KTeV Results on Radiative Decays

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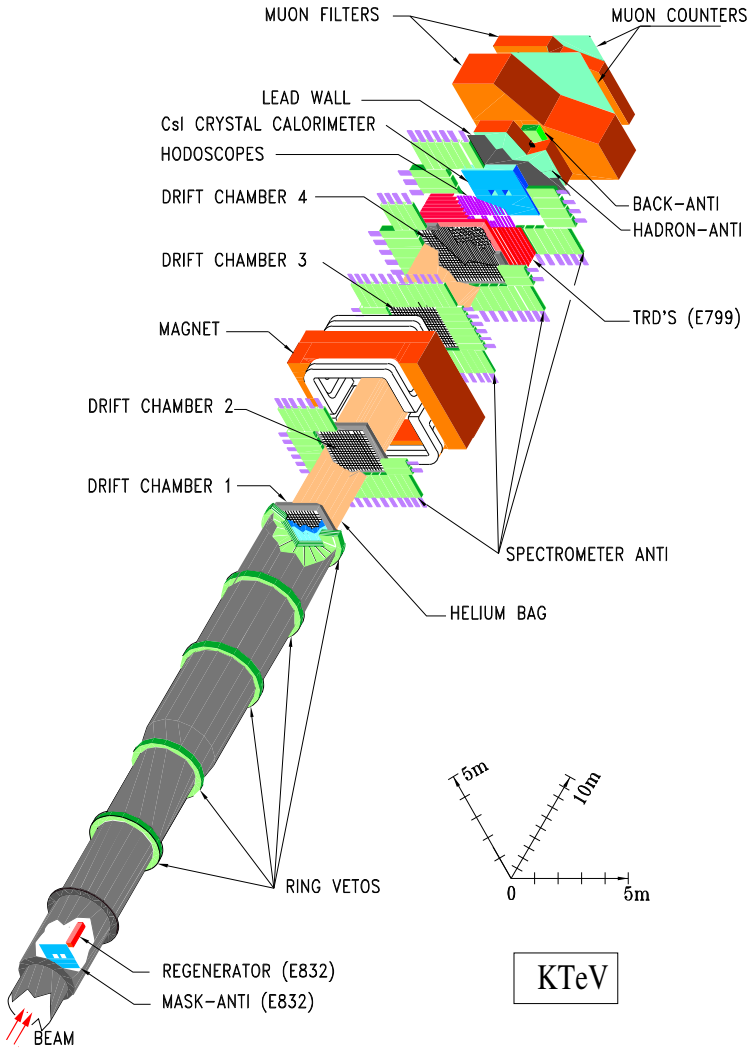
(KTeV Collaboration)

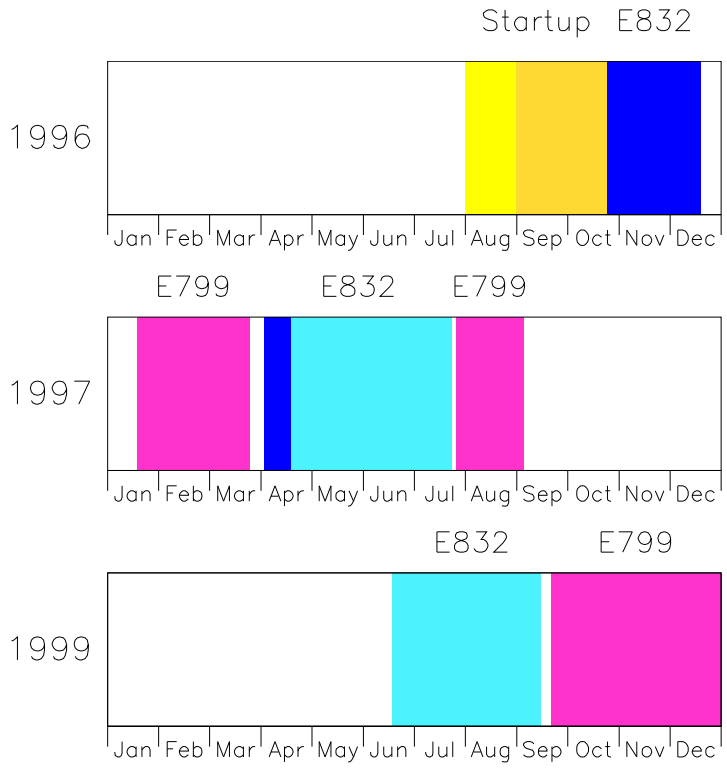
- The KTeV Experiment
- Probe of ChPT.
  - $K_L \to \pi^0\gamma\gamma$
  - $K_L \to \pi^0 e^+ e^- \gamma$
  - $K_L \to \pi^\pm e^\mp \nu e^+ e^-$
- Summary

The KTeV Detector

- CsI Calorimeter
  - Energy Resolution:
    $\sigma(E)/E = 2.0\%/\sqrt{E} \oplus 0.45\%$
  - Spatial: $\sim$ 1mm.
  - π/e rejection $>$ 700.
- Spectrometer
  - Better than 100μm.
- Large TRDs
  - π/e rejection $>$ 200.
- Intense beams: 5×10^{12} p/spill
  - Low neutron component.

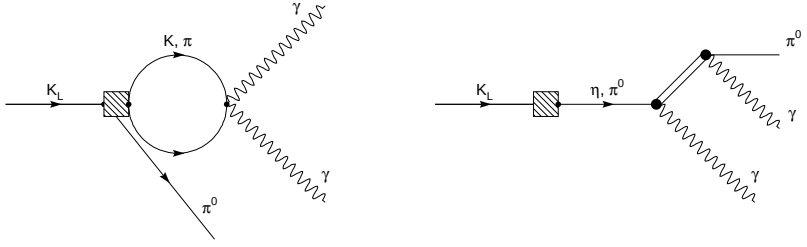


Data Sample



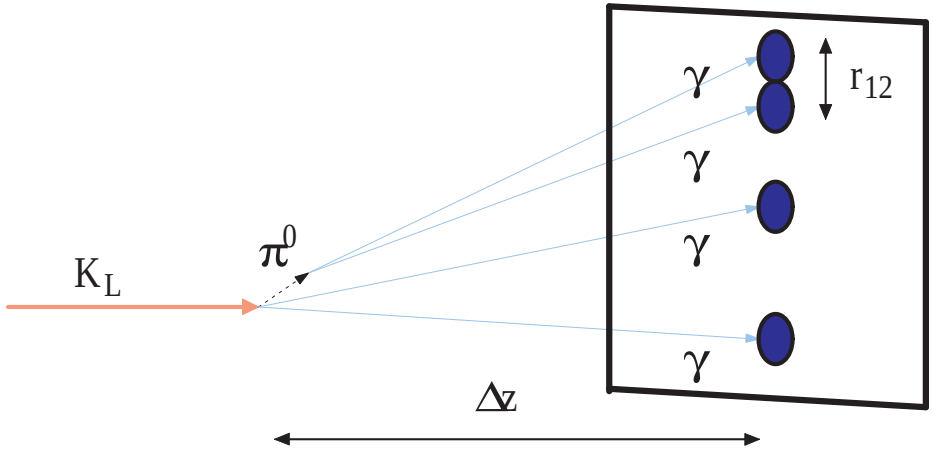
- ϵ'/ϵ Running (E832): 1996, 1997, 1999
- Rare decay Running (E799): 1997, 1999
- Analyses shown utilize full E832/E799 data sets.

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



- $\mathcal{O}(p^4)$ chiral perturbation calculations
  - No free parameters $\to$ BR$(K_L \to \pi^0\gamma\gamma) = 0.6 \times 10^{-6}$
  - Prediction low by factor of 2-3.
  - $\mathcal{O}(p^6)$ calculations increase rate.
  - Addition of VMD terms further increases rate (a_V).
- Results from $K_L \to \pi^0\gamma\gamma$ can determine CP violating/conserving contributions to $K_L \to \pi^0 e^+ e^-$.

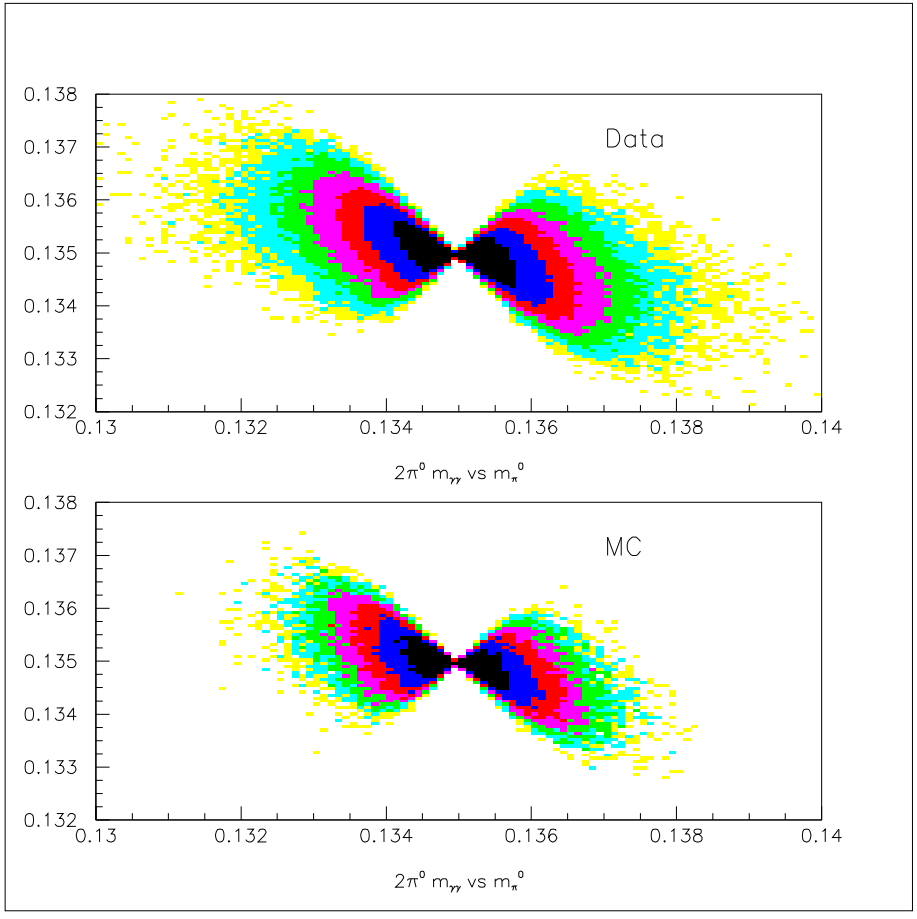
$K_L \to \pi^0\gamma\gamma$ Event Topology



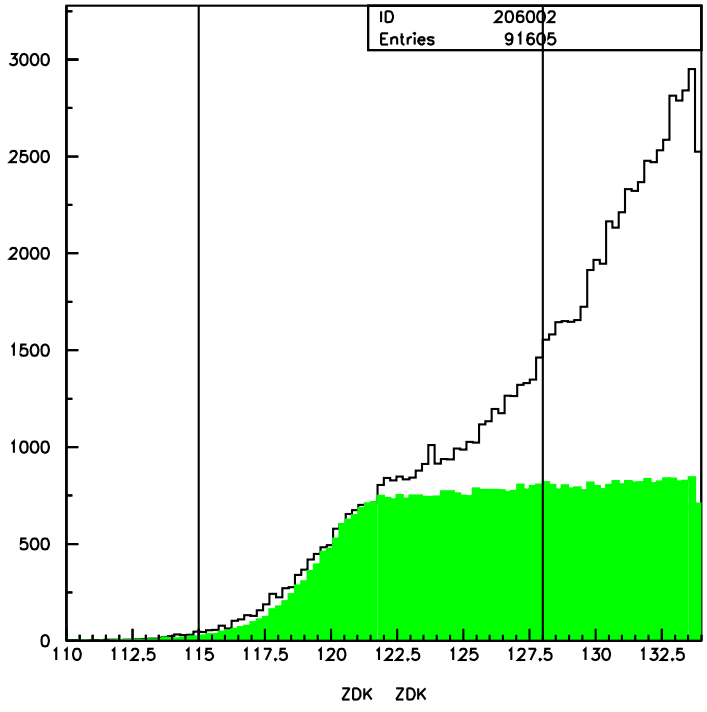
- Four photons.
  - Three possible combinations of photons.
- Form $\gamma\gamma$ mass combinations.
  - Choose combination with best π^0 mass.
  - Only one combination per event.
- $m_{\gamma\gamma} \times \Delta z = \sqrt{E_1 E_2} \times r_{12}$
  - Cannot reconstruct kaon mass.

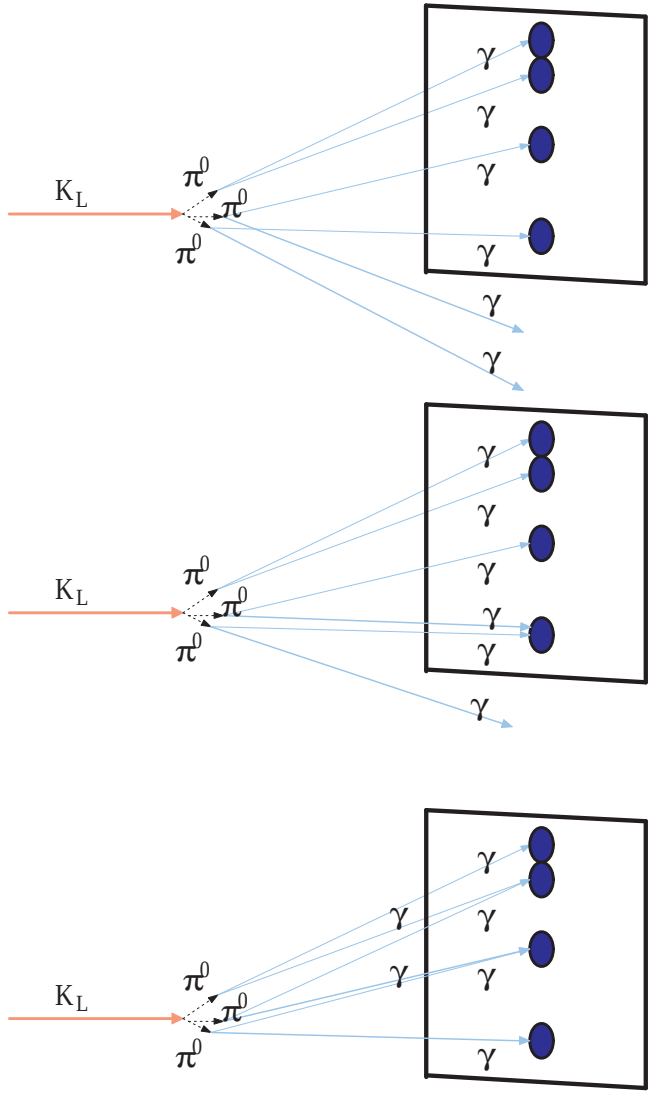
$K_L \to 2\pi^0$ Background

- $K_L \to 2\pi^0$ decays have same topology as signal.
- Three possible combinations of four photons.
- Reject events where both $\gamma\gamma$ combinations form good π^0.



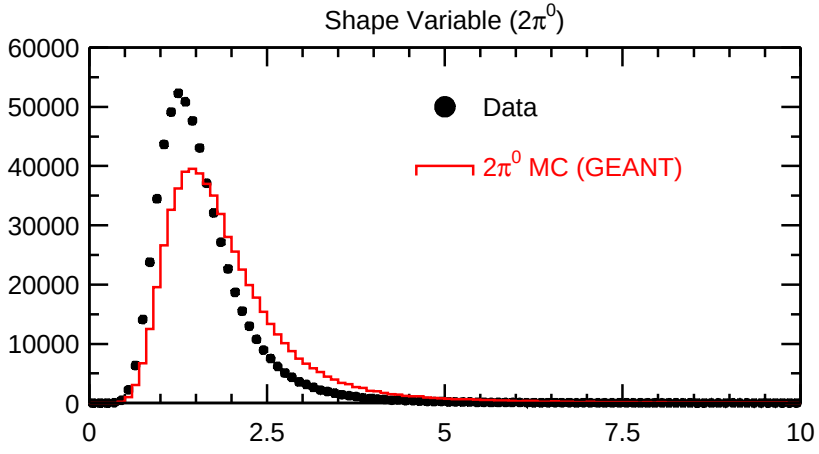
$K_L \to 3\pi^0$ background

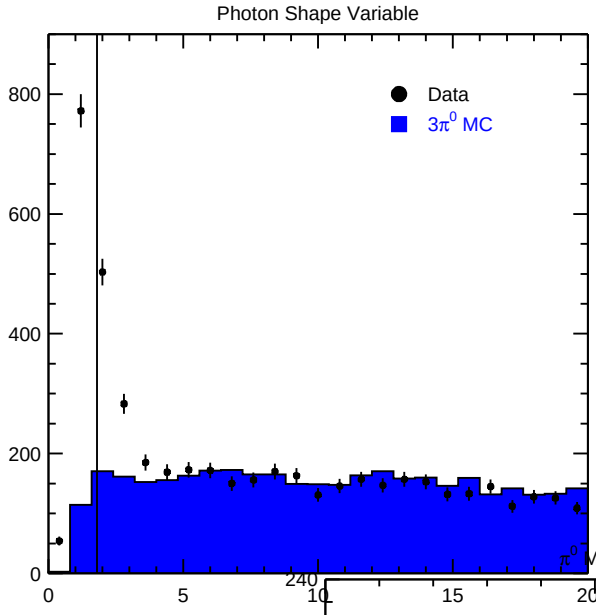


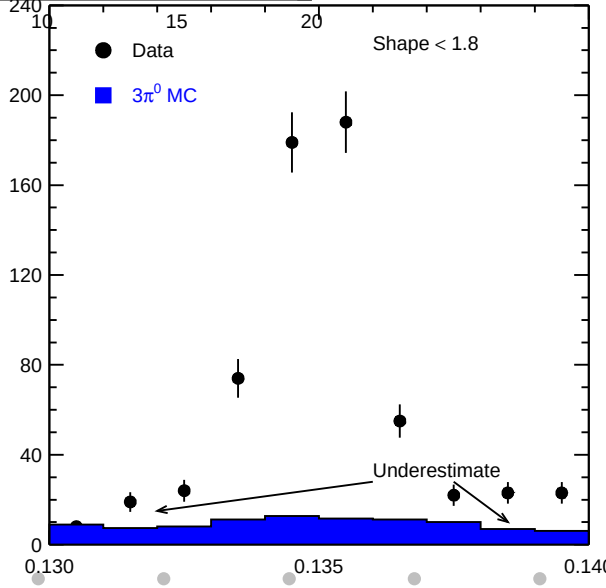


- Major background comes from $3\pi^0$ decays with 4 clusters in the calorimeter.
  - With missing γ, event reconstructs downstream.
  - Photon vetoes help reduce this background.

Photon Shape from Published Result

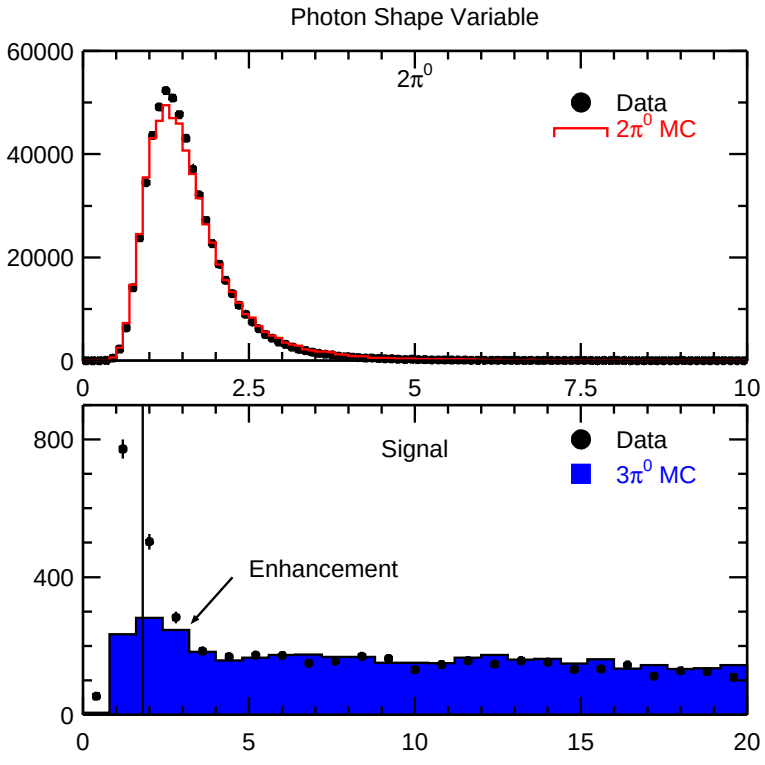




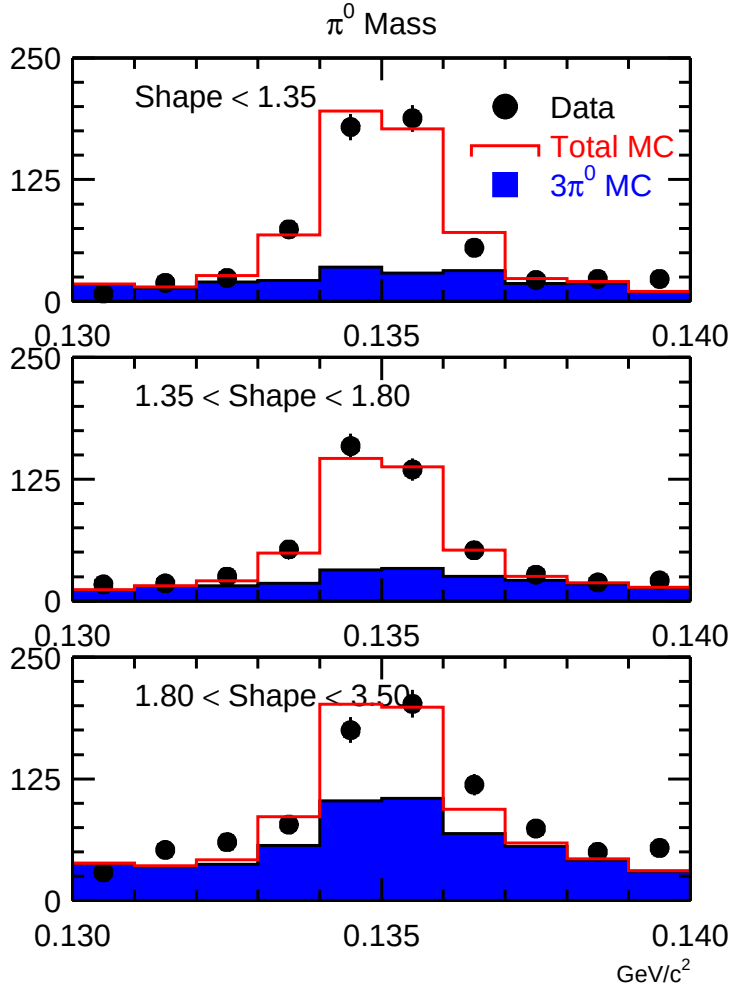


- Photon shape variable used to reduce background from $K_L \longrightarrow \pi^0\pi^0\pi^0$ events.
- Shape variable mismatch between data and MC.
- Underestimates $3\pi^0$ background in regions of low photon shape variable.

Improved Photon Simulation

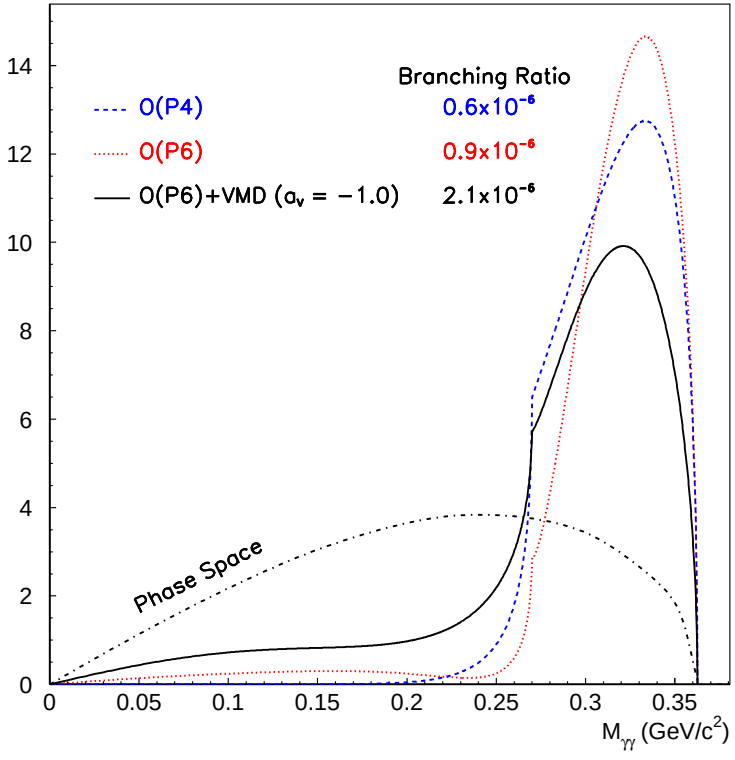


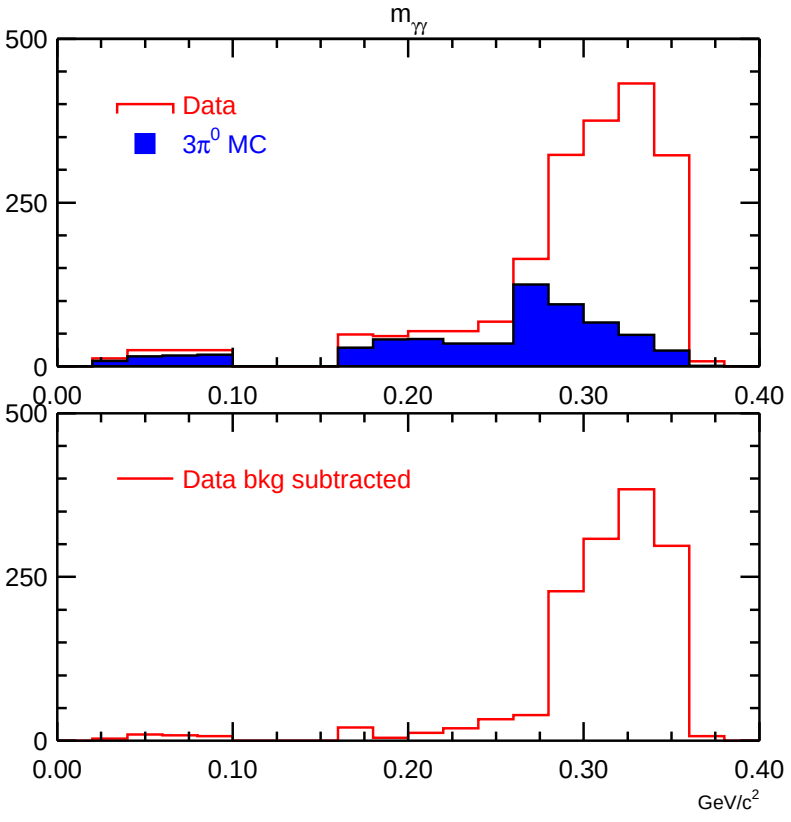
- Use data to model showers.
- Better data/MC agreement.
- Result: Increase of background.



- Better agreement in m_{π^0} tails.

Final $\gamma\gamma$ Mass





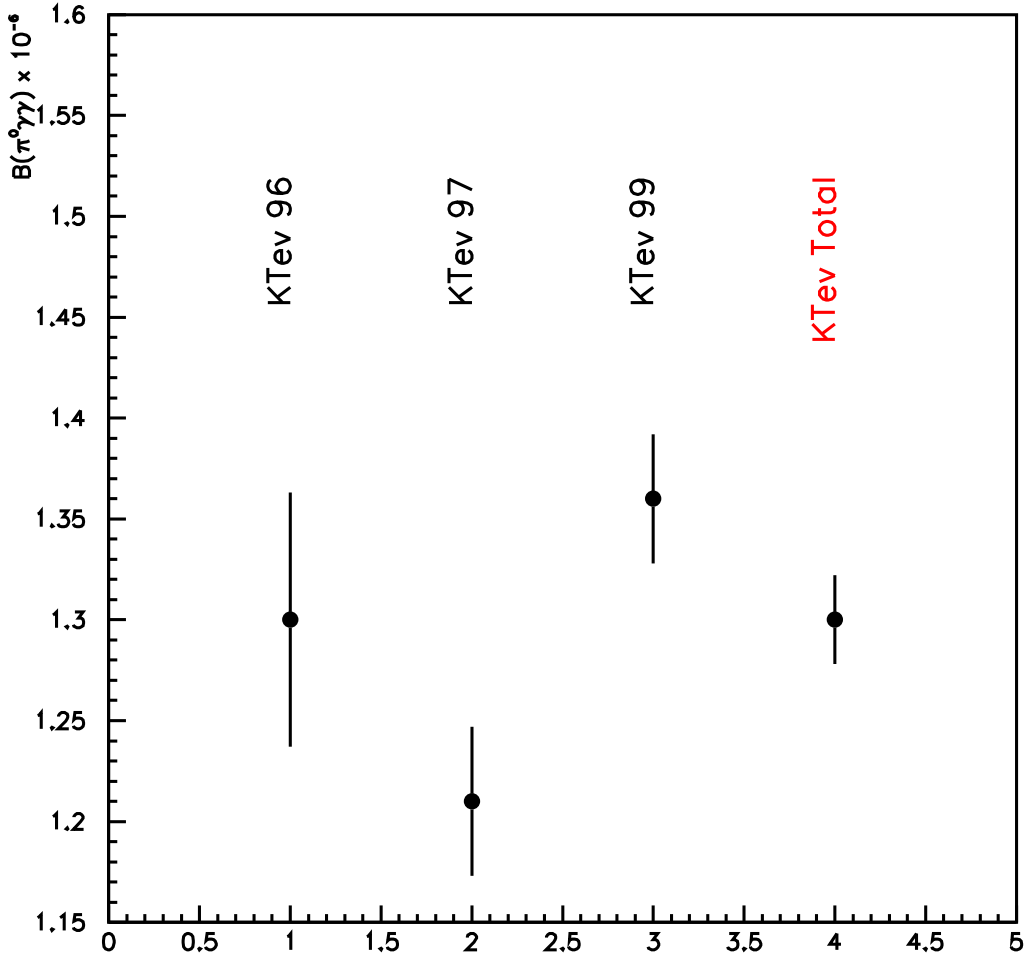
- Candidates: 1982, Background: 601, $K_L \to 2\pi^0$ events: 919,322

Branching Ratio Results

Source of Uncertainty	Percent	
a_V dependence	1.5	
$3\pi^0$ background	1.3	
MC statistics		1.0
Normalization		0.9
Photon Shape	1.1	
Tracking Chambers	0.9	
$2\pi^0$ branching ratio	0.9	
Photon vetoes	0.9	
Kaon Energy	0.7	
Decay Vertex	0.4	
Total	2.9	

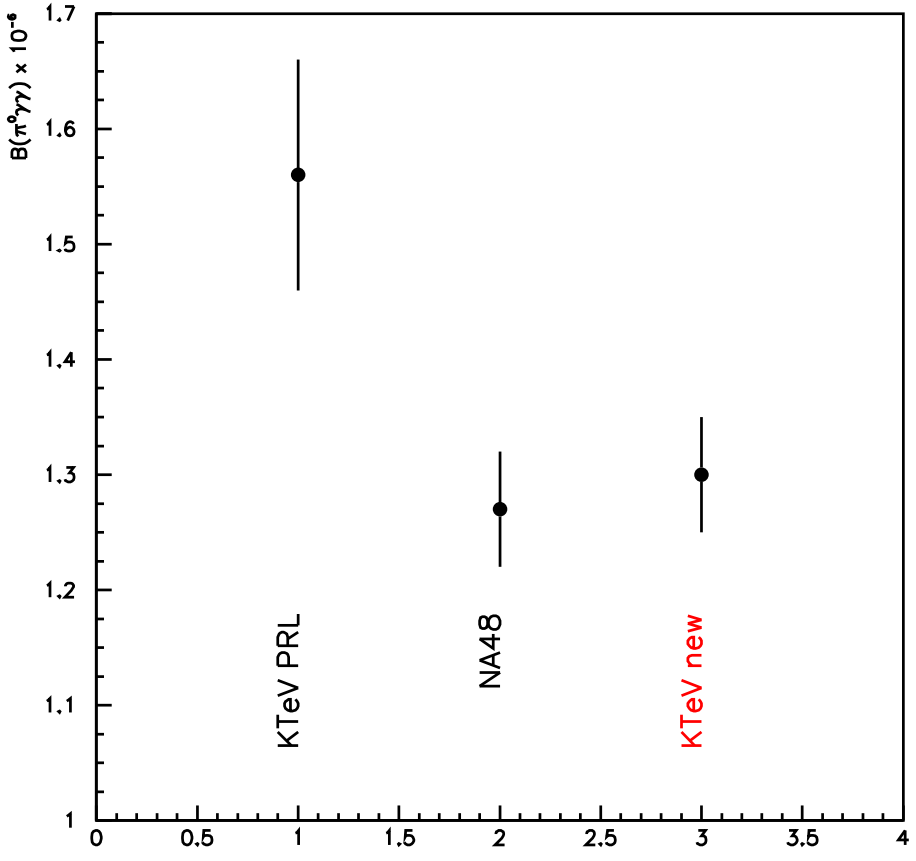
KTeV Preliminary

BR = $(1.30 \pm 0.03 \pm 0.04) \times 10^{-6}$

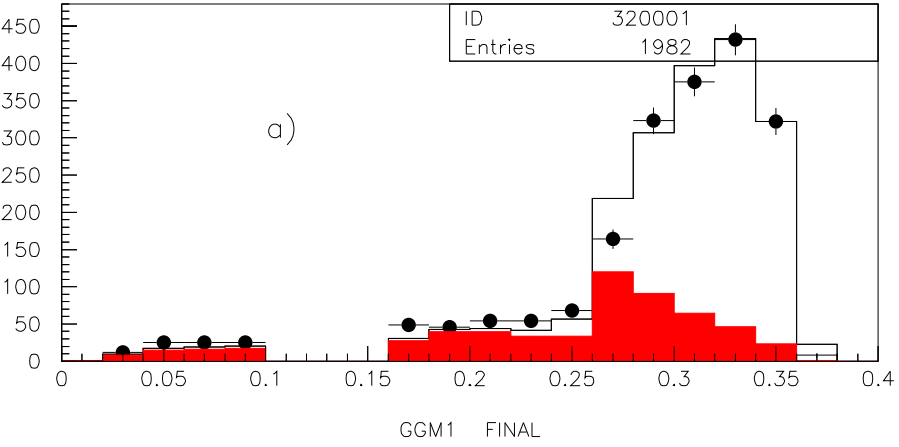


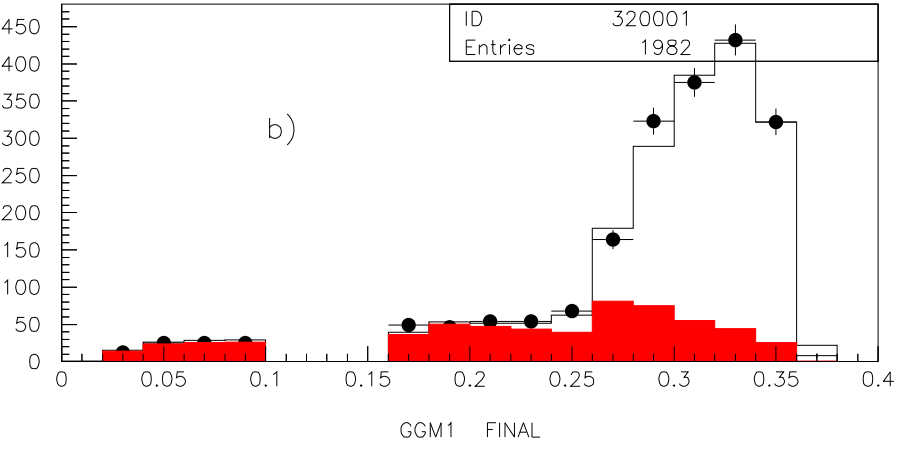
Branching Ratio Results

- Underestimate of background led to higher value in previous KTeV result.
  - New results consistent with published NA48 result.
- Result supercedes previous KTeV result.
- All BR adjusted to new $K_L \to \pi^0\pi^0$ BR.



a_V Measurement

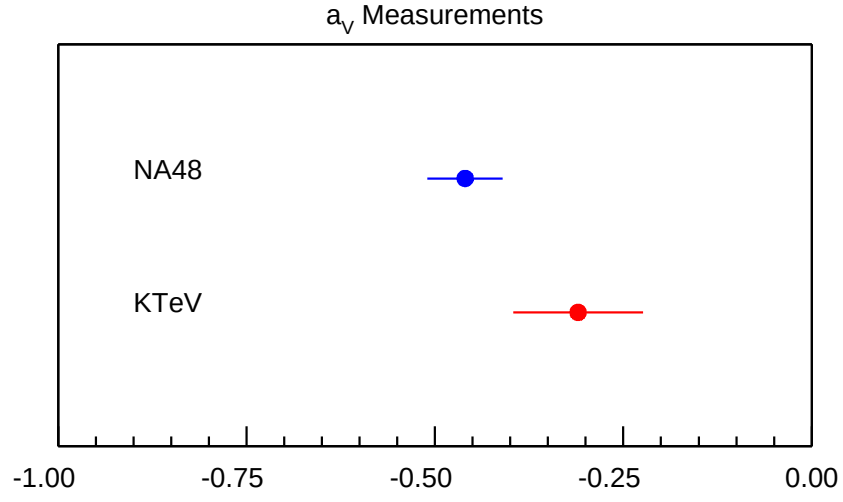




KTeV Preliminary

$$a_V = -0.31 \pm 0.05 \pm 0.07$$

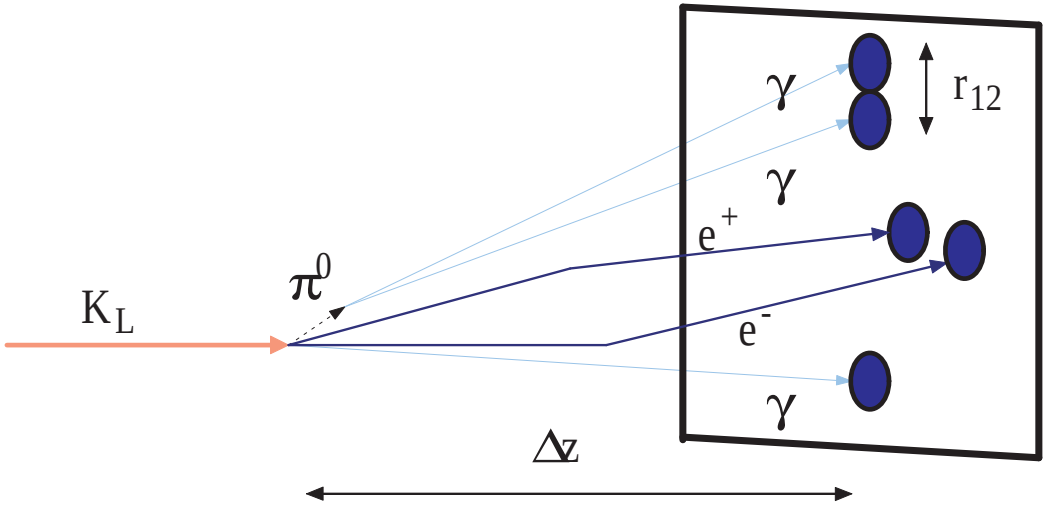
Source of the error	Error (%)
Photon veto cut	12.6
Z vertex cut	15.5
$3\pi^0$ background composition	8.5
$3\pi^0$ background level	6.9
Photon shape	3.6
Total	23.1



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

- BR($K_L \to \pi^0 e^+ e^- \gamma$) > BR($K_L \to \pi^0 e^+ e^-$).
  - CP violation in $K_L \to \pi^0 e^+ e^-$.
- Measurement of $K_L \to \pi^0 e^+ e^- \gamma$ useful for understanding $K_L \to \pi^0 e^+ e^-$ dynamics.
  - Similar spectrums for $K_L \to \pi^0 e^+ e^- \gamma$ and $K_L \to \pi^0 \gamma\gamma$.
- ChPT Predictions:
  - $O(p^4)$: 1.0×10^{-8}.
  - $O(p^6)$: 2.4×10^{-8} [PRD 56, 1605].
- KTeV Result: BR = $(2.34 \pm 0.35 \pm 0.13) \times 10^{-8}$ [PRL 87, 21801 (2001)]
  - Note: Also used old $K_L \to \pi^0 \pi^0$ BR.

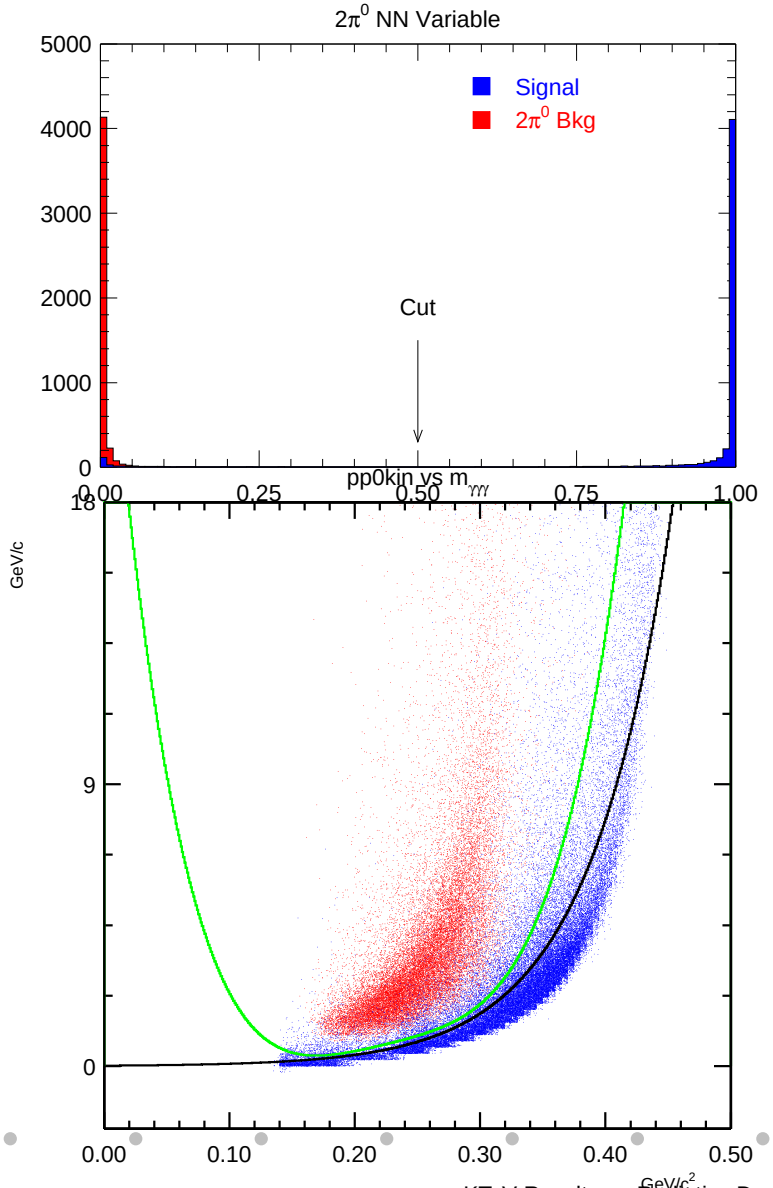
$K_L \to \pi^0 e^+ e^- \gamma$ Topology



- Three photons and two electrons.
  - Three possible combinations of photons.
- Form $\gamma\gamma$ mass combinations.
  - Choose combination with best π^0 mass.
- Decay vertex from e^+e^- pair.
  - Allows one to reconstruct kaon mass.

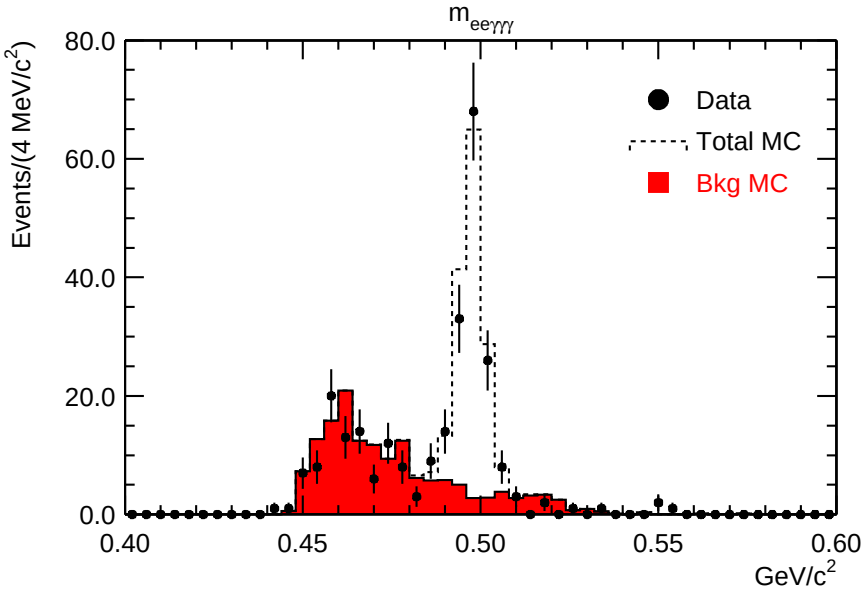
$K_L \to \pi^0 e^+ e^- \gamma$ Backgrounds

- Reduce $K_L \to \pi^0 \pi^0$ backgrounds using a neural net.
  - Same topology as signal.
  - Use $m_{\gamma\gamma}$ and $m_{e^+e^-\gamma}$ to form neural net.
- Reduce $K_L \to \pi^0 \pi^0 \pi^0$ backgrounds using kinematics.
  - Use longitudinal momentum of e^+e^- in the kaon rest frame and $m_{\gamma\gamma\gamma}$.
  - Green curve (new), Black curve (PRL result).



Final Mass Plot

Systematic	Error (%)
MC Statistics	4.2
a_V dependence	3.8
K_L and π^0 BR	2.8
$3\pi^0$ bkg	0.8
acceptance	0.4
$2\pi^0$ background	0.1
Total	6.4



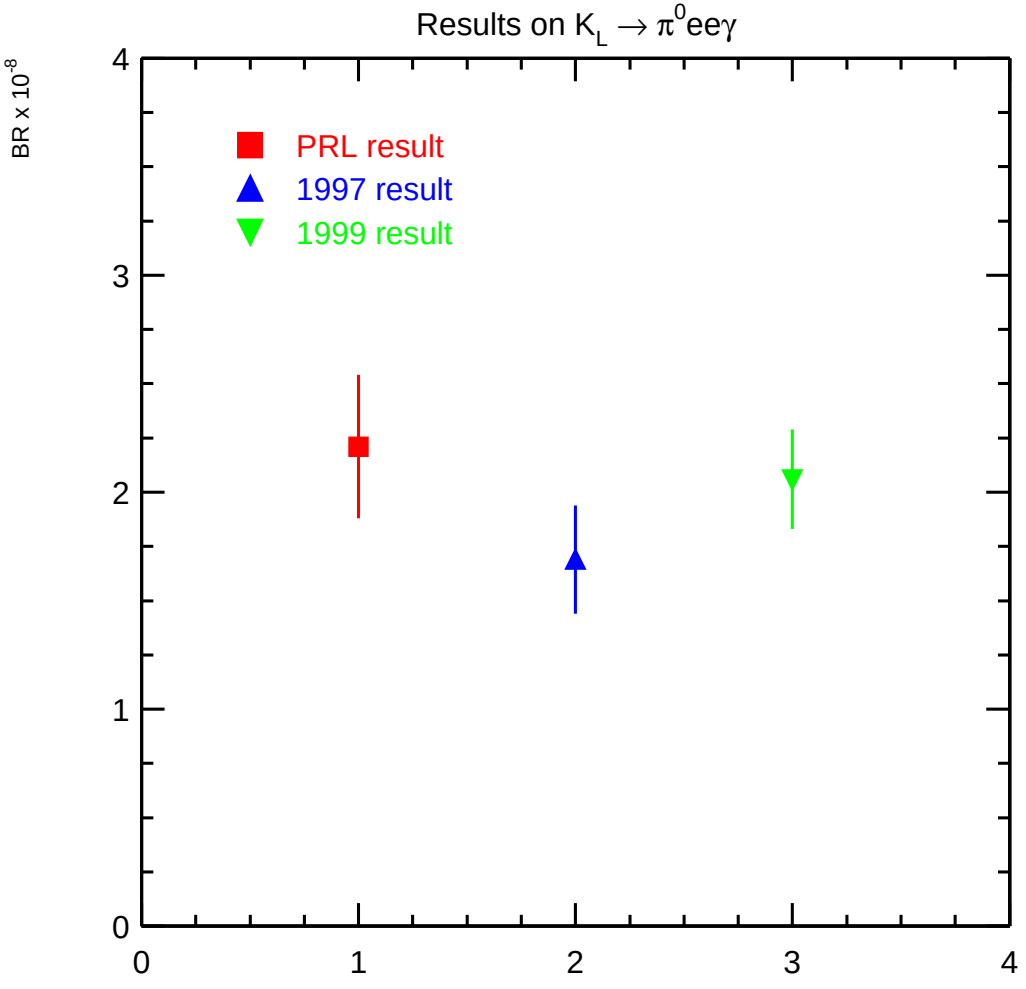
- 139 $K_L \to \pi^0 e^+ e^- \gamma$ candidate events.
- Background estimated to be 14.4 events from $2\pi^0$ and $3\pi^0$ events.
- Normalization mode is $K_L \to \pi^0 \pi^0_D$.

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

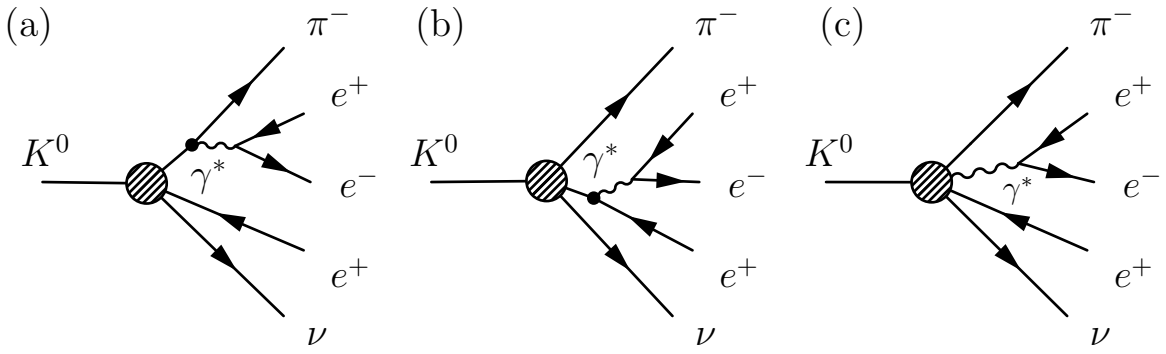
- Result from full 1997-1999 KTeV data.
- Consistent with previous result.
- Over 2$\times$ more data.

KTeV Preliminary

$$\mathrm{BR} = (1.90 \pm 0.16 \pm 0.12) \times 10^{-8}$$



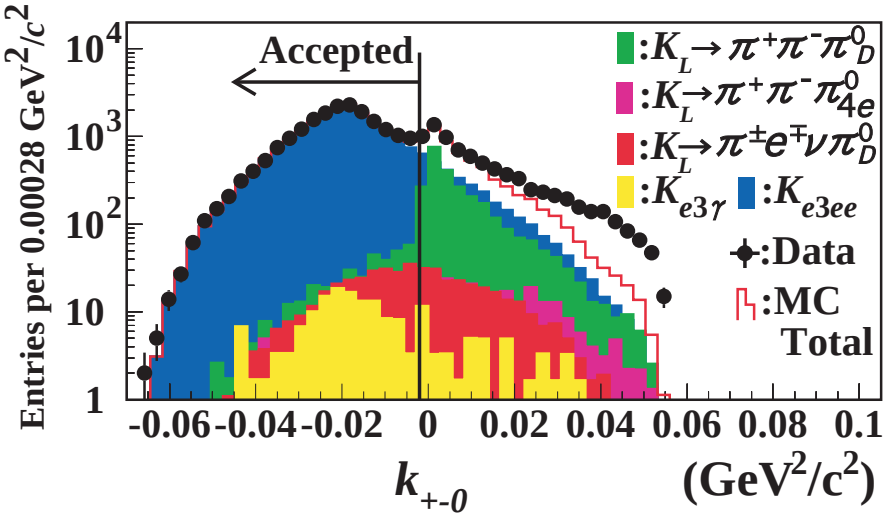
$K_L \to \pi e \nu e^+ e^-$ Introduction



- $K_L \to \pi^\pm e^\mp \nu e^+ e^-$
- Two possible mechanisms.
  - Inner bremsstrahlung (electron/pion)
  - Virtual photon radiated from intermediate state of $K - \pi$ current.
- Model of $K - \pi$ current can be used to study low energy QCD.
  - In particular NLO(p^4) ChPT. [J. Gasser *et al.*, Eur. Phys. J. **C40** 205 (2005)].
- Decay mode has not been seen before.

$K_L \to \pi e \nu e^+ e^-$ Reconstruction

- Require four tracks from common vertex: 3 electrons, 1 pion.
  - Two possible e^+e^- combinations.
  - Choose combination with smallest invariant mass.
- Backgrounds reduced using particle ID.
  - E/p in calorimeter.
  - Pion rejection from TRD.
- Remove $K_L \to \pi^\pm e^\mp \nu$ using $M_{e^+e^-} > 5$ MeV/c^2.



- Major background from $K_L \to \pi^+\pi^-\pi^0_D$ events with missing $\pi^\pm$ and γ conversion.
  - Suppressed with k_{+-0}.
  - Longitudinal momentum squared of π^0 in frame with $\pi^+\pi^-$ transverse to K_L.

$K_L \to \pi e \nu e^+ e^-$ Result

- 20,225 Candidate events
  - 1017.1 ± 24.7 background events.
- Dominant background is $K_L \to \pi^+ \pi^- \pi^0_D$.
  - Other contributions from $K_L \to \pi^\pm e^\mp \nu \pi^0_D$, $K_L \to \pi^+ \pi^- \pi^0_{4e}$, $K_L \to \pi^\pm e^\mp \nu \gamma$.

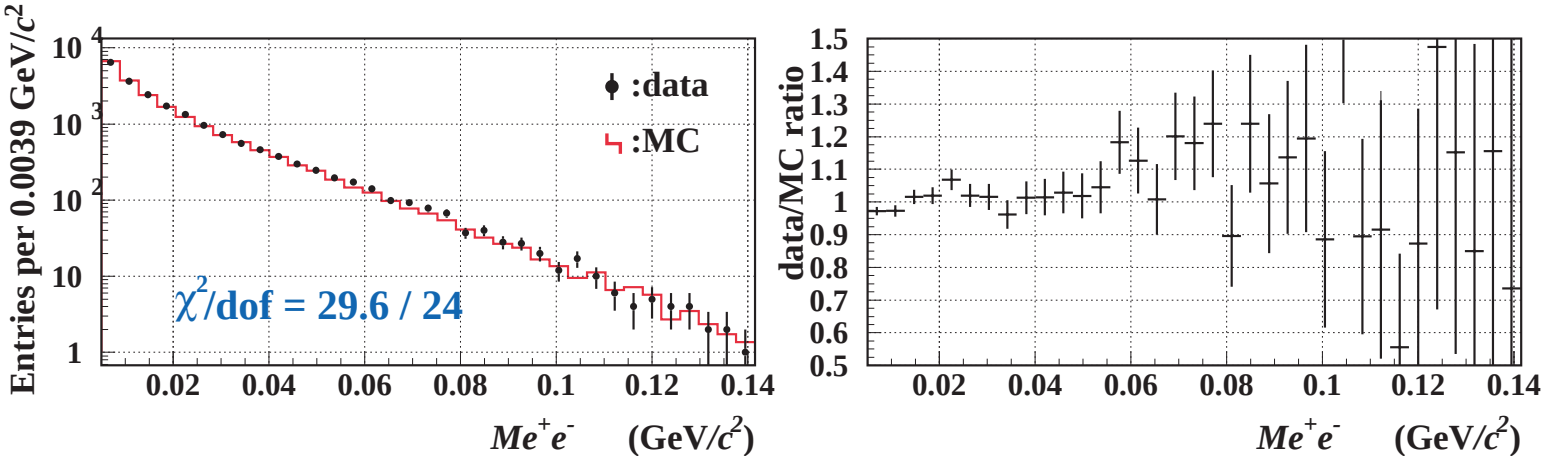
KTeV Preliminary

$$\text{BR} = (1.29 \pm 0.01 \pm 0.04) \times 10^{-5}$$

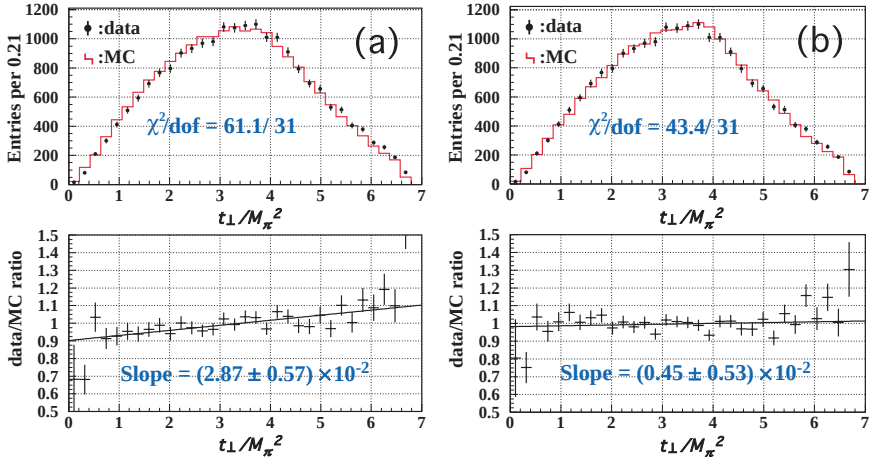
$M_{e^+e^-} > 5$ MeV/c^2, $E^*_{e^+e^-} > 30$ MeV

Systematic	Uncertainty
Unobserved Photon in Norm	1.03
Vertex χ^2 cut	0.70
Radiative Corrections	0.51
Efficiency correction	0.46
Kaon Energy	0.35
$M_{e^+e^-}$ cutoff	0.18
Background estimation	0.05
MC Statistics	0.32
Total	1.51

$K_L \to \pi e \nu e^+ e^-$ Dynamics



- NLO(p^4) ChPT models $K_L \to \pi e \nu e^+ e^-$ dynamics well.
- $K - \pi$ form factor can be characterized by the transverse momentum transfer.
  - Leading order calculation show data/MC mismatch.
  - Better agreement with NLO(p^4) ChPT model.



Summary

- New KTeV results. (Preliminary)
  - BR$(K_L \to \pi^0\gamma\gamma) = (1.30 \pm 0.03 \pm 0.04) \times 10^{-6}$
    - Resolves discrepancy between previous measurements.
    - Competitive with NA48 result.
  - BR$(K_L \to \pi^0 e^+ e^- \gamma) = (1.90 \pm 0.16 \pm 0.12) \times 10^{-8}$
    - Nearly $\times 2$ improvement over previous result.
  - BR$(K_L \to \pi^\pm e^\mp \nu e^+ e^-) = (1.29 \pm 0.01 \pm 0.04) \times 10^{-5}$
    - $M_{e^+e^-} > 5$ MeV/c^2, $E^*_{e^+e^-} > 30$ MeV.
    - First observation.
- Help to improve understanding of low energy theories.
  - Data consistent with ChPT.

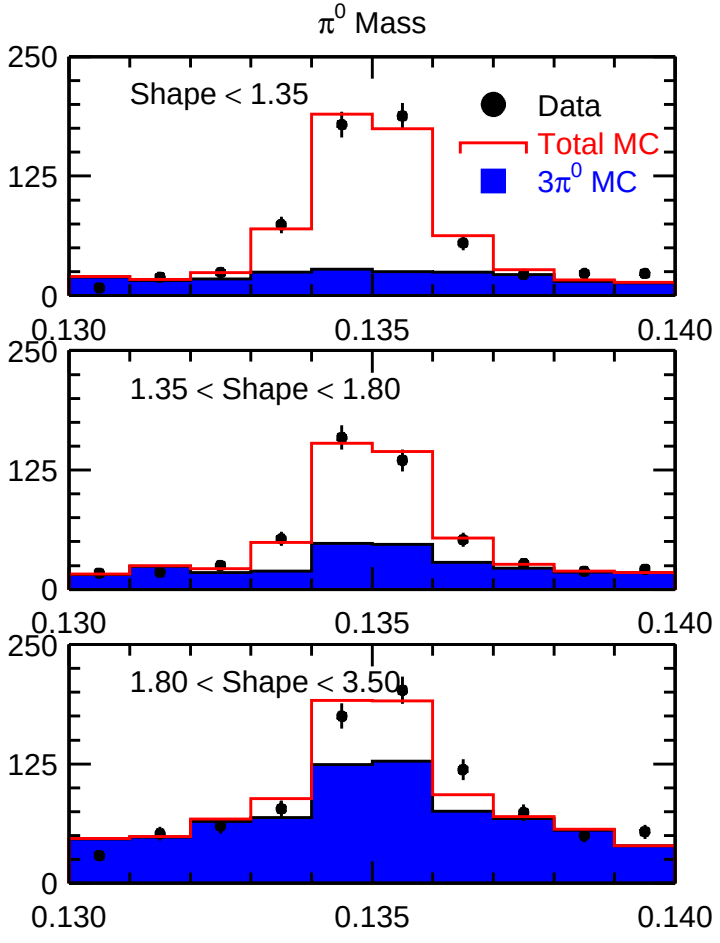
Backup Slides

Photon Shape Cross Check

- Crosscheck:
  - Reweight default $3\pi^0$ MC to match π^0 mass in bins of photon shape variable.
  - Similar bkg estimates.

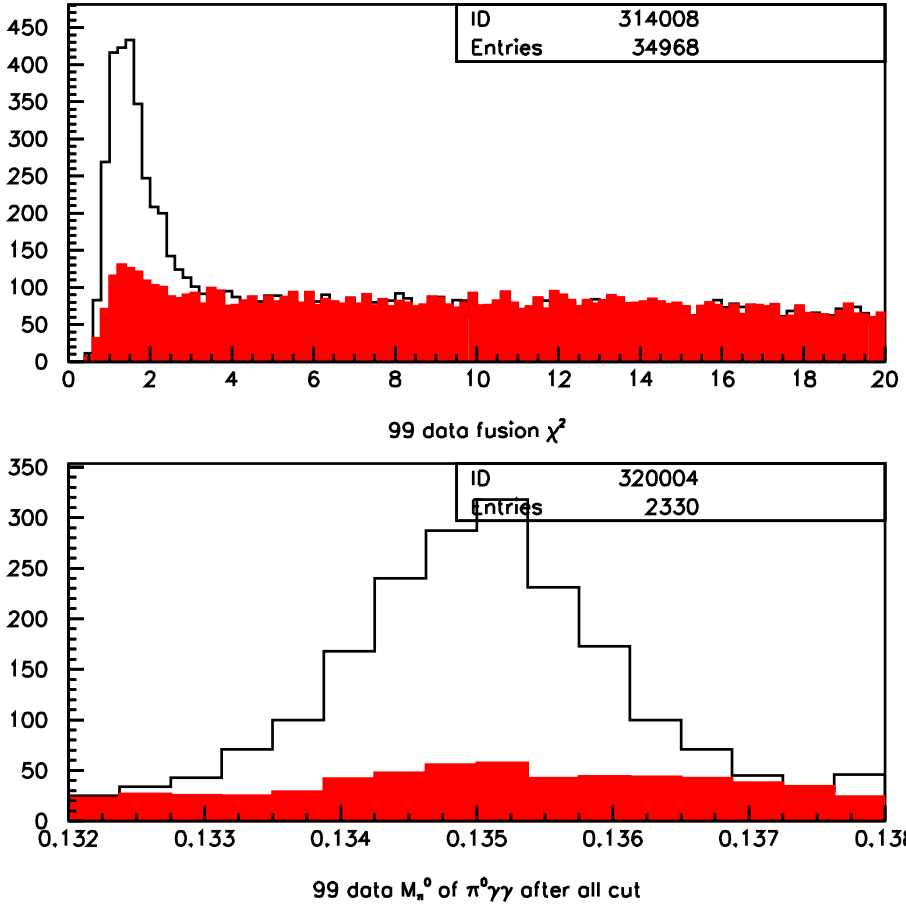
99 Data Bkg Estimate

MC Set	# Bkg
Default MC	157
New MC	288
Reweighted MC	323



Background Normalization

- After all cuts, background dominated by $K_L \to 3\pi^0$.
- Background normalized using $2\pi^0/3\pi^0$ branching ratios.
- Good agreement in photon shape and m_{π^0} distributions.



Data/MC comparisons

- Data/MC comparisons of high statistics $K_L \to 2\pi^0$ mode.
  - Left: Data (dots) MC (red hist)
  - Right: Data/MC ratio
- $K_L \to 2\pi^0$ variables.
  - Decay position
  - kaon energy
  - π^0 mass
  - shape variable