KTeV Results on Chiral Perturbation Theory

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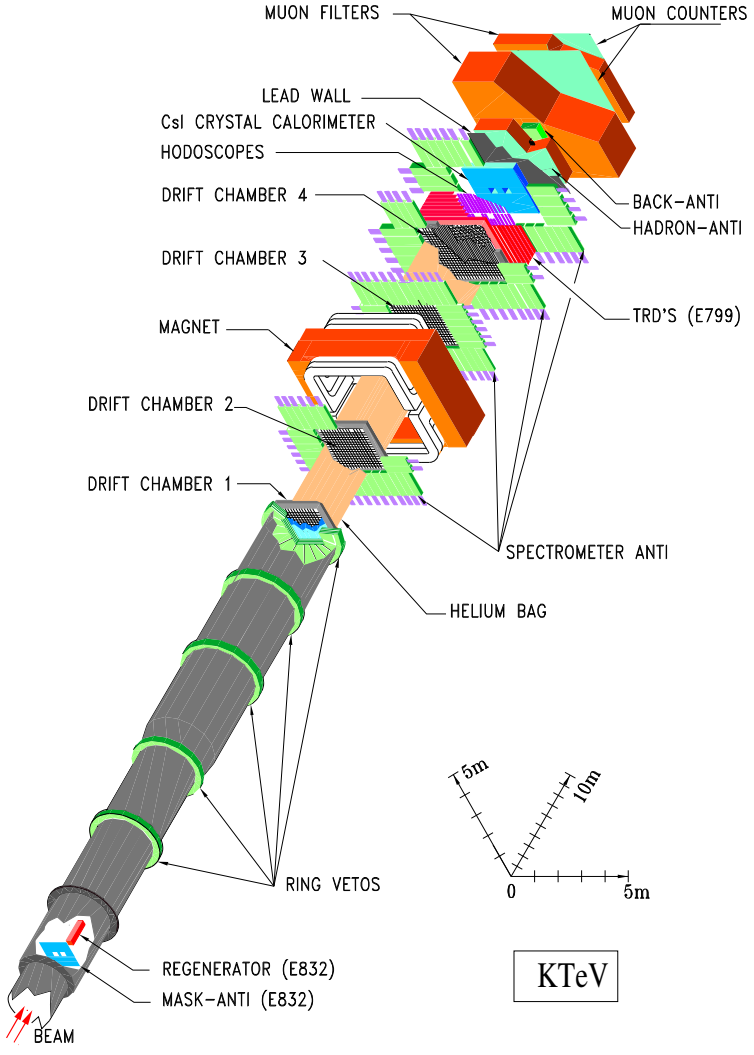
(KTeV Collaboration)

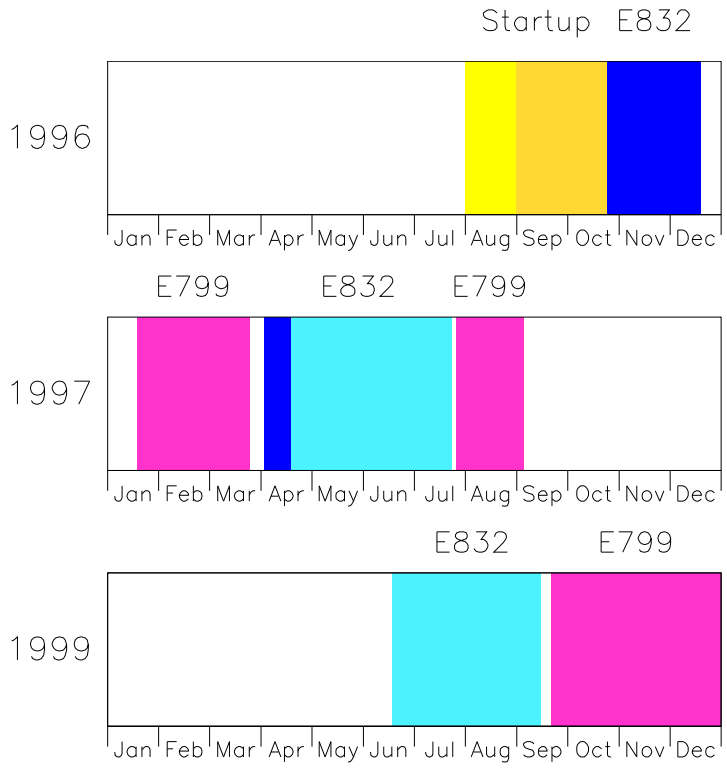
- The KTeV Experiment
- Probe of ChPT at $O(p^6)$.
  - $K_L \to \pi^0\gamma\gamma$
  - $K_L \to \pi^0 e^+ e^- \gamma$
  - $K_L \to \pi^0\pi^0\gamma$
- Summary

The KTeV Detector

- Calorimeter
  - 3100 CsI crystals.
  - Energy Resolution:
    $\sigma(E)/E = 2.0\%/\sqrt{E} \oplus 0.45\%$
  - Spatial: $\sim$ 1mm.
- Spectrometer
  - Better than 100μm.
- Clean beams.

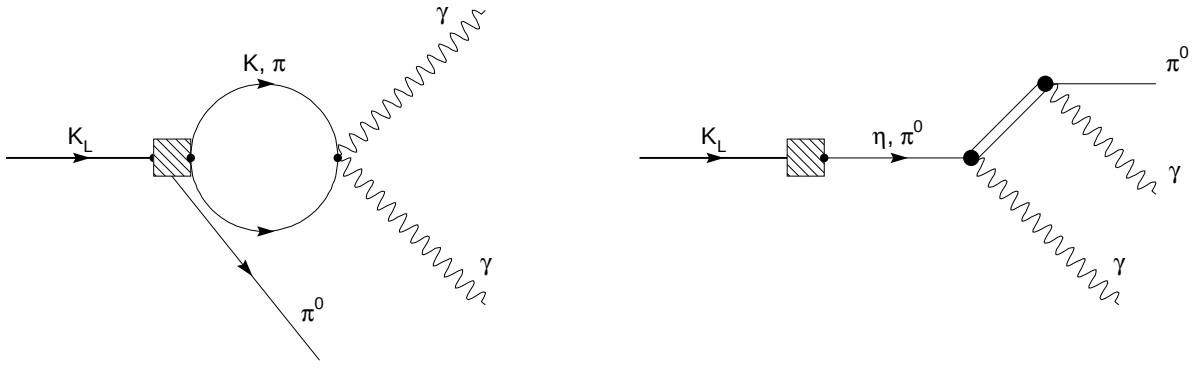


Data Sample



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

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

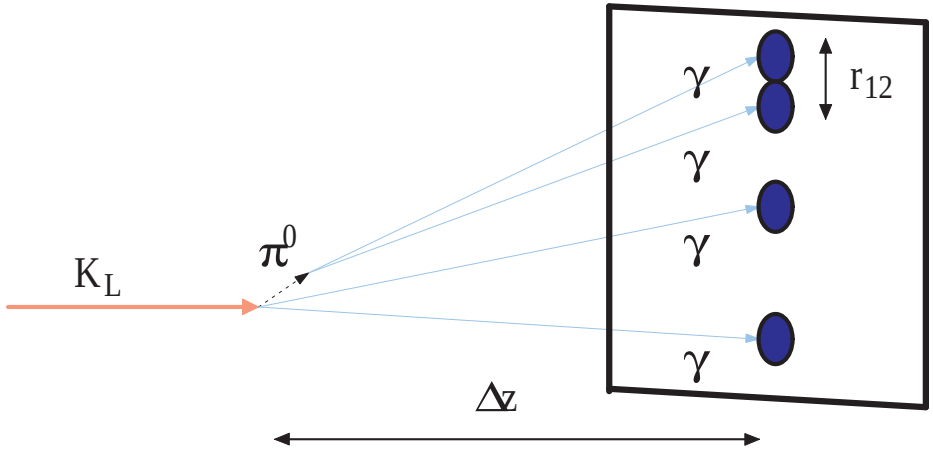


- $\mathcal{O}(p^4)$ chiral perturbation calculations
  - No free parameters $\to$ BR$(K_L \to \pi^0\gamma\gamma) = 0.6 \times 10^{-6}$
  - Prediction low by factor of 2-3.
  - $\gamma\gamma$ in $J = 0$ state
    - $K_L \to \pi^0 e^+ e^-$ contribution is helicity suppressed
      - Direct CP violation in $K_L \to \pi^0 e^+ e^-$.

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

- $\mathcal{O}(p^6)$ calculations.
  - Rate increases by 30%
- Addition of VMD terms
  - Parametrized by a_V.
    - Distinctive shape for $m_{\gamma\gamma}$
  - $\gamma\gamma$ in $J = 2$ state
    - Large contribution to $K_L \to \pi^0 e^+ e^-$
- Experimental Results
  - BR$= (1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$ (KTeV) [PRL 83, 917 (1999)]
  - BR$= (1.36 \pm 0.03 \pm 0.04) \times 10^{-6}$ (NA48) [PL B536, 229 (2002)]
  - Note: Used old value of $K_L \to \pi^0\pi^0$ ($\sim 8\%$).

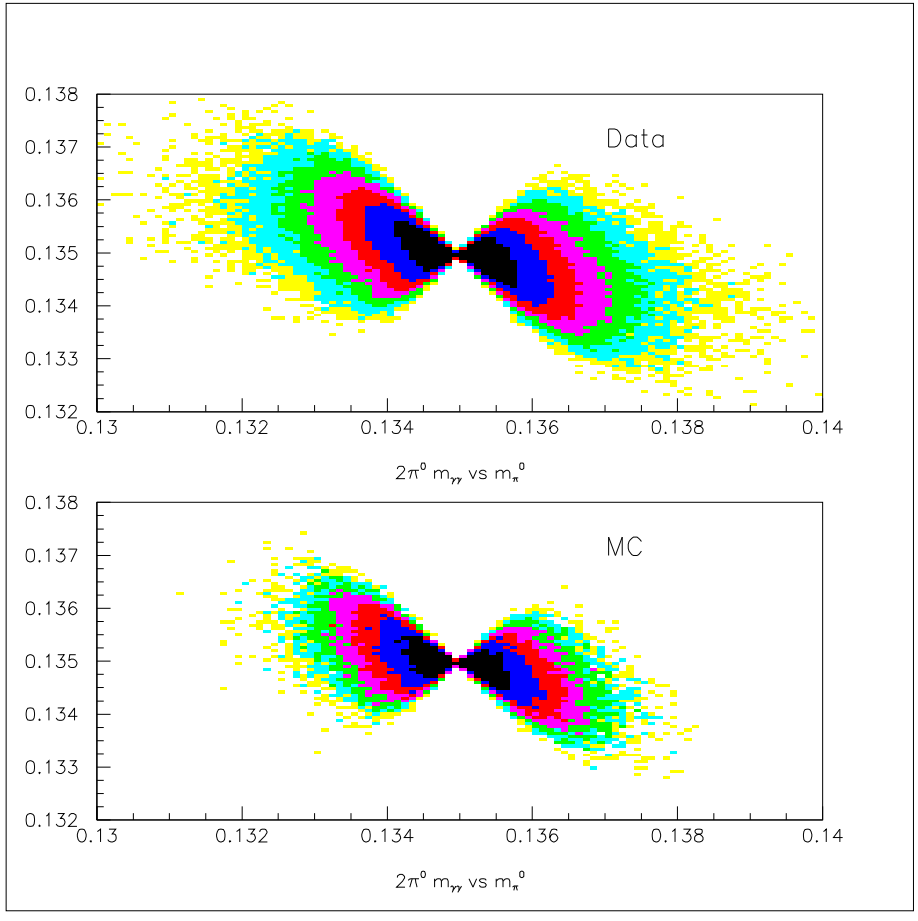
$K_L \to \pi^0\gamma\gamma$ Event Topology



- 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.

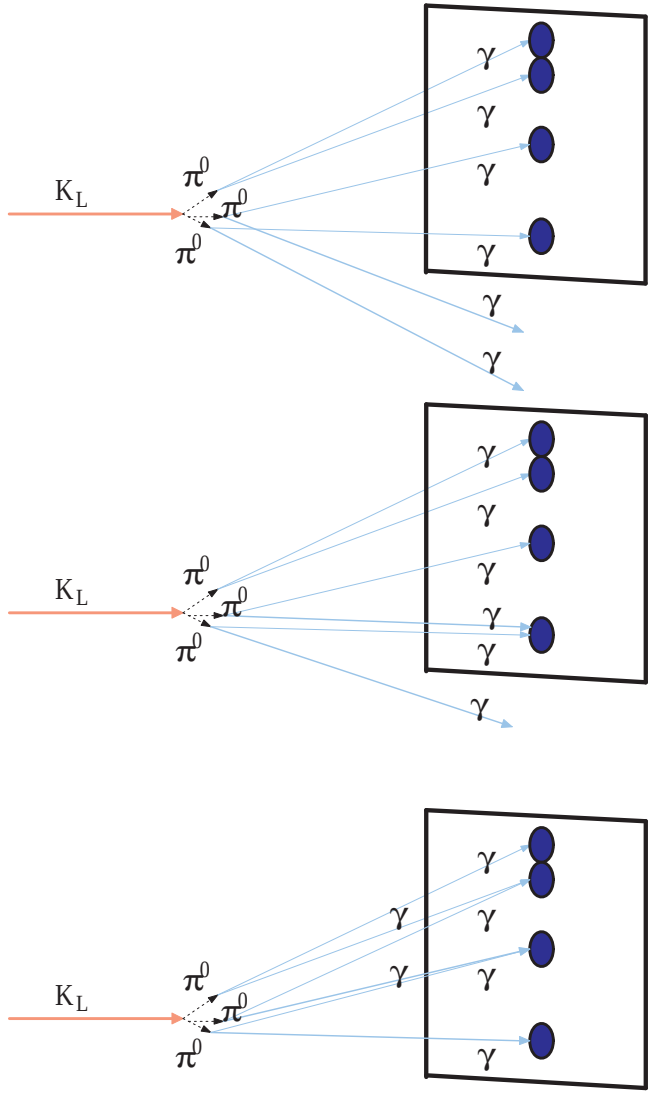
$K_L \to 2\pi^0$ Background

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



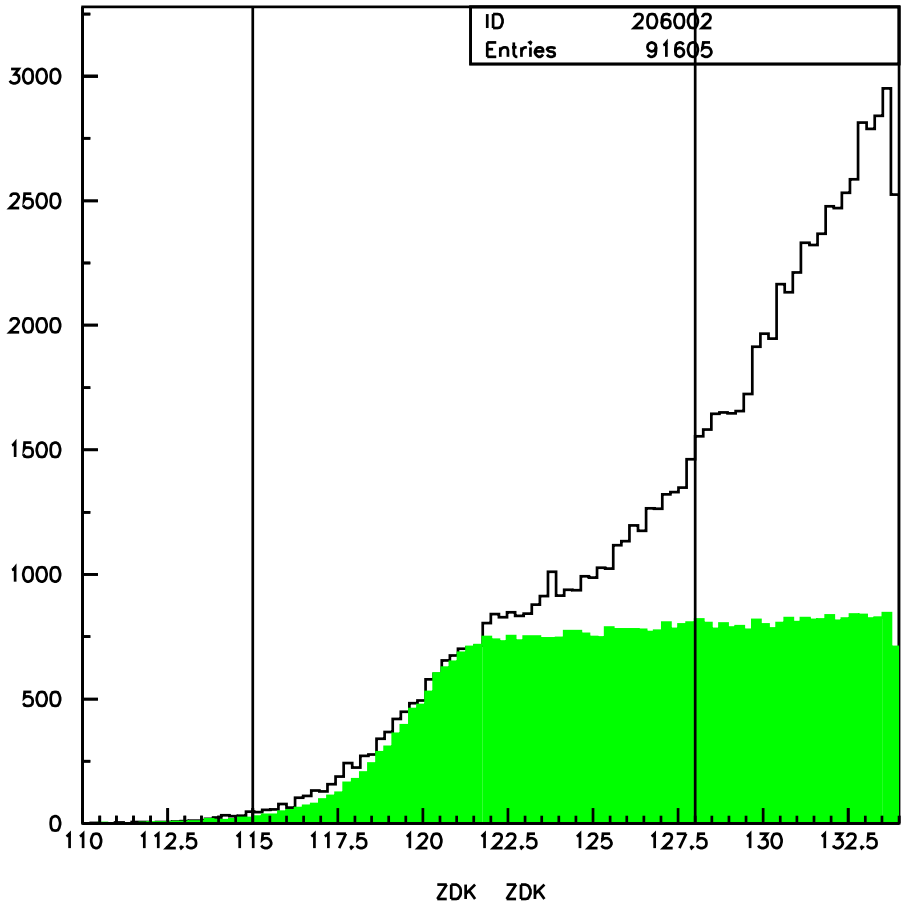
$K_L \to 3\pi^0$ background

- Two lost photons.
  - Event reconstructs downstream.
  - Photons may hit photon vetoes.
- One lost photon.
  - Event reconstructs downstream.
  - Photon may hit photon veto.
  - Two photons overlap in calorimeter.
- No lost photons.
  - Four photons overlap in calorimeter.



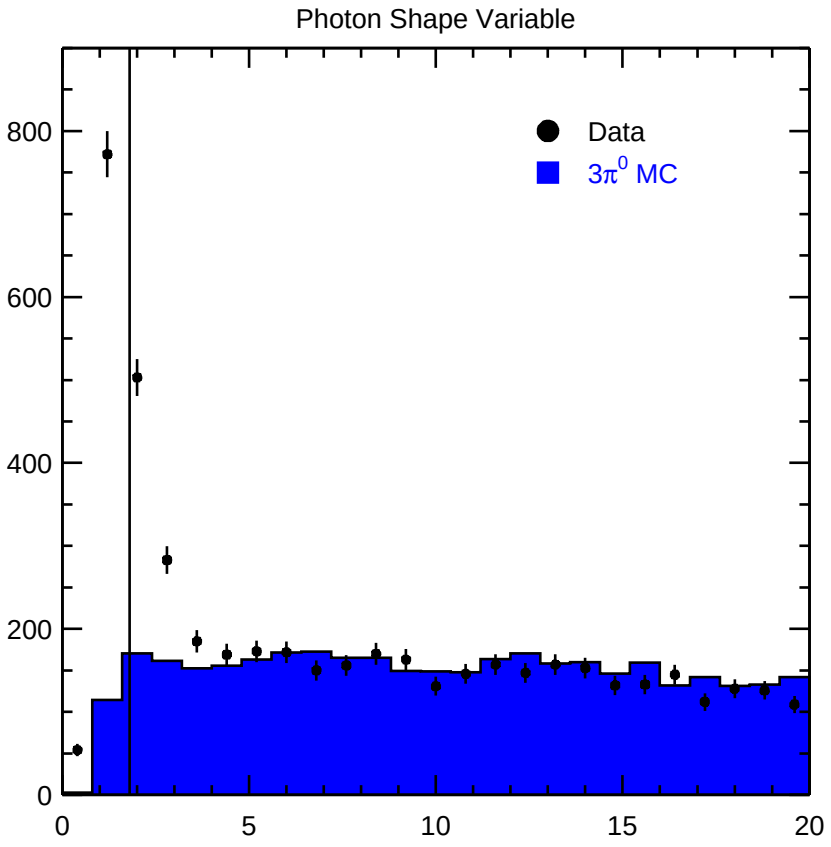
Reconstructed Z position

- Events with missing photons reconstruct downstream.
- Can reduce $3\pi^0$ bkg by re-stricting decay position.

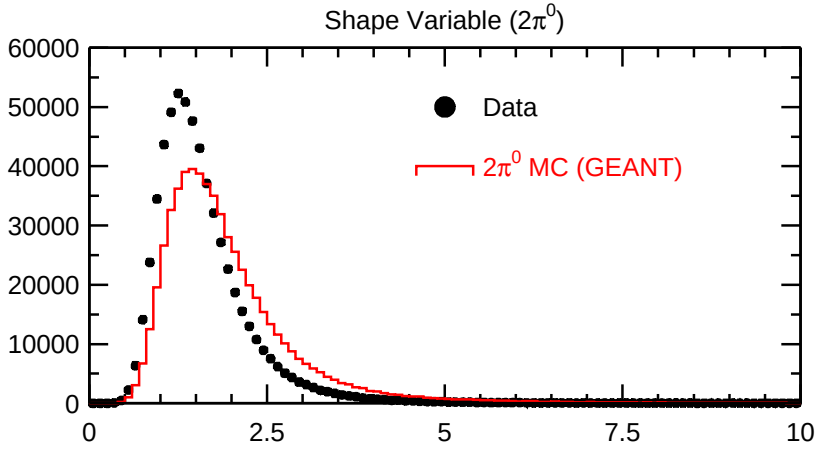


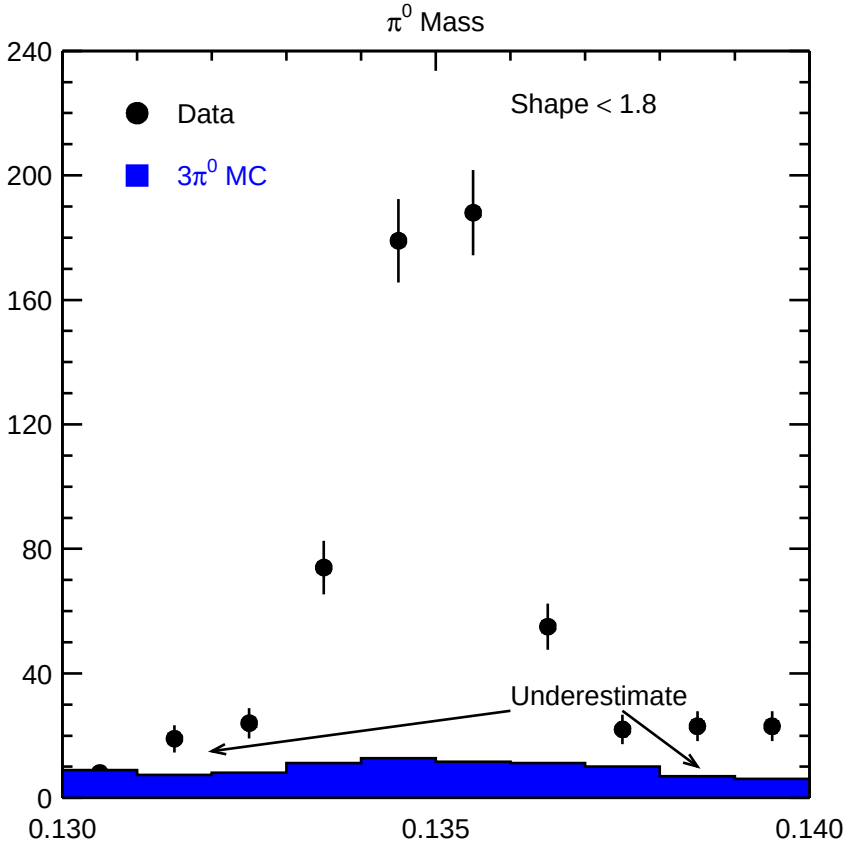
Photon Shape Variable

- Reduce $K_L \to 3\pi^0$ background using photon shape.
  - 3x3 array of crystals containing shower core.
  - Compare measured to ideal shape.
- Low values of photon shape variable $\to$ no overlap.



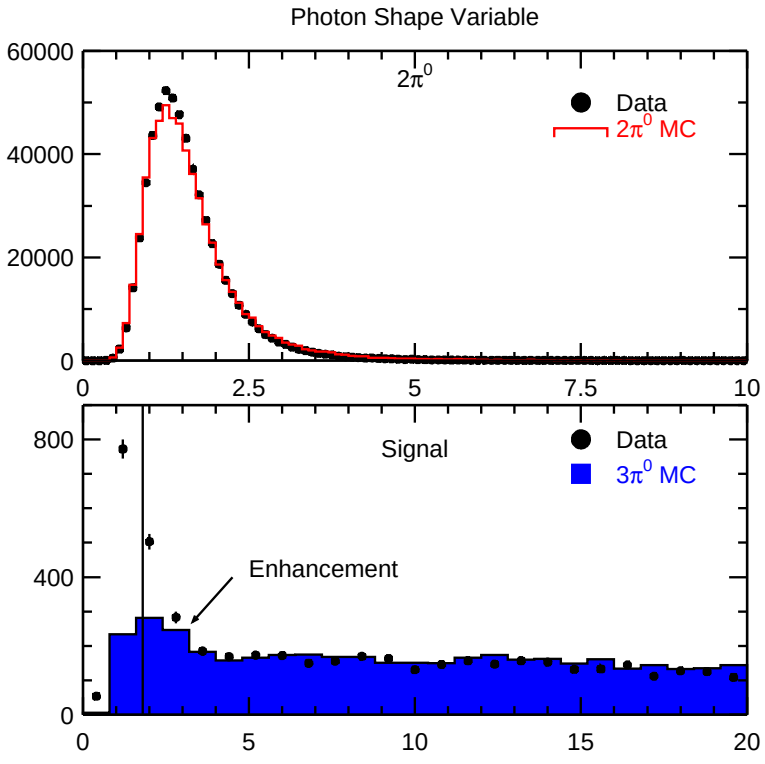
Photon Shape from Published Result



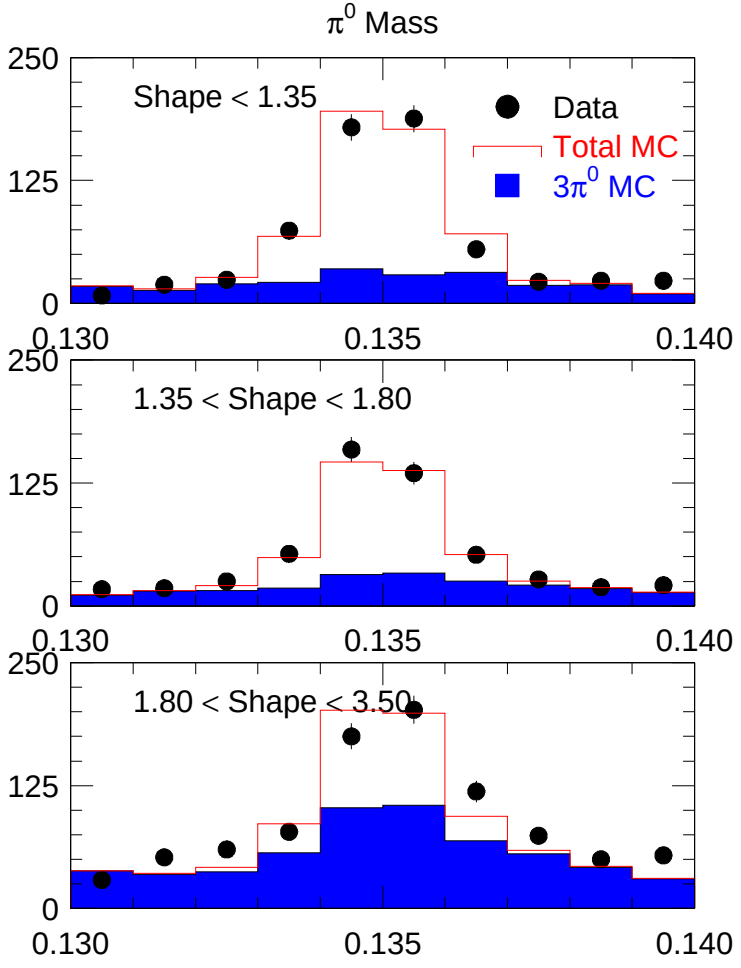


- NA48/KTeV discrepancy.
  - Reexamination of published result.
- Shape variable mismatch.
- Underestimates background in regions of low photon shape variable.

Improved Photon Simulation



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



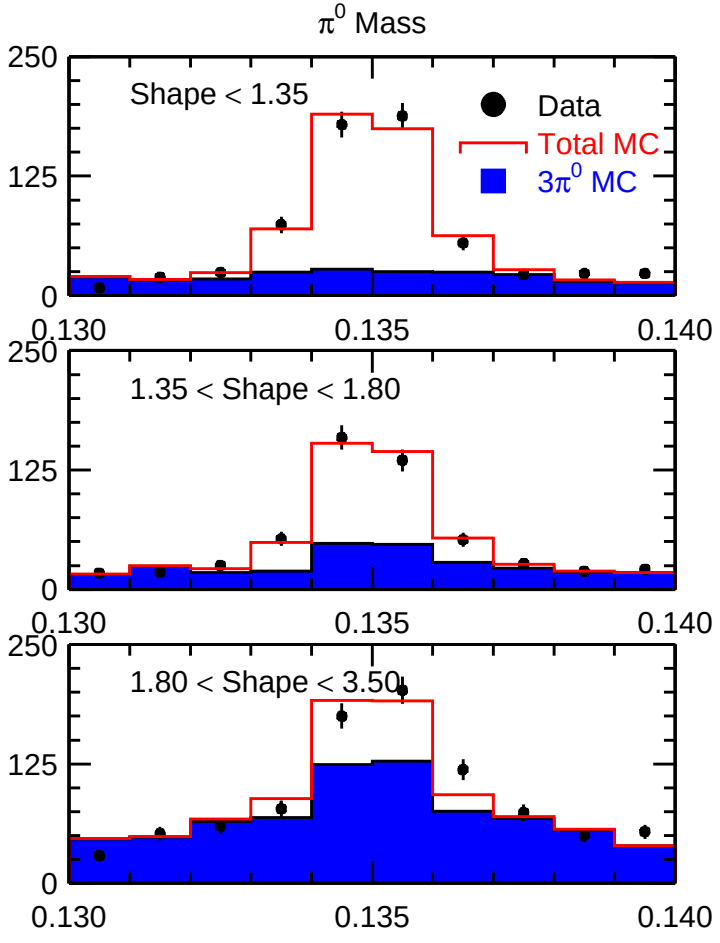
- Better agreement in m_{π^0} tails.

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.

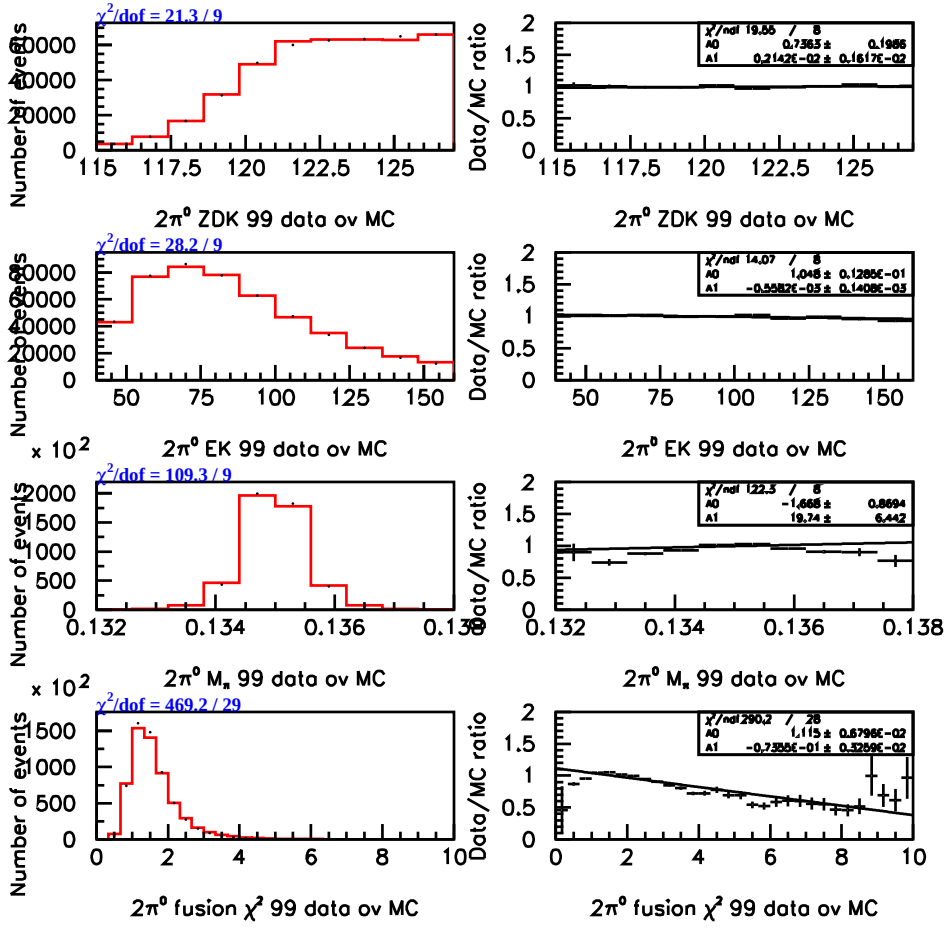
99 Data Bkg Estimate

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

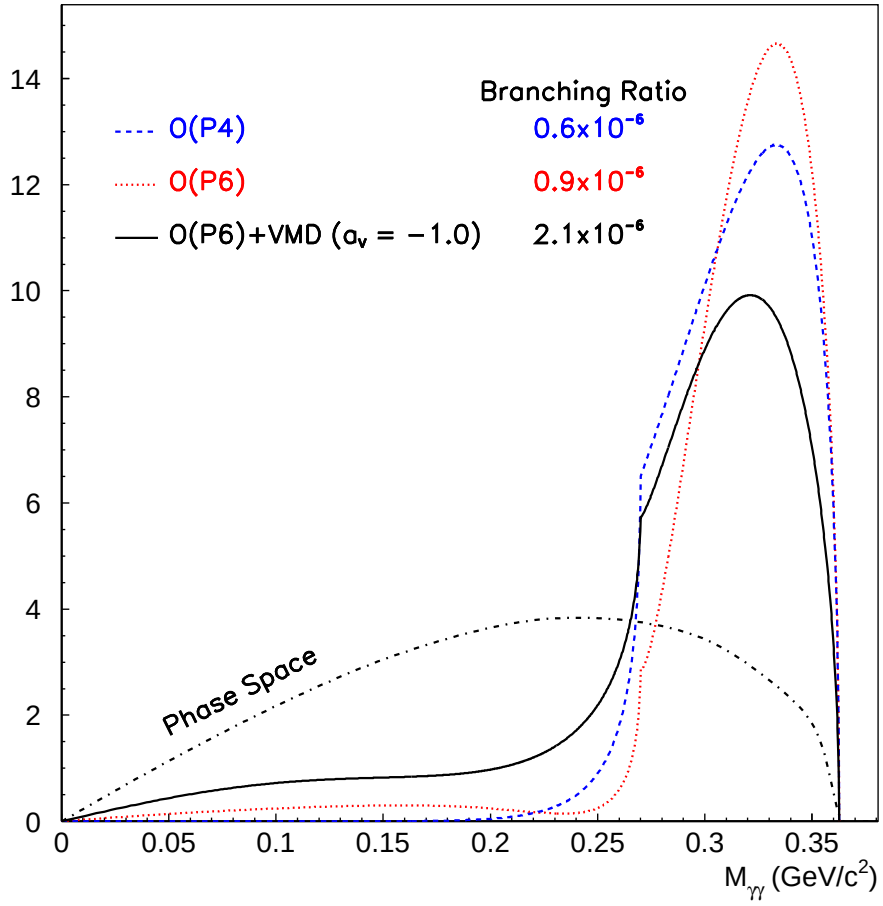


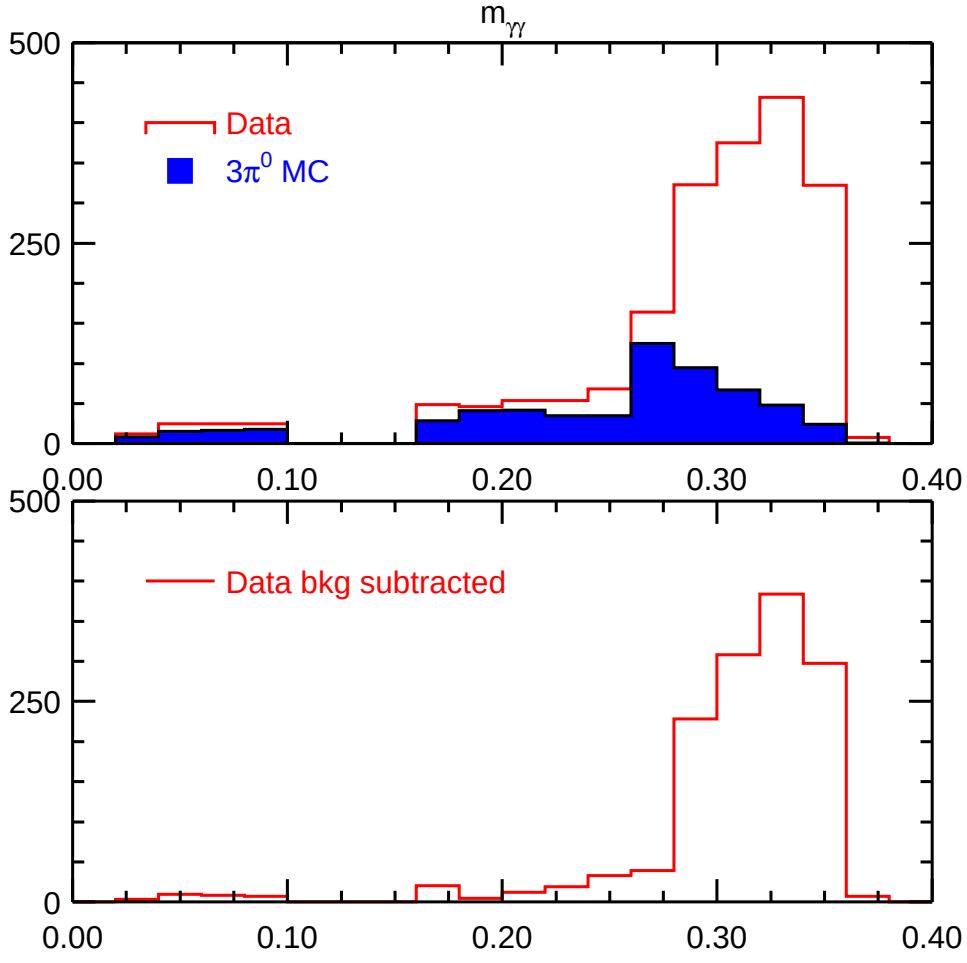
Data/MC comparisons

- 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



Final $\gamma\gamma$ Mass



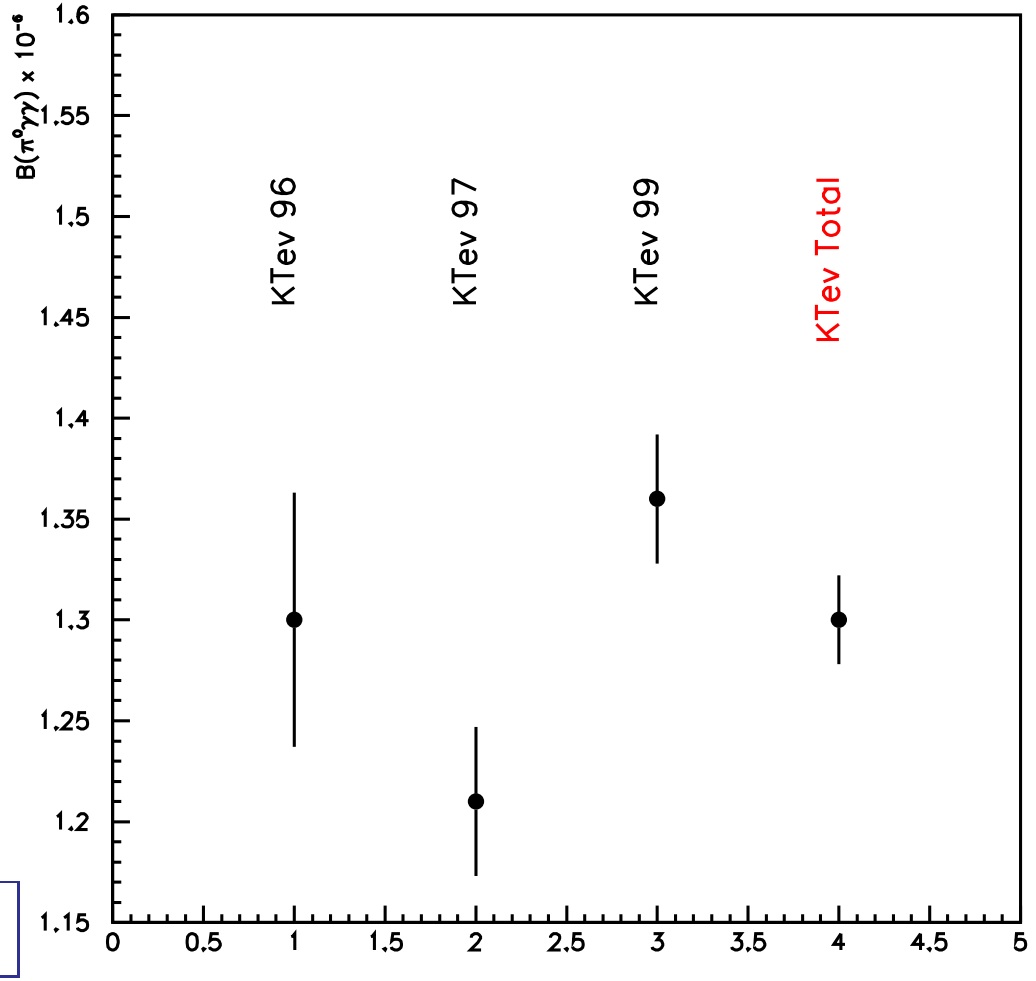


Branching Ratio Results

- Data
  - Candidates: 1982
  - $K_L \to 2\pi^0$ events: 919322
  - Background: 601
- BR = $\frac{N-N_{bkg}}{N_{2\pi^0}} \frac{\epsilon_{2\pi^0}}{\epsilon_{\pi^0\gamma\gamma}} BR(K_L \to 2\pi^0)$
- 1996: $(1.30 \pm 0.06) \times 10^{-6}$
- 1997: $(1.21 \pm 0.04) \times 10^{-6}$
- 1999: $(1.36 \pm 0.03) \times 10^{-6}$

Weighted Average

$BR(K_L \to \pi^0\gamma\gamma) = (1.30 \pm 0.03) \times 10^{-6}$.



Systematics

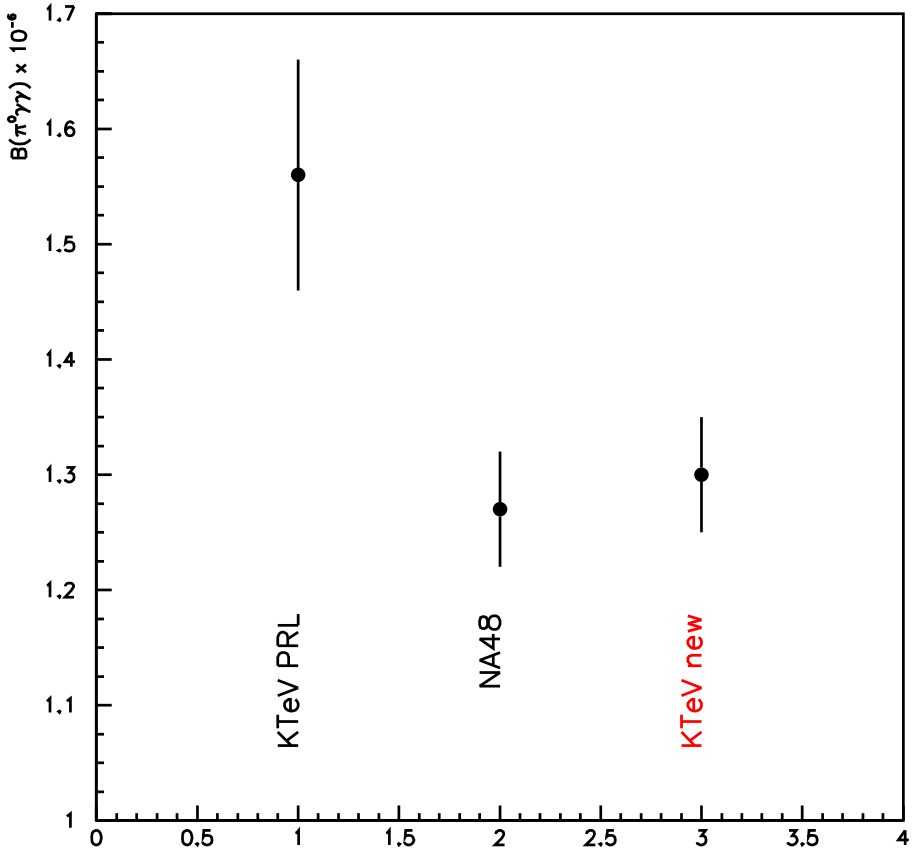
Source of Uncertainty	Uncertainty (%)	
a_V dependence	1.5	
$3\pi^0$ background	1.3	
MC statistics		1.0
Normalization		0.9
Photon Shape	1.1	
Tracking Chambers	0.9	
$2\pi^0$ branching ratio	0.9	
Photon vetoes	0.9	
Kaon Energy	0.7	
Decay Vertex	0.4	
Total	2.9	

Branching Ratio Results

KTeV Preliminary

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

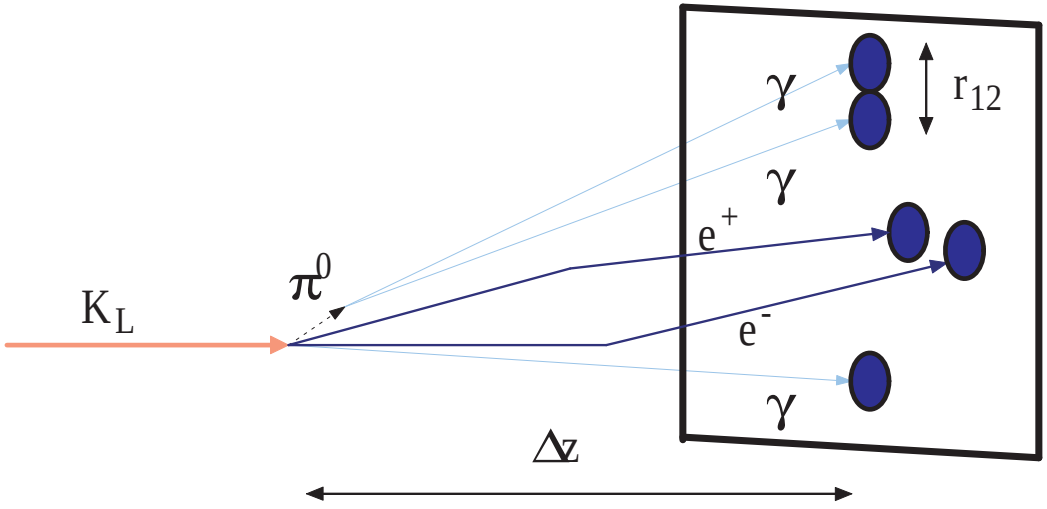
- Underestimate of background led to higher value in previous KTeV result.
- Result supercedes previous KTeV result.
- All BR adjusted to new $K_L \to \pi^0\pi^0$ BR.



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

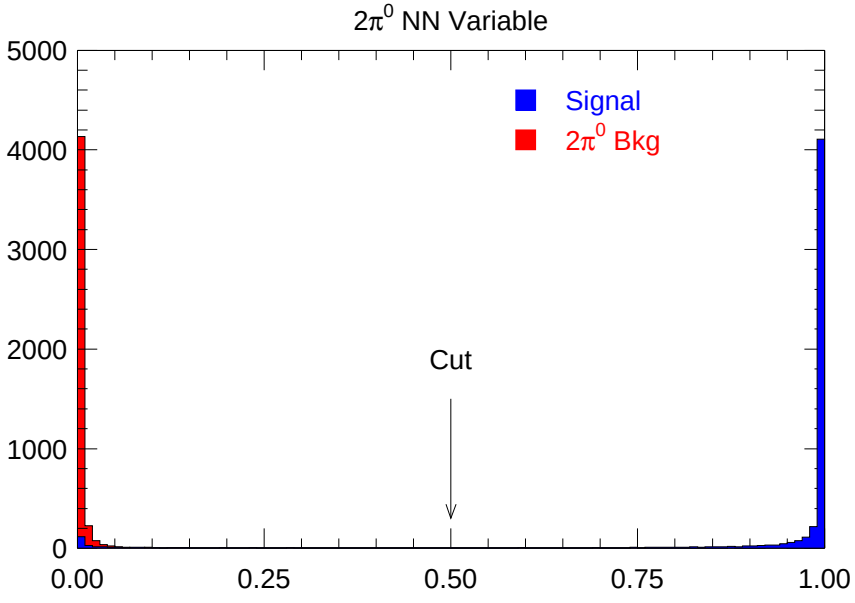
- BR($K_L \to \pi^0 e^+ e^- \gamma$) > BR($K_L \to \pi^0 e^+ e^-$).
  - CP conservation requires 2γ coupling to e^+e^- pair in $K_L \to \pi^0 e^+ e^-$.
- Measurement of $K_L \to \pi^0 e^+ e^- \gamma$ useful for understanding CP violation in $K_L \to \pi^0 e^+ e^-$.
  - Similar spectrums for $K_L \to \pi^0 e^+ e^- \gamma$ 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.

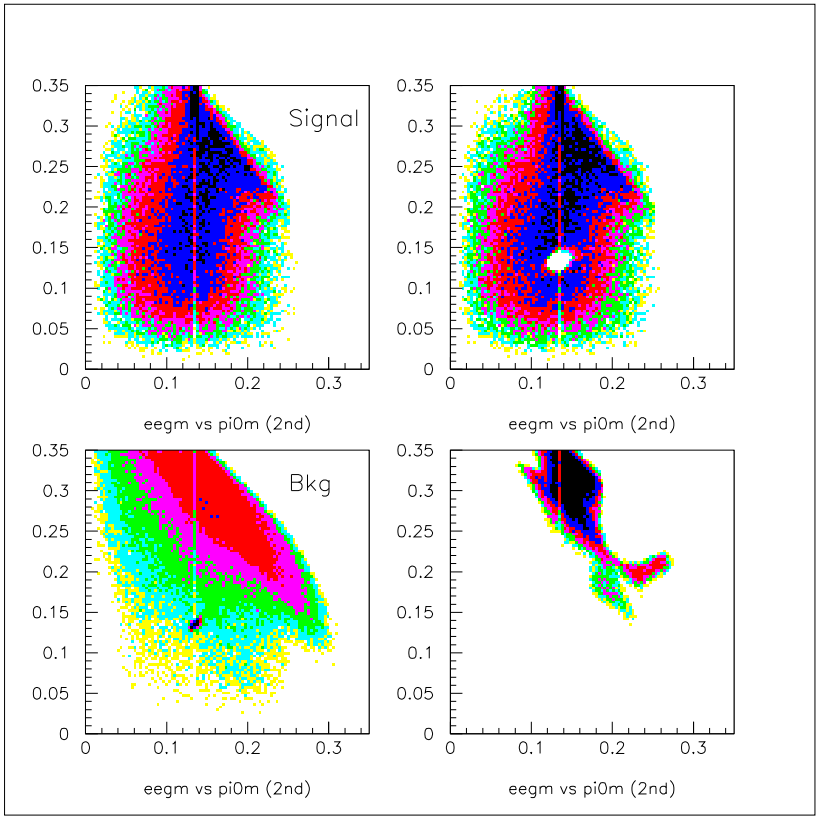
$K_L \to \pi^0 e^+ e^- \gamma$ Topology



- 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.

$K_L \to 2\pi^0$ Background

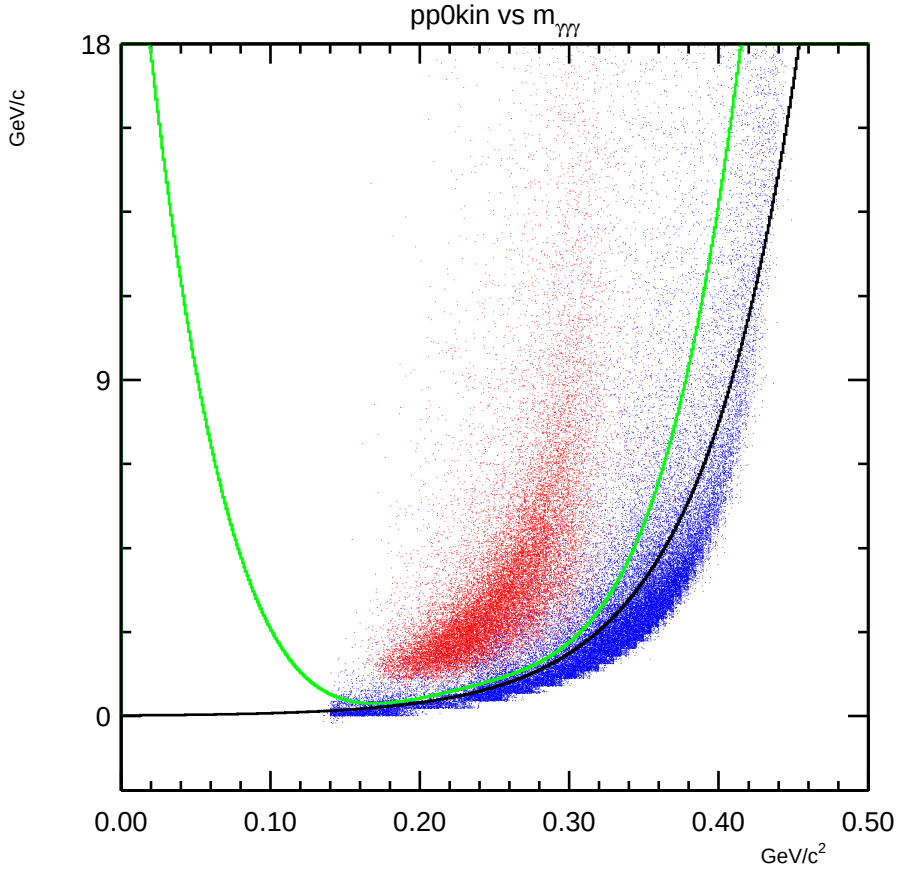




- $K_L \to \pi^0\pi^0$, $\pi^0 \to e^+e^-\gamma$
- Same topology as signal.
- Use $m_{\gamma\gamma}$ and $m_{e^+e^-\gamma}$ to form neural net.

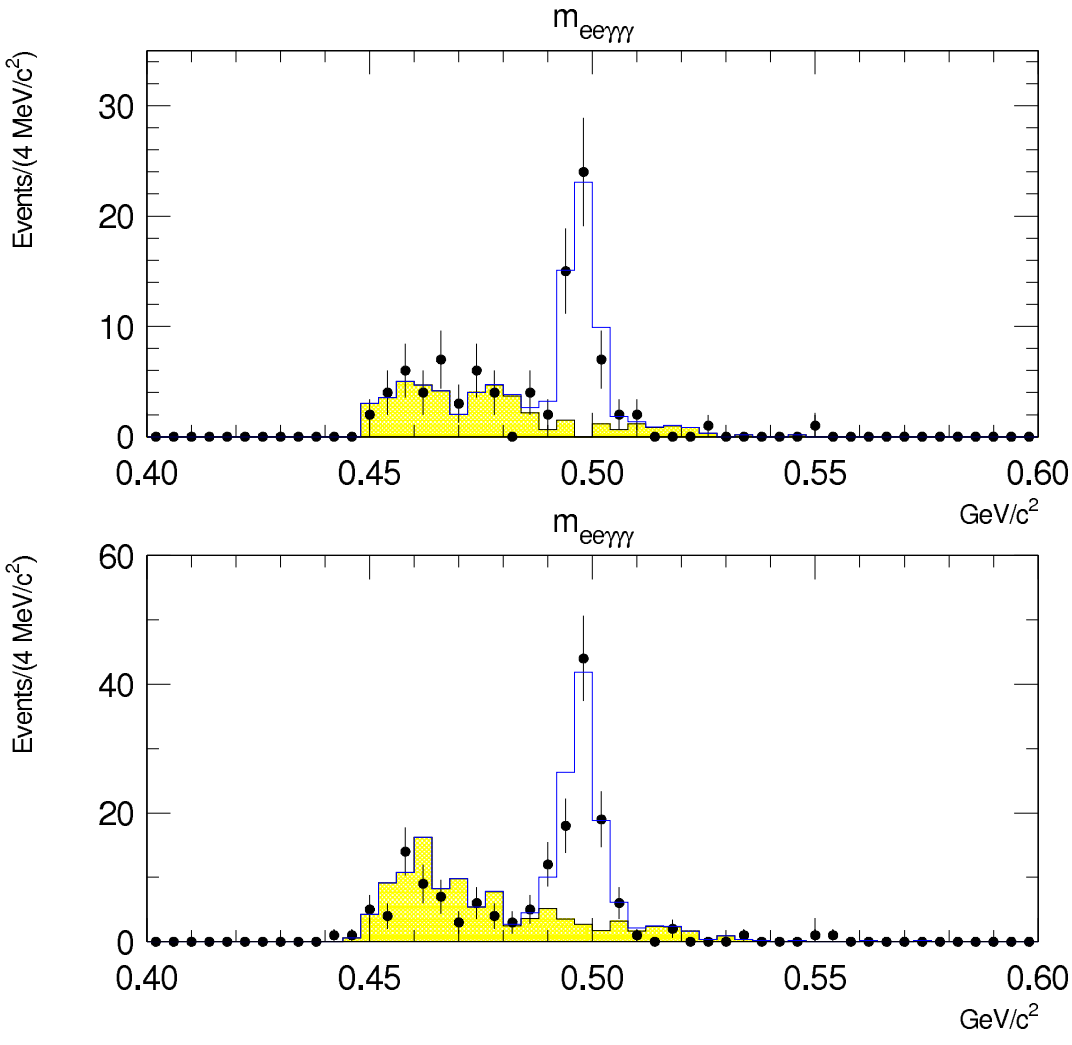
$K_L \to 3\pi^0$ Background (Kinematics)

- $K_L \to \pi^0\pi^0\pi^0$, $\pi^0 \to e^+e^-\gamma$, missing γ.
- Photon vetoes significantly reduce this bkg.
- Use missing momentum of π^0 and $m_{\gamma\gamma\gamma}$.
- Green curve (new), Black curve (PRL result).

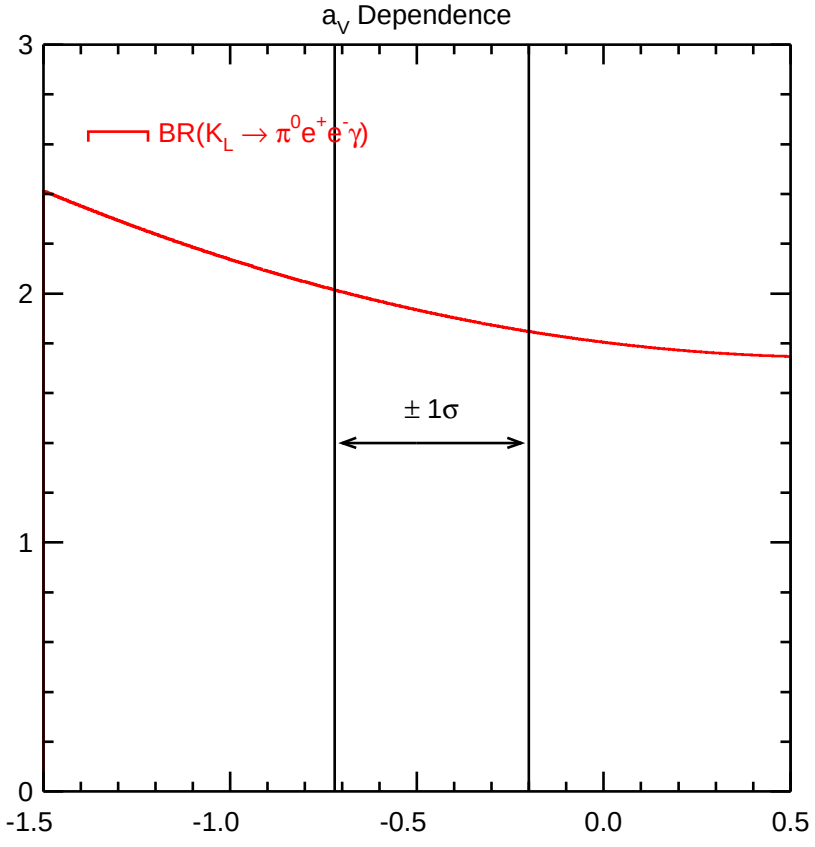


Kaon mass plots

- 47 candidates in 1997
  - 2.7 ± 1.0 bkg events.
- 92 candidates in 1999
  - 11.7 ± 2.3 bkg events.

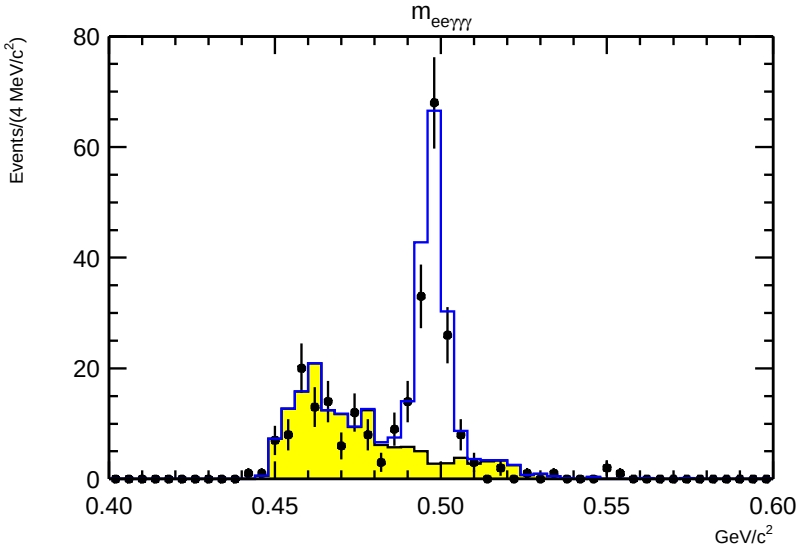


$K_L \to \pi^0 e^+ e^- \gamma$ Systematics



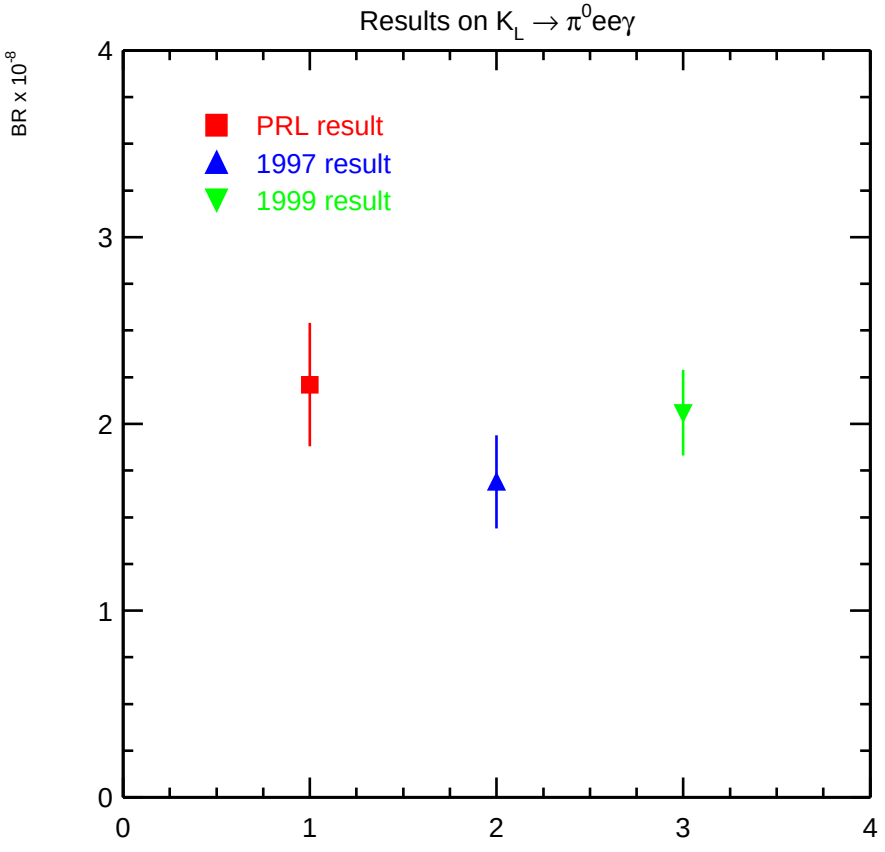
Systematic	Error (%)
MC Statistics	4.2
a_V dependence	3.8
K_L and π^0 BR	2.8
$3\pi^0$ bkg	0.8
acceptance	0.4
$2\pi^0$ background	0.1
Total	6.4

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

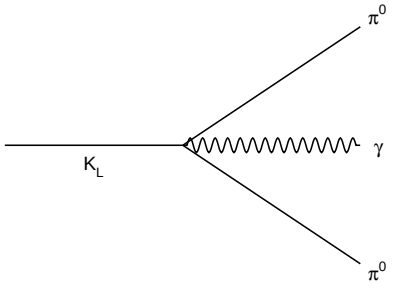


KTeV Preliminary

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



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

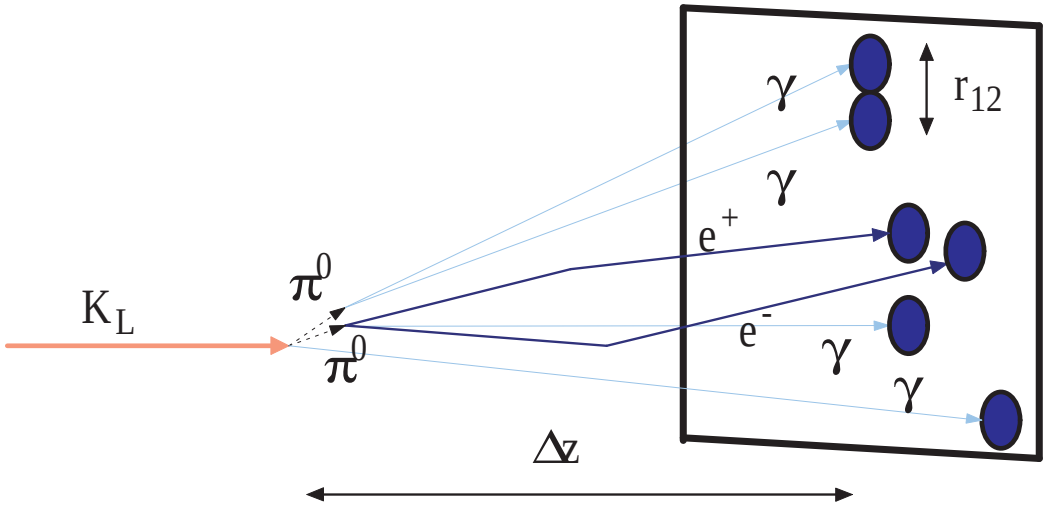


Proceeds through direct emission process.

- E2 term dominates.
- Gauge invariance and Bose statistics rule out M1 and E1 terms.

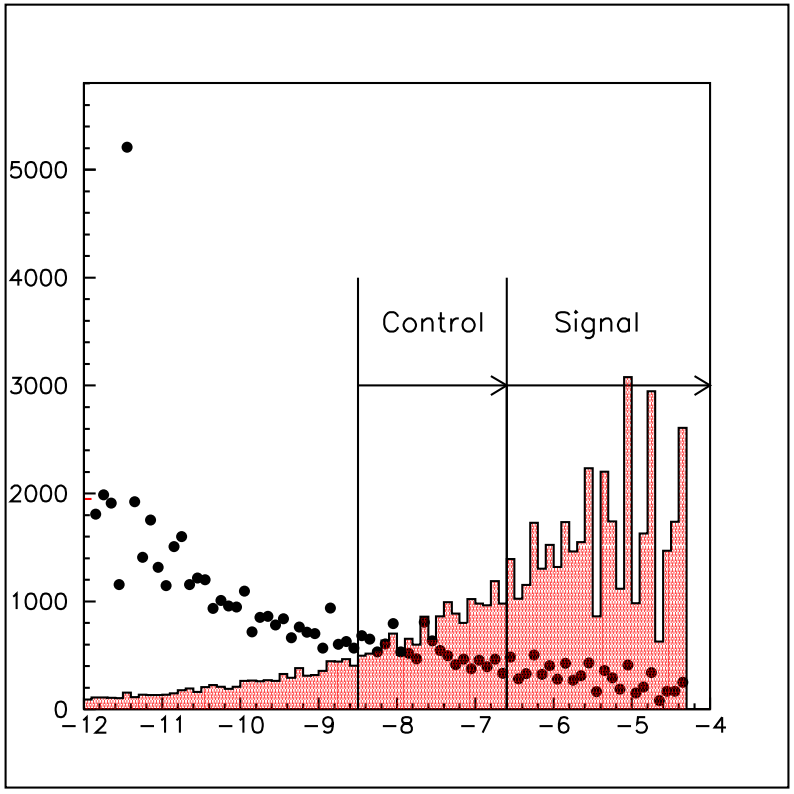
- Chiral Perturbation.
  - Process vanishes at $O(p^4)$.
  - Probe of $O(p^6)$.
- Branching Ratio Predictions.
  - BR($K_L \to \pi^0\pi^0\gamma$) $< 1 \times 10^{-8}$ (from $K_L \to \pi^+\pi^-\gamma$, [PL B307, 182])
  - BR($K_L \to \pi^0\pi^0\gamma$) $< 7 \times 10^{-11}$ (from $O(p^6)$, [NP B413, 321])

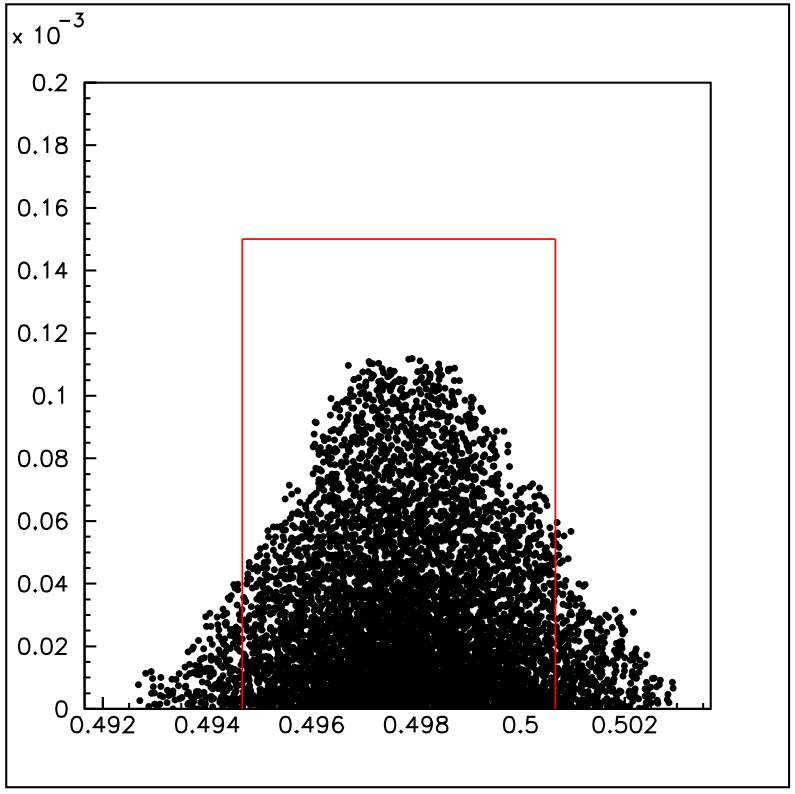
$K_L \to \pi^0\pi^0\gamma$ Topology



- Four photons and two electrons.
  - $\pi^0 \to e^+e^-\gamma$ and $\pi^0 \to \gamma\gamma$.
  - Choice driven by two-track trigger.
- $K_L \to \pi^0\pi^0\pi^0$, $\pi^0 \to e^+e^-\gamma$
  - Largest background.
  - Also used for normalization.

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

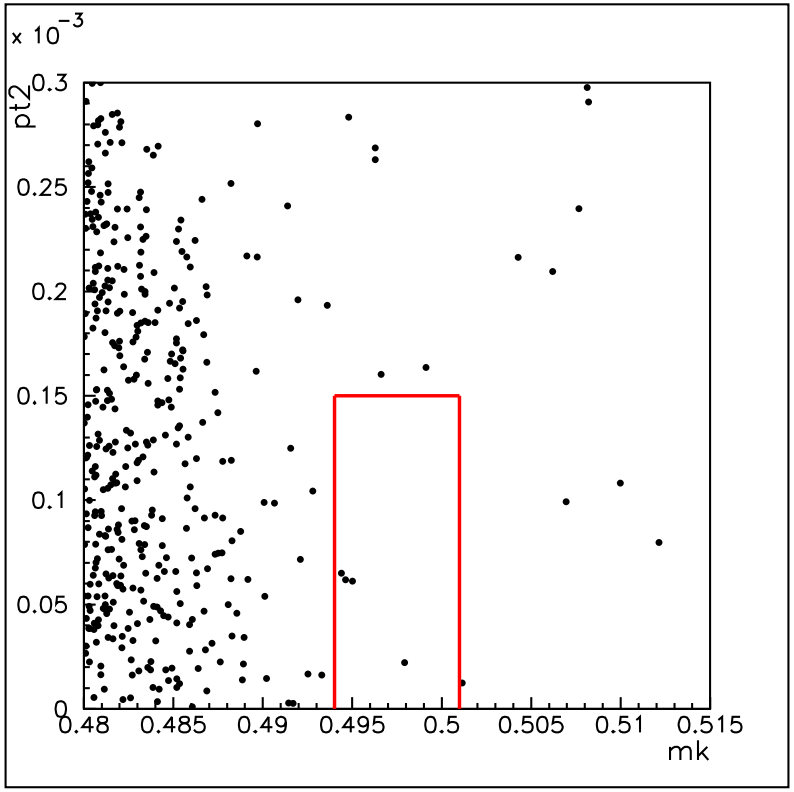


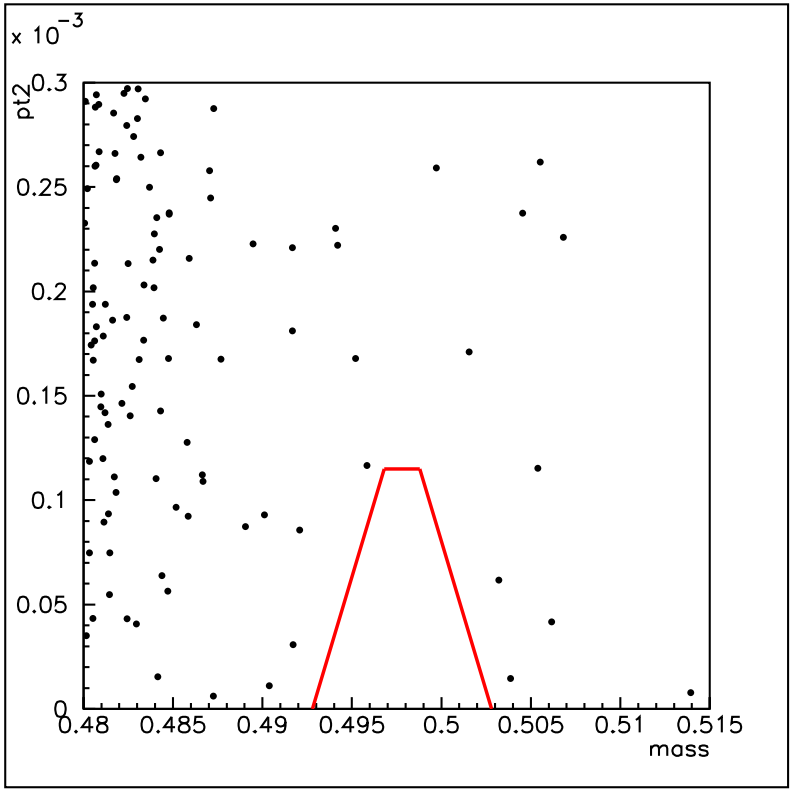


- $L = log(P(m_K)P(p_T^2))$
- Probability distribution for 1999.

- p_T^2 versus m_K.
- Square signal box for 1997 sample.

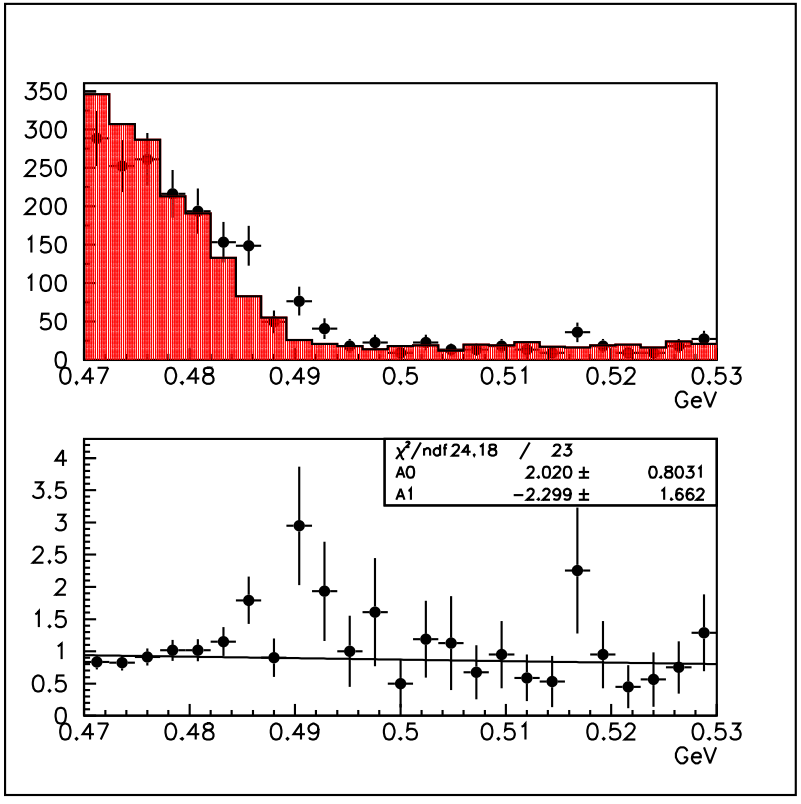
Background Monte Carlo

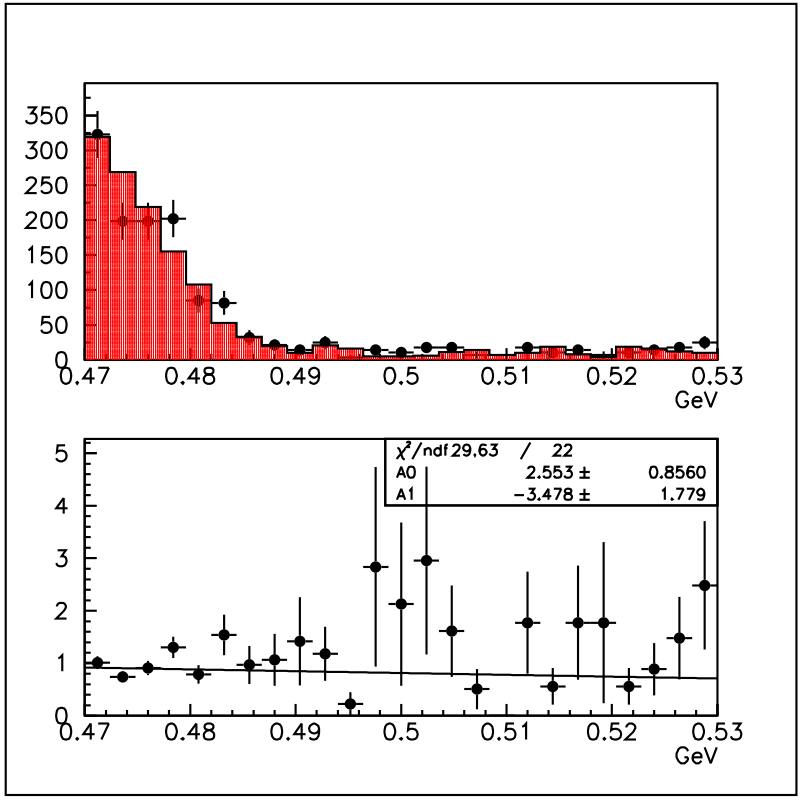




- $K_L \to \pi^0\pi^0\pi^0$ Monte Carlo.
- Approximately 4X MC generated.

$K_L \to 3\pi^0$ Data/MC



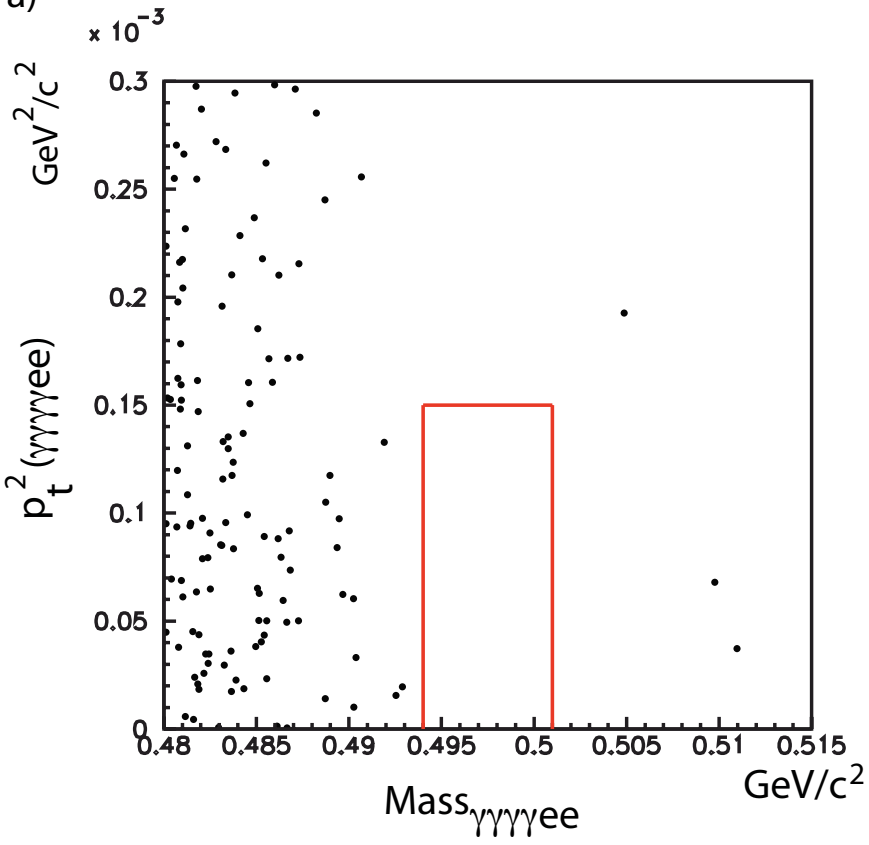


- Background Data/MC comparisons.
- Reasonable agreement.

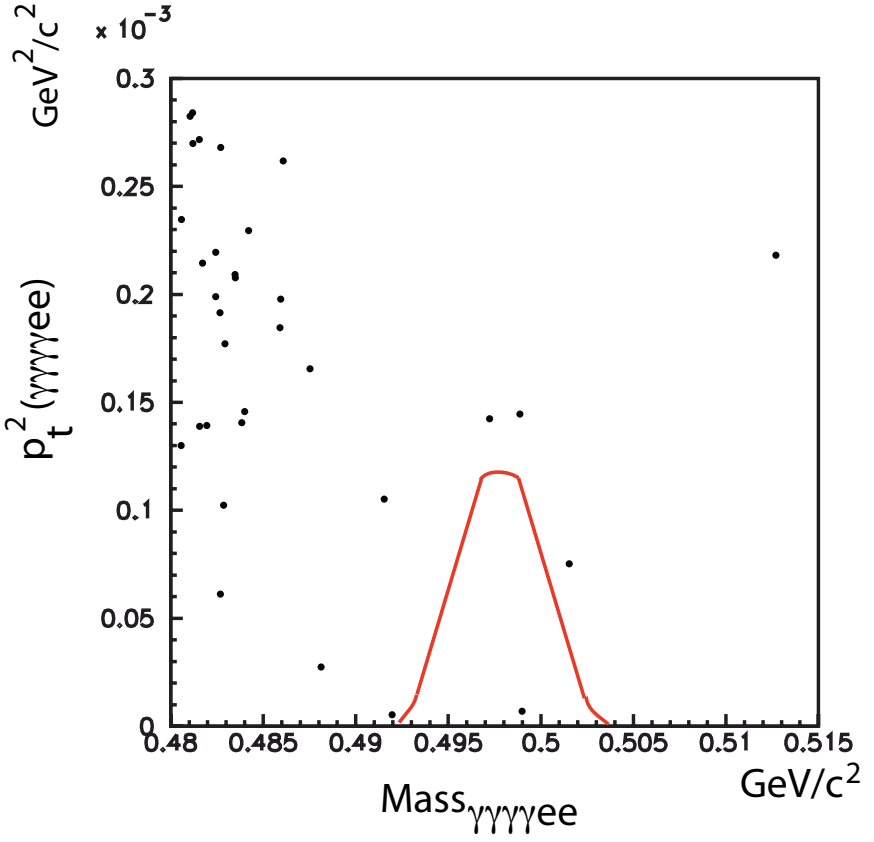
$K_L \to \pi^0\pi^0\gamma$

52 54

a)



b)



- One event seen in 1999, none in 1997.
- Probability of event as bkg: 10%.

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

- Kaon flux: 6.09×10^{11} decays.
- Upper limit based upon 1 event.

$$\text{BR}(K_L \to \pi^0\pi^0\gamma) < 2.32 \times 10^{-7}$$

- NA31: BR$(K_L \to \pi^0\pi^0\gamma) < 5.6 \times 10^{-6}$

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$(K_L \to \pi^0\pi^0\gamma) < 2.32 \times 10^{-7}$
    - Approximately $\times 20$ improvement.
- Help to improve understanding of low energy theories.
  - Data consistent with ChPT $O(p^6)$.