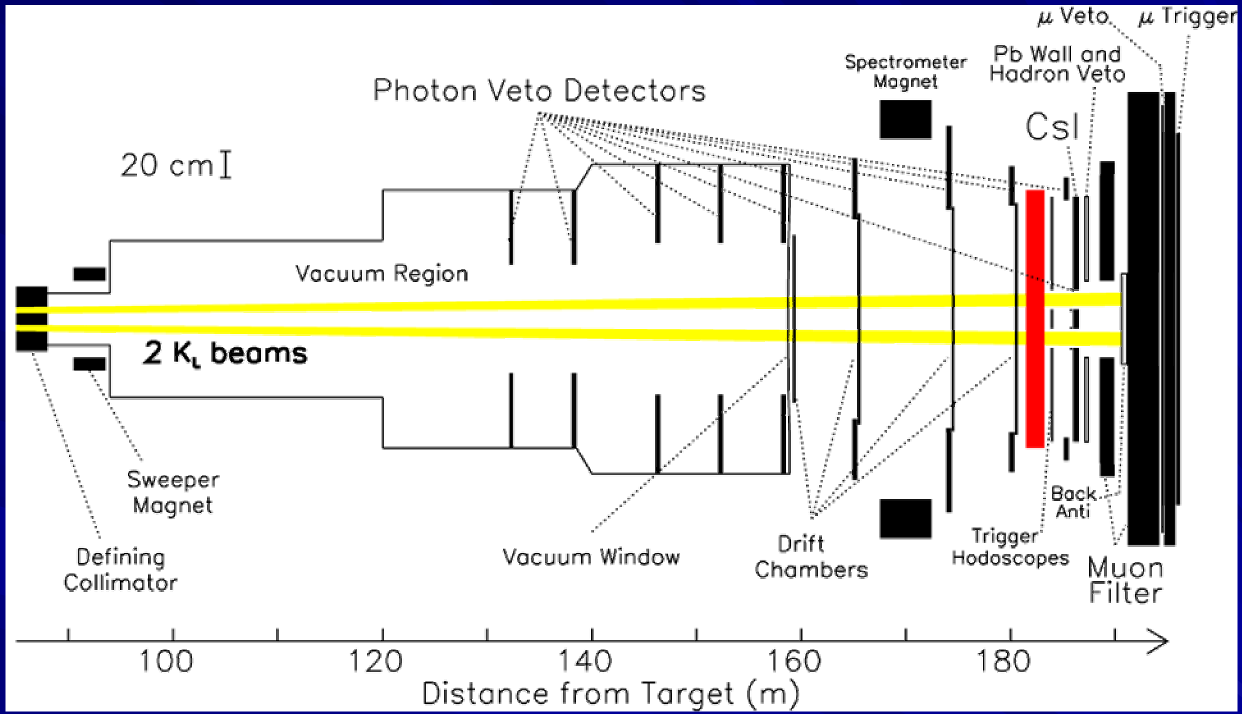
- The KTeV experiment
- $K_L \to \pi^+\pi^-\gamma$
- $K_L \to \pi^0\pi^0\gamma$
- $K_L \to \pi^\pm e^\mp \nu e^+e^-$
- $\pi^0 \to e^+e^-$
- $K_L \to e^+e^-\gamma$

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: Re(ε'/ε)
- Two beams of neutral kaons
- 60m vacuum decay region

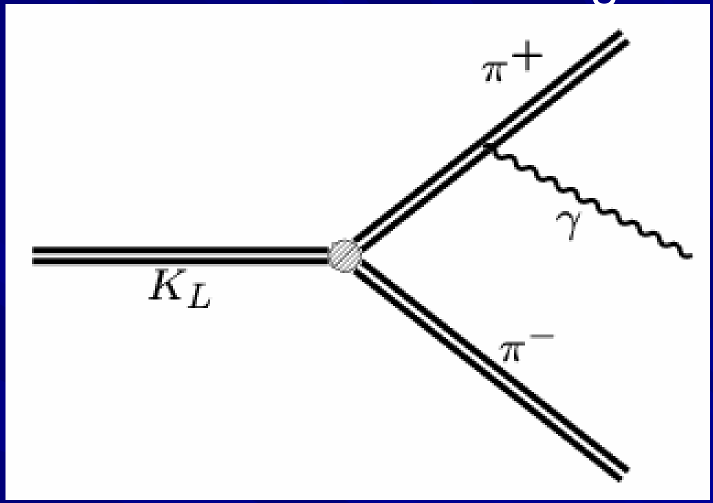


- A momentum spectrometer consisting of 4 drift chambers and an analysis magnet: $\sigma(P)/P = 0.38\% \ (+) \ 0.016\% * P(GeV/c)$
- A transition radiation detector (TRD) for e/π separation (E799 only)
- 3100 crystal CsI calorimeter: $\sigma(E)/E = 0.45\% \ (+) \ 2\%/\sqrt{E(GeV)}$
- A muon filter consisting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

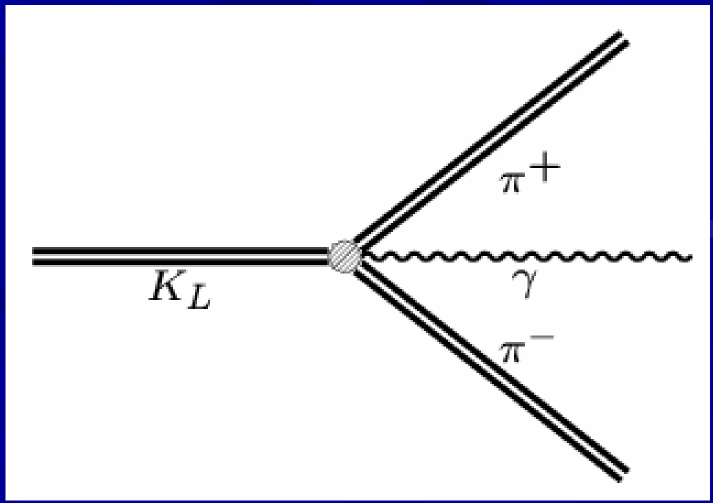
The Decay $K_L \to \pi^+\pi^-\gamma$

- composed of 2 processes
  - Inner Bremsstrahlung from CP violating decay $K_L \to \pi^+\pi^-$
  - 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

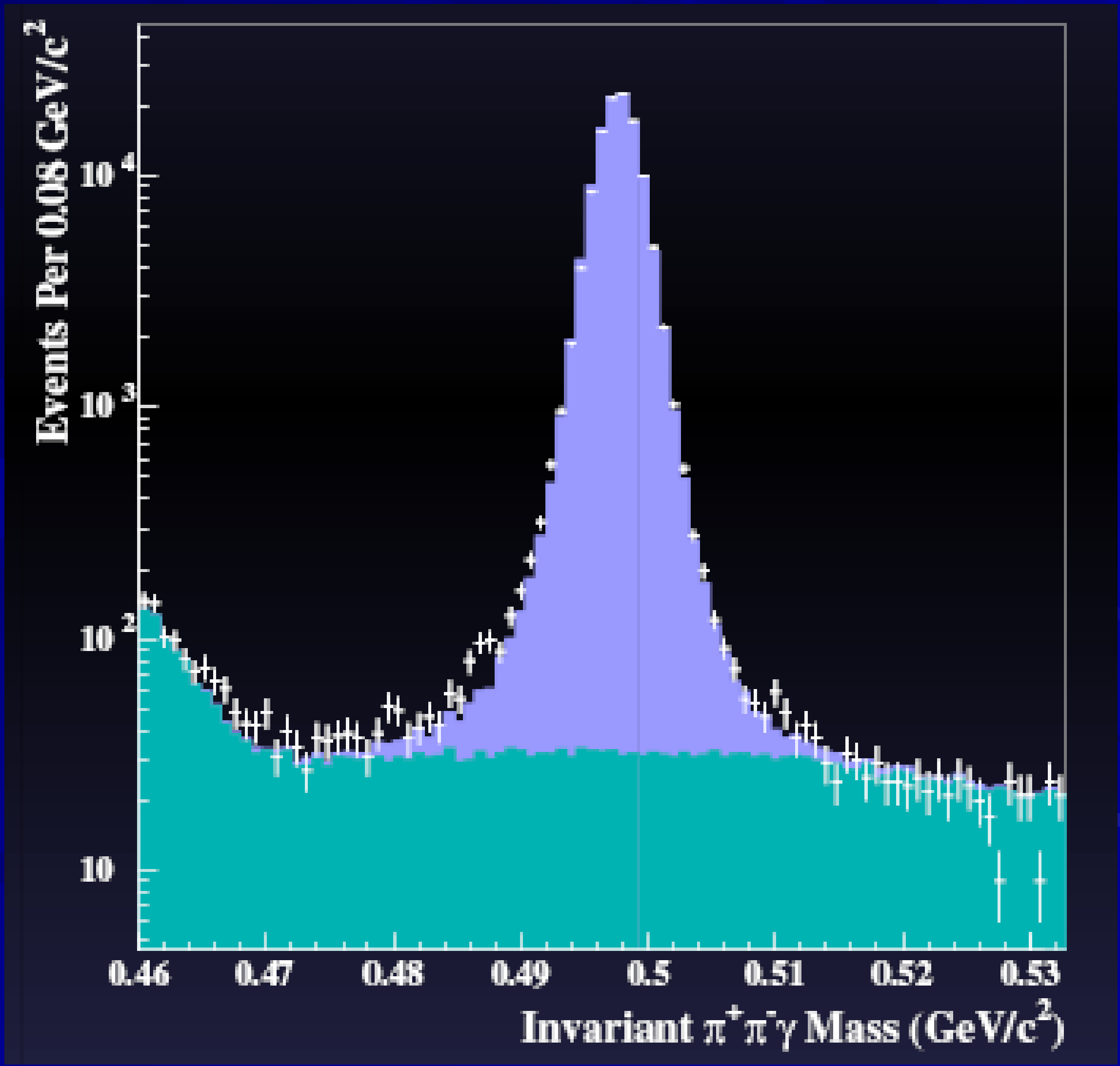


Direct Emission



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

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



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

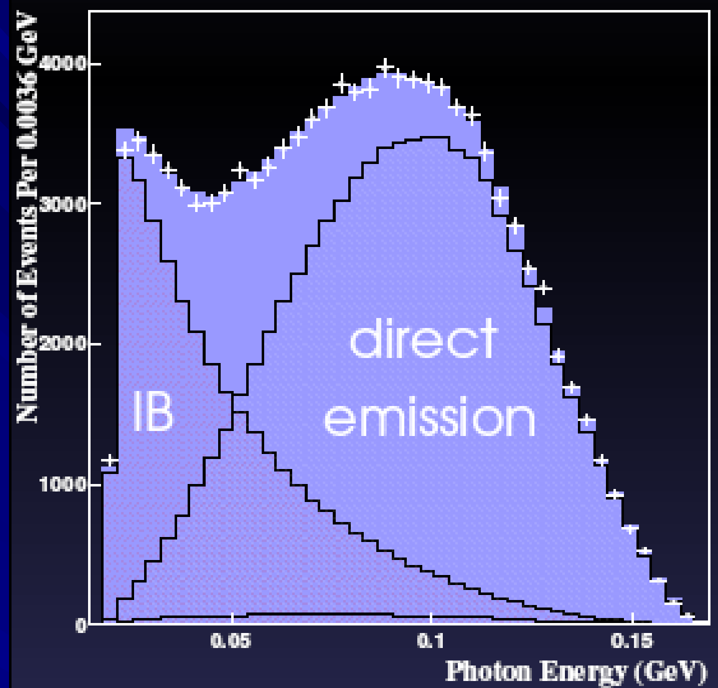
- We fit for the 3 parameters in the DE decay amplitudes shown below

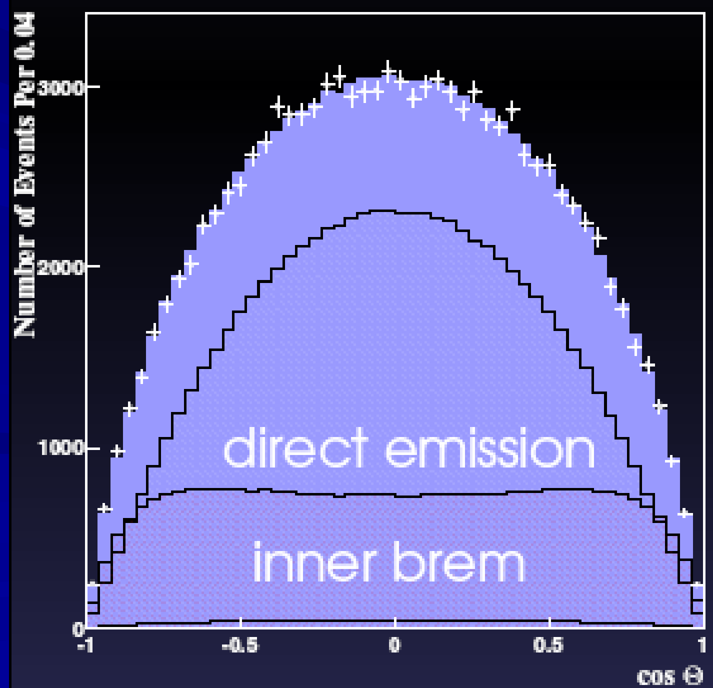
$$E_{IB}(K_L) = \left(4\frac{M_K^2}{E_\gamma^2}\right)\frac{\eta_{+-}e^{i\delta_0}}{1-\beta^2 cos^2(\theta)}$$

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

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

- A 2D likelihood fit is performed using $\pi^0 \to$:
  - E_γ in the K_L rest frame
  - $\cos(\theta_{\gamma,\pi+})$ in the $\pi^+\pi^-$ rest frame





Preliminary $K_L \to \pi^+\pi^-\gamma$ 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 $K_L \to \pi^0\pi^0\gamma$

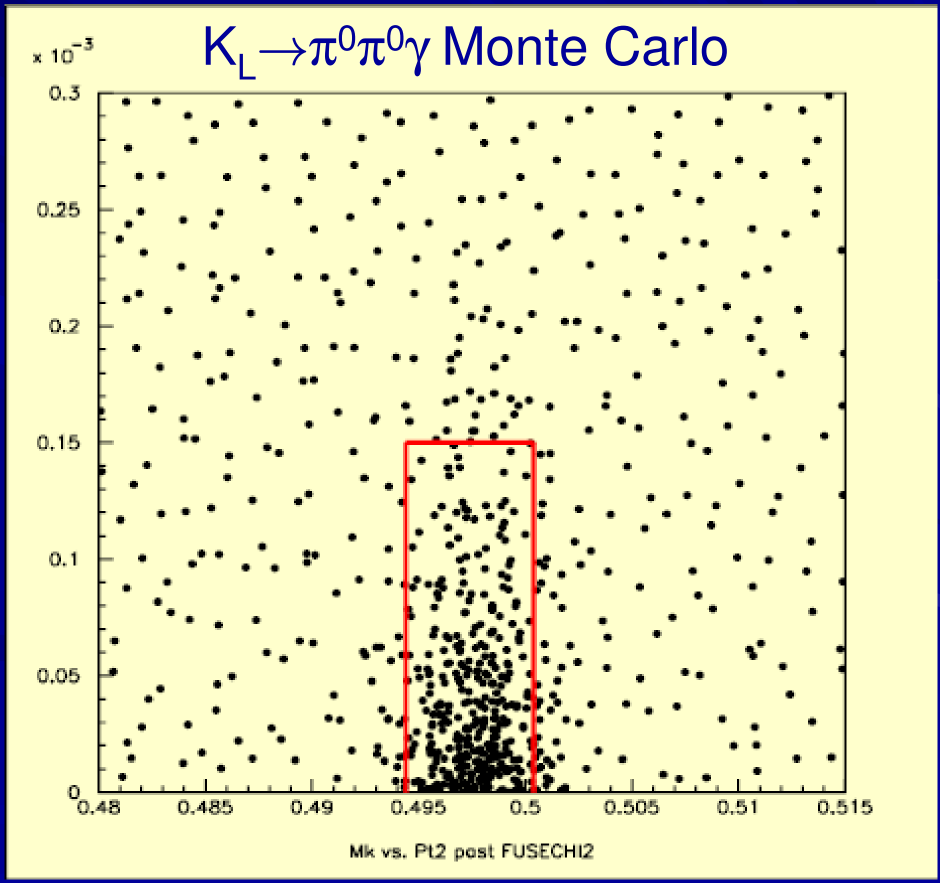
- This decay can only proceed via direct emission from the $K_L\pi^0\pi^0$ vertex
- Since the two pions in this decay are identical, the lowest contributing multipole moment is L=2
  - E2 direct emission is CP conserving
  - M2 direct emission is CP violating
- The decay amplitude vanishes to $O(p^4)$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

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

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

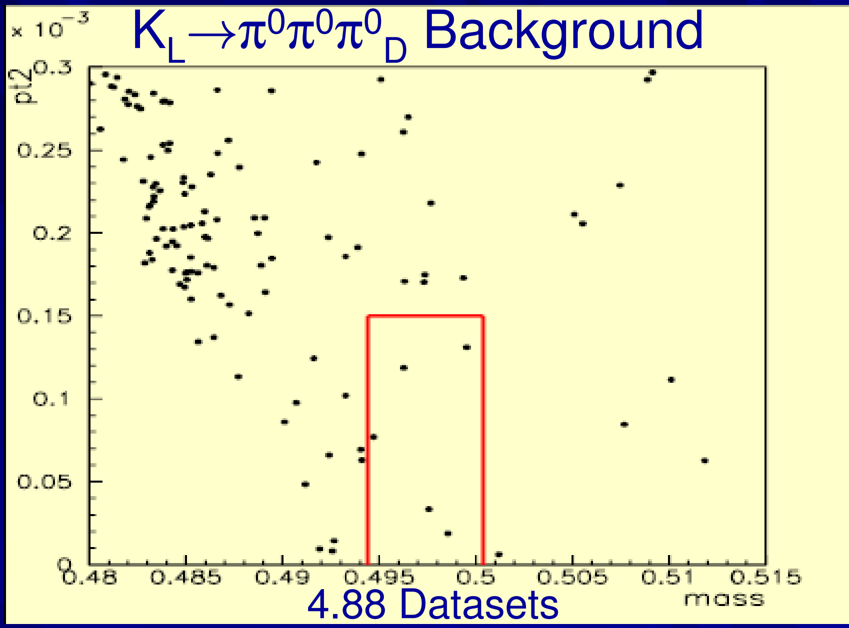
p_t^2 vs M_K for $K_L \to \pi^0\pi^0\gamma$ Monte Carlo.

The signal box is shown in red

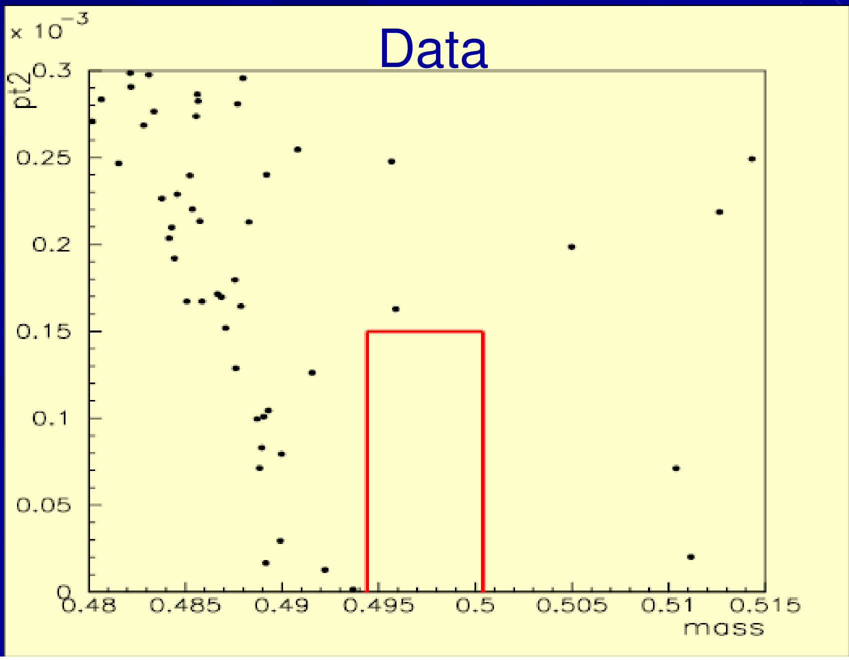


Preliminary $K_L \rightarrow \pi^0\pi^0\gamma$ Results

- This result is from 40% of the total data set ($N_K = 2.4*10^{11}$)
- expected background of 1.66 ± 0.59 events
- $BR(K_L \rightarrow \pi^0\pi^0\gamma) < 2.52*10^{-7}$ (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



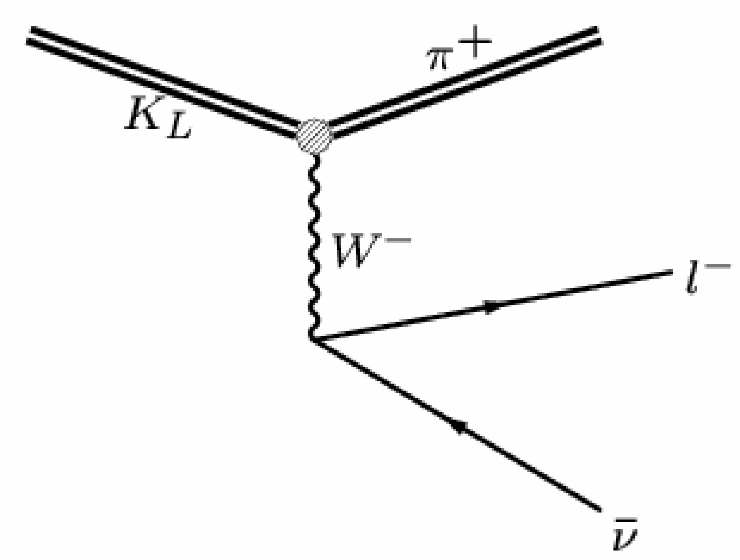
The Decay $K_L \to \pi^\pm e^\mp \nu e^+ e^-$

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

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

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

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

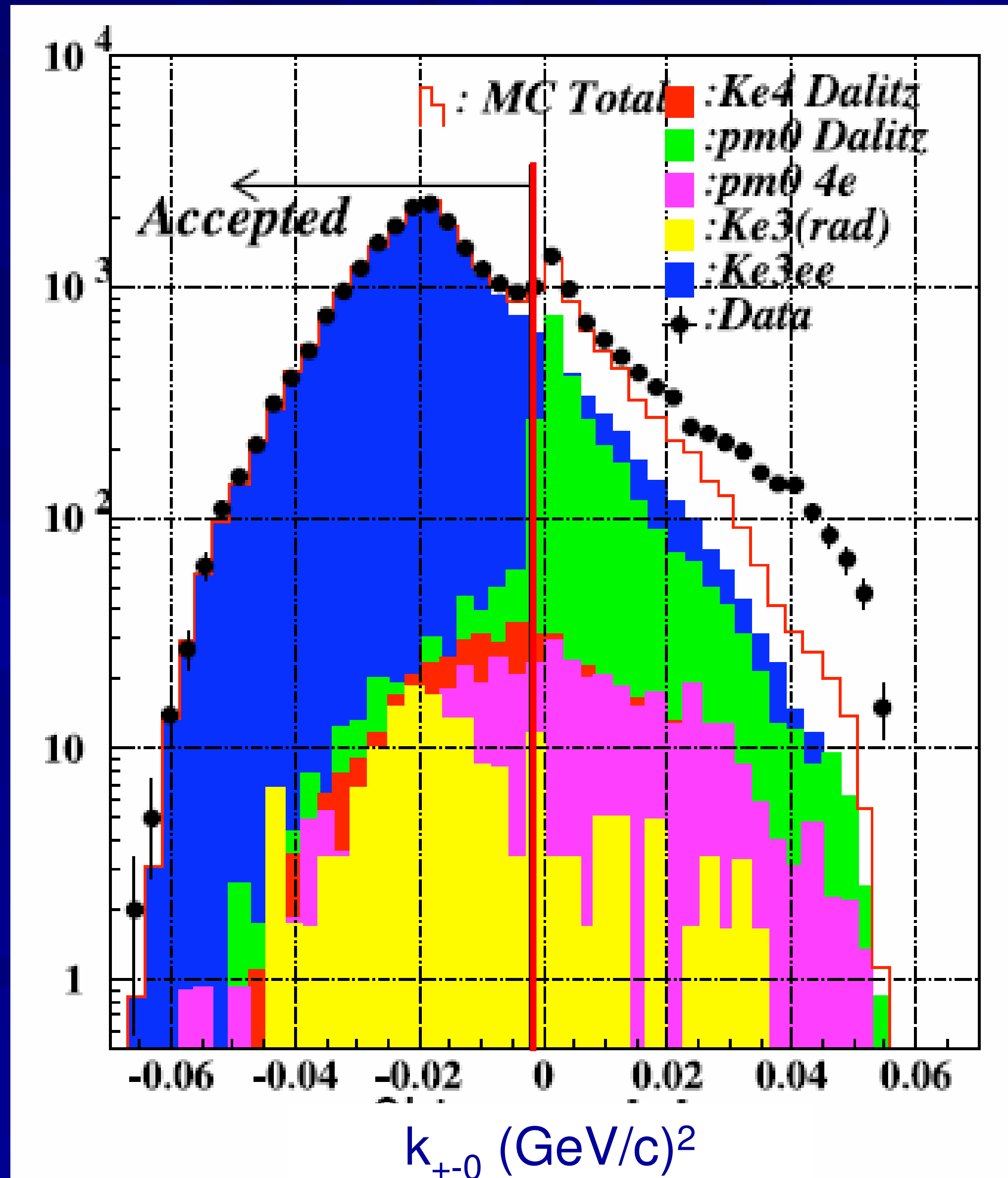


- For now, only the preliminary branching ratio result for $K_L \to \pi^\pm e^\mp \nu e^+ e^-$ will be presented

$K_L \to \pi^{\pm} e^{\mp} \nu e^+ e^-$ Reconstruction

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

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



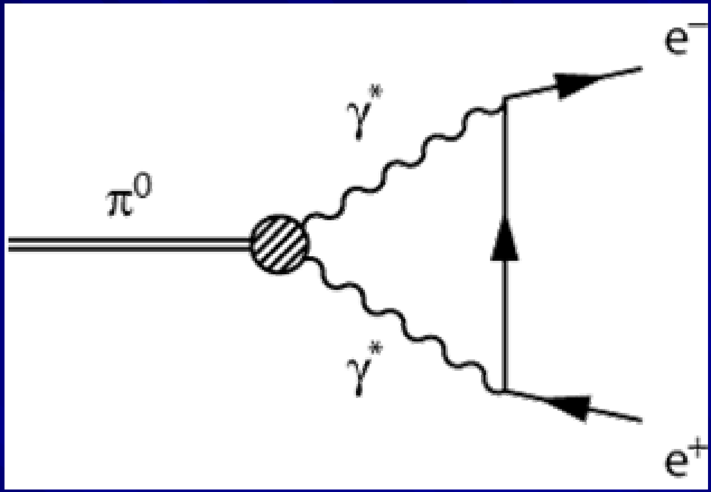
Preliminary $K_L \rightarrow \pi^{\pm} e^{\mp} \nu e^+ e^-$ Results

- 19466 signal events were isolated with a background of 4.95%
- The $K_L \rightarrow \pi^{\pm} e^{\mp} \nu e^+ e^-$ rate was normalized to the $K_L \rightarrow \pi^+ \pi^- \pi^0_D$ ($\pi^0_D \rightarrow e^+ e^- \gamma$) rate
- We find 300526 normalization mode events with a background of 2.23%
- BR($K_L \rightarrow \pi^{\pm} e^{\mp} \nu e^+ e^-, M_{e^+e^-} > 5 \text{MeV}/c^2$)

$$= (1.606 \pm 0.012(\text{stat}) \; {}^{+0.026}_{-0.016}(\text{syst}) \; \pm 0.045(\text{ext syst})) * 10^{-5}$$

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

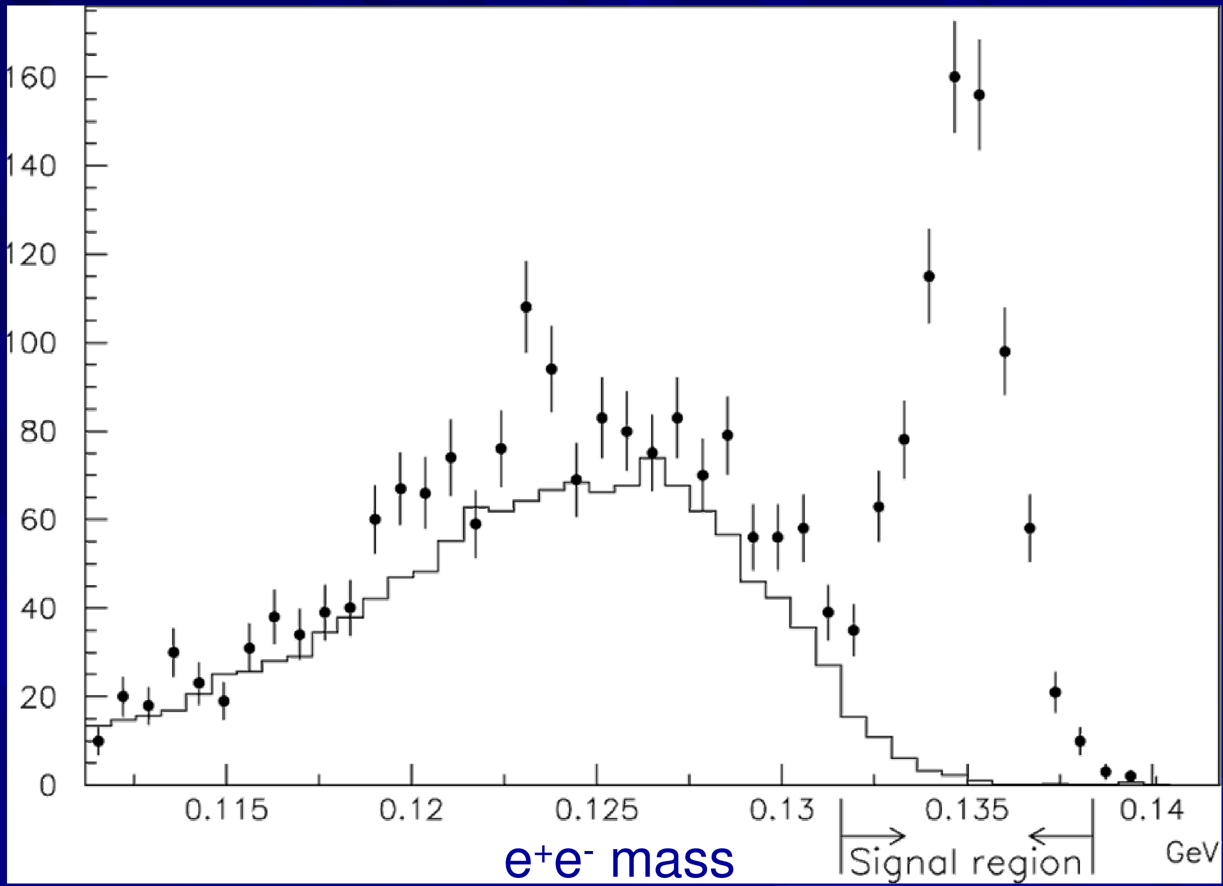
- $\pi^0 \rightarrow e^+e^-$ proceeds through a loop process at lowest order
- The contribution from on-shell photons sets a unitary bound on the rate:
  - $\Gamma(\pi^0 \rightarrow e^+e^-)/\Gamma(\pi^0 \rightarrow \gamma\gamma) \geq 4.75 * 10^{-8}$



- vector meson dominance (VMD) models predict a branching ratio of
  - $BR(\pi^0 \rightarrow e^+e^-) = 6.2\text{-}6.4 * 10^{-8}$
- Predictions from chiral perturbation theory have a range of
  - $BR(\pi^0 \rightarrow e^+e^-) = 6.4\text{-}8.3 * 10^{-8}$

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

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



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

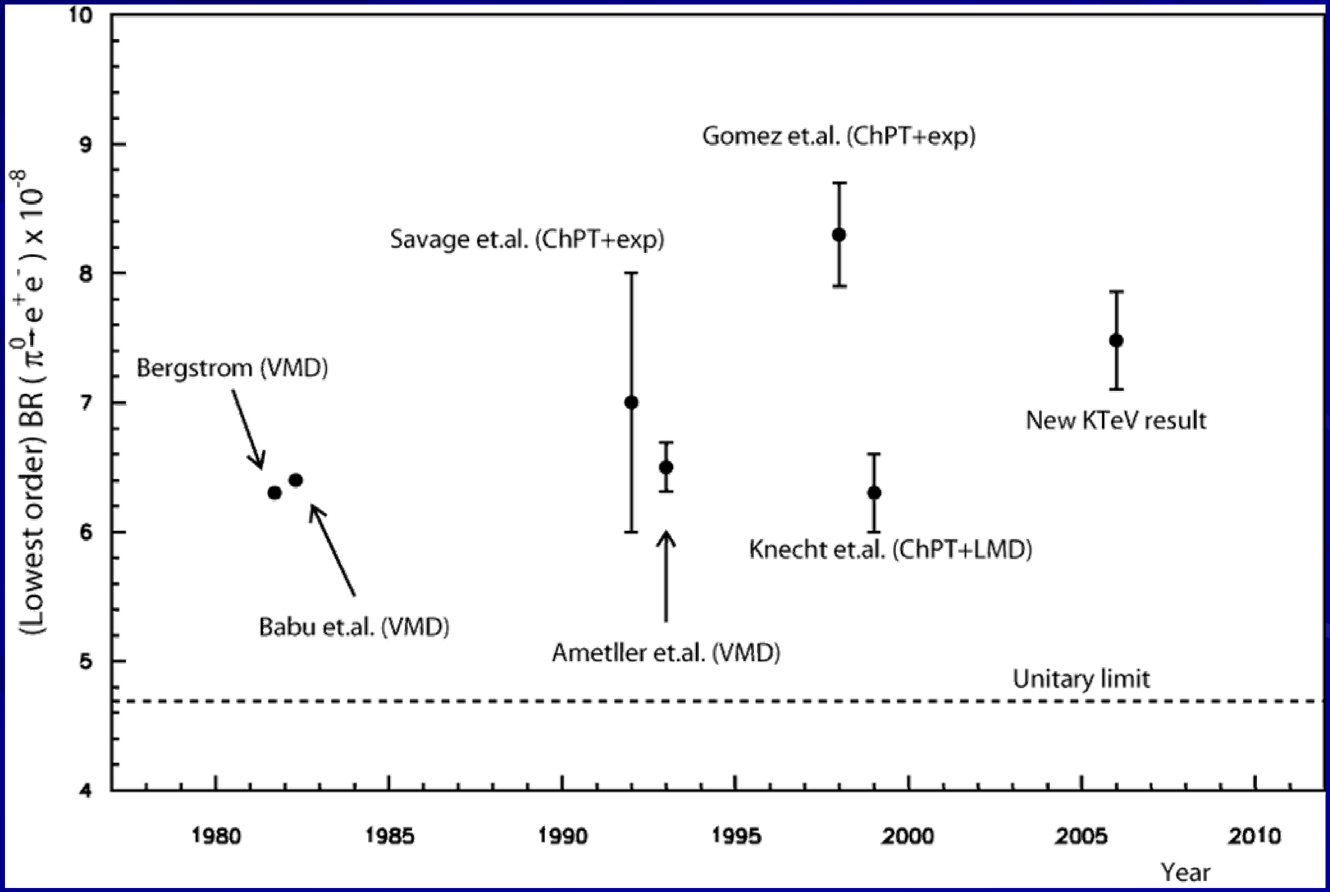
Preliminary $\pi^0 \rightarrow e^+e^-$ Results

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

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

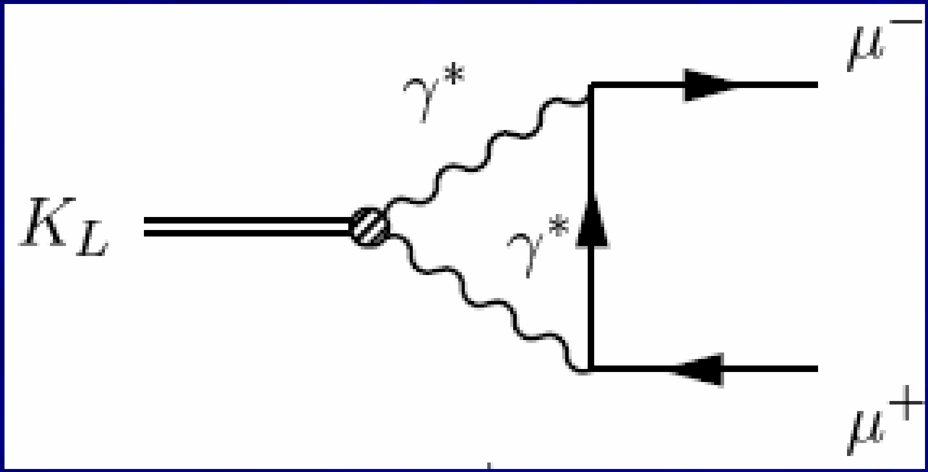
$$BR(\pi^0 \to e^+e^-, x > 0.95) = (6.56 \pm 0.26(stat) \pm 0.23(sys)) * 10^{-8}$$

- The systematic error now includes:
  - 2.7% Dalitz branching ratio uncertainty
  - 0.5% π^0 slope parameter uncertainty
- The plots shows a comparison between the tree level rate and various theory calculations

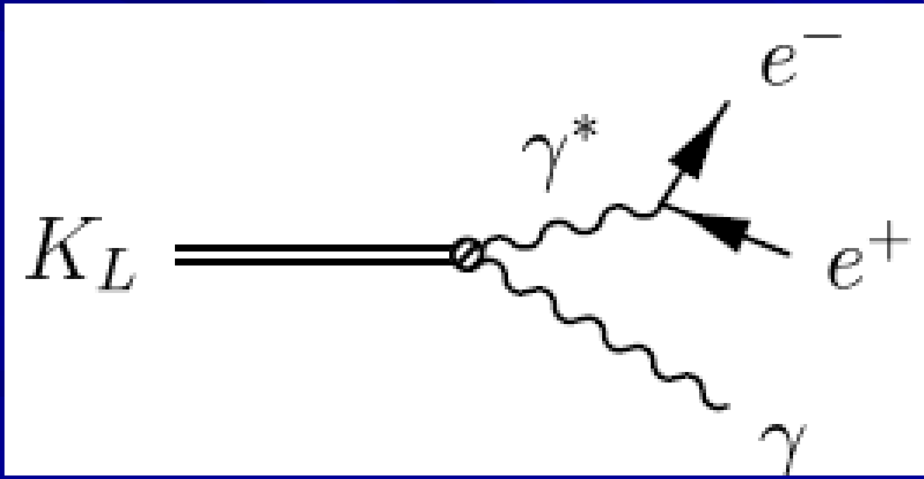


The Decay $K_L \to e^+e^-\gamma$

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



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



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

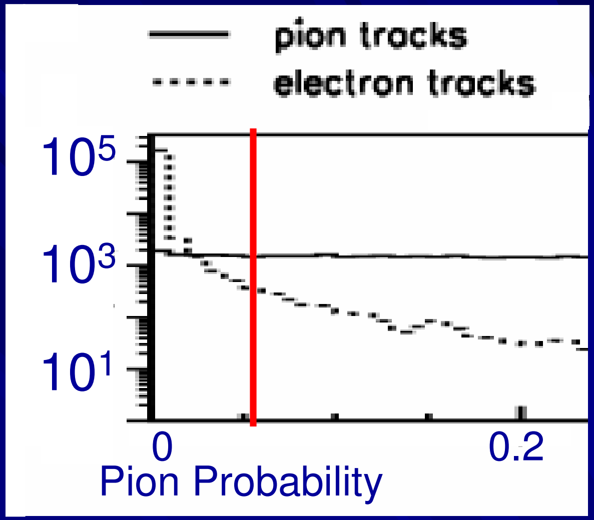
$K_L\gamma^*\gamma$ Form Factor

- 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

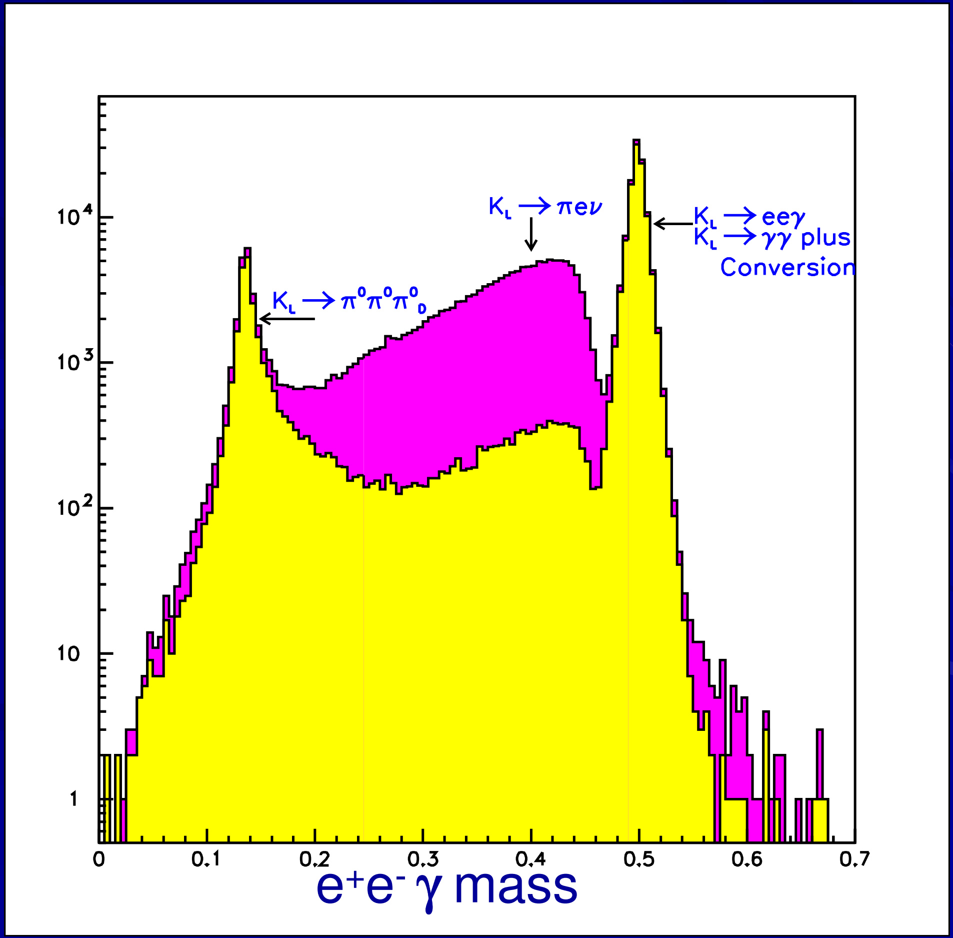
$$f_{BMS}(x) = \frac{1}{1 - x \cdot \frac{M_K^2}{M_\rho^2}} + \frac{\boxed{C \ \alpha_{K*}}}{1 - x \cdot \frac{M_K^2}{M_{K*}^2}} \left(\frac{4}{3} - \frac{1}{1 - x \cdot \frac{M_K^2}{M_\rho^2}} - \frac{1}{9}\frac{1}{1 - x \cdot \frac{M_K^2}{M_\omega^2}} - \frac{2}{9}\frac{1}{1 - x \cdot \frac{M_K^2}{M_\phi^2}}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

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

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

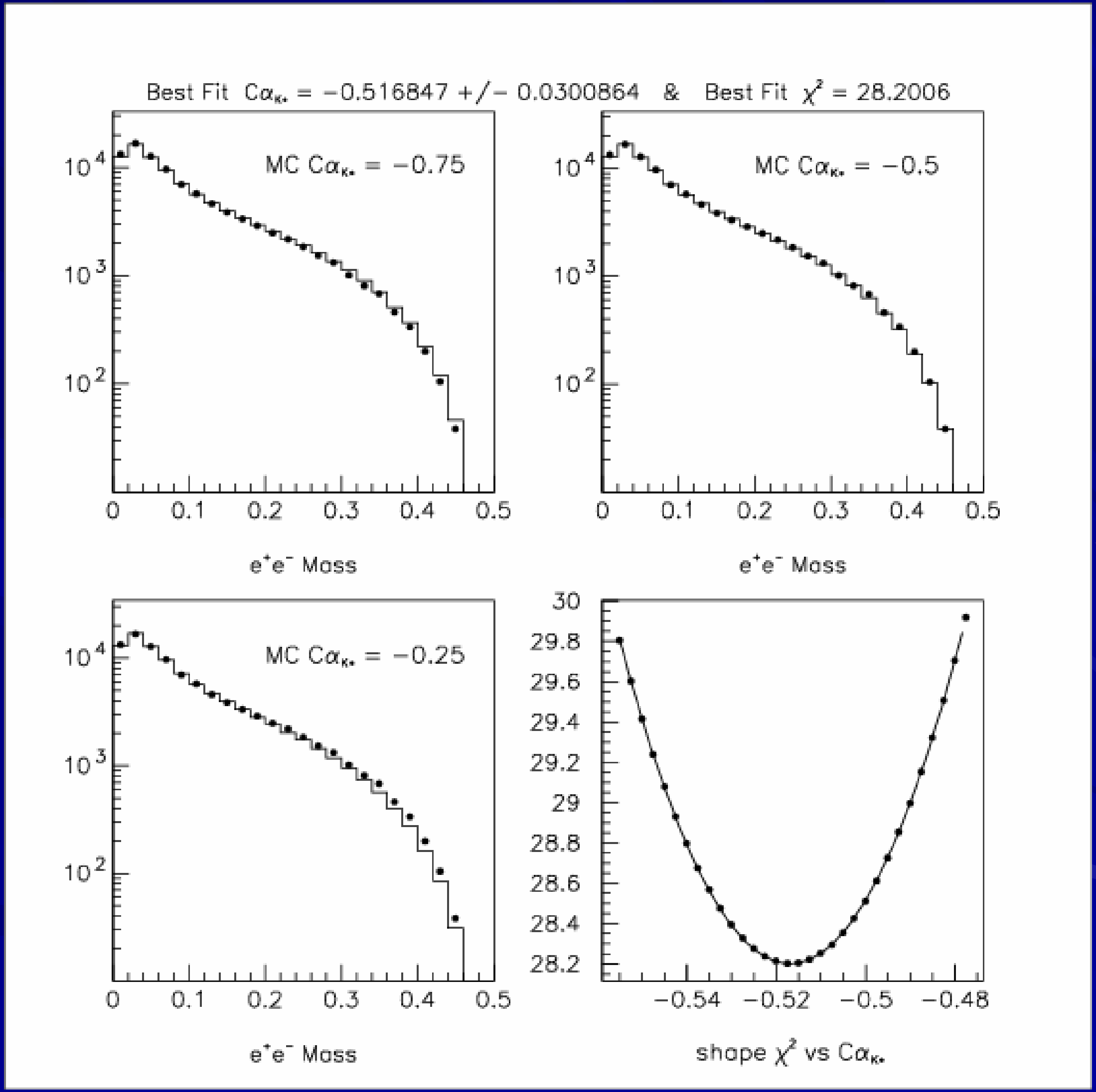


- The main background is $K_L \to \pi^\pm e^\mp \nu$ with an accidental γ where the $\pi^\pm$ is misidentified as an $e^\pm$
- Using the π/e separation provided by the TRD, this background is greatly reduced



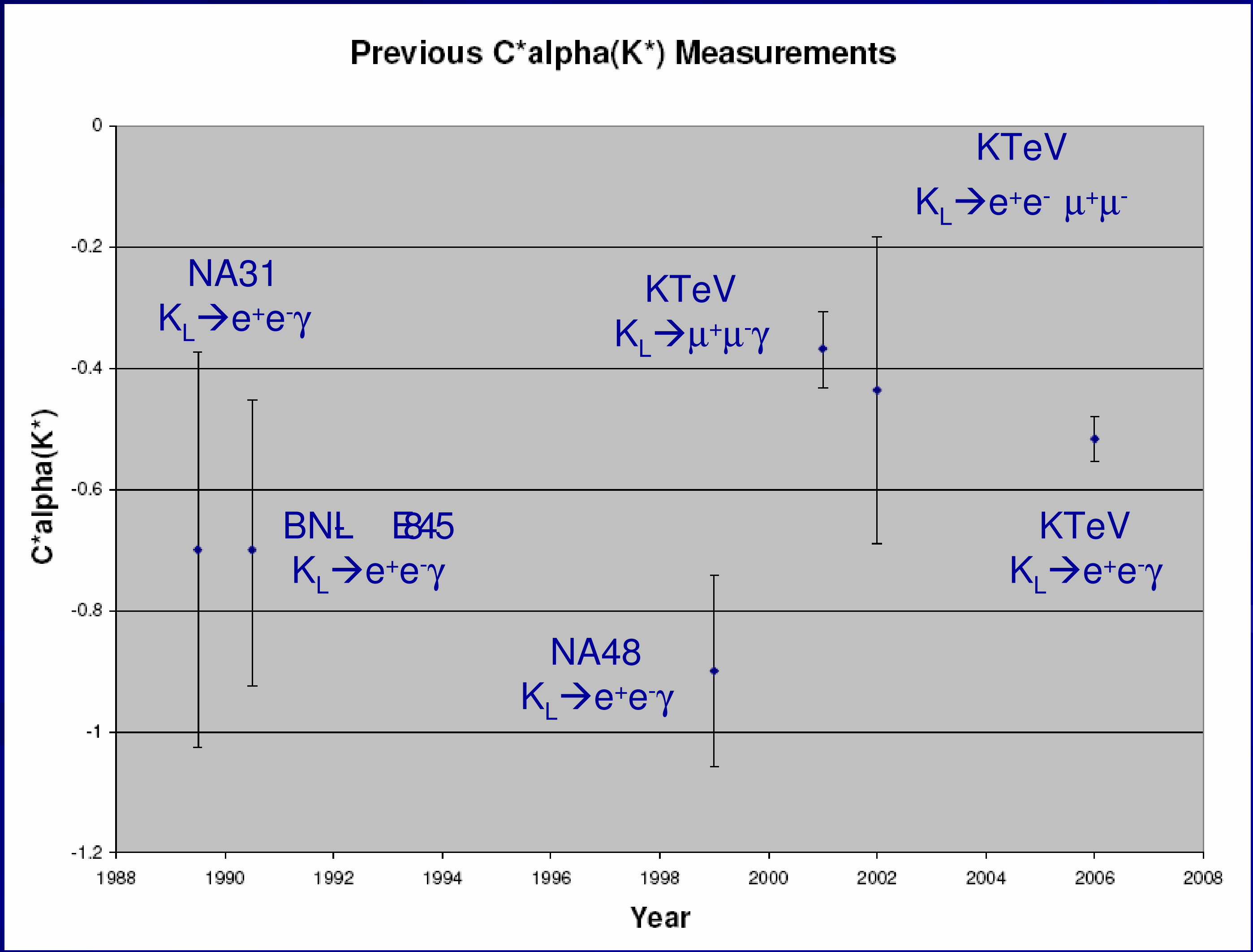
$K_L \to e^+e^-\gamma$ Form Factor Measurement

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



Corrected Preliminary $K_L \to e^+e^-\gamma$ Results

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



Summary

- Preliminary $K_L \to \pi^+\pi^-\gamma$ Results
  - $g_{M1} = 1.198 \pm 0.035(stat) \pm 0.086(syst)$
  - $a_1/a_2 = -0.738 \pm 0.007(stat) \pm 0.018(syst)$
  - $g_{E1} < 0.21$ (90% confidence)
- Preliminary $K_L \to \pi^0\pi^0\gamma$ Results
  - $BR(K_L \to \pi^0\pi^0\gamma) < 2.52 * 10^{-7}$ (90% confidence)
- Preliminary $K_L \to \pi^\pm e^\mp \nu e^+e^-$ Results
  - $BR(K_L \to \pi^\pm e^\mp \nu e^+ e^-, M_{e^+e^-} > 5MeV/c^2)$
    $= (1.606 \pm 0.012(stat)\ ^{+0.026}_{-0.016}(syst) \pm 0.045(ext\ syst)) * 10^{-5}$
- Preliminary $\pi^0 \to e^+e^-$ Results
  - $BR(\pi^0 \to e^+e^-) = (6.56 \pm 0.26(stat) \pm 0.23(syst)) * 10^{-8}$
- Corrected Preliminary $K_L \to e^+e^-\gamma$ Results
  - $BR(K_L \to e^+e^-\gamma)$
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