Analysis of $K_L \to \pi^0 e^+ e^- \gamma$

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- Data Analysis
- Systematics
- Branching Ratio
- Things to do

Introduction

- Important for understanding ChPT and $K_L \to \pi^0 e^+ e^-$.
- Combined 1997 & 1999 analysis.
- Previous Result
  - 48 Events.
  - BR($K_L \to \pi^0 e^+ e^- \gamma$) = $(2.34 \pm 0.35 \pm 0.13)$
- In this result, we reoptimize cuts & look at ways to improve the background rejection.

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

- 2ENCLUS events.
  - Look for two tracks and five clusters.
  - Require good vertex.
- Reconstruct $\pi^0 \to \gamma\gamma$
  - Require a good π^0 from three possible $\gamma\gamma$ combinations.
  - Use neutral vertex for determining π^0 mass.
- Major backgrounds.
  - $K_L \to \pi^0\pi^0 \qquad \pi^0 \to e^+e^-\gamma$
  - $K_L \to \pi^0\pi^0\pi^0 \qquad \pi^0 \to e^+e^-\gamma$

List of Cuts

Stage	Cut	Requirement
Crunch		
	2E-NCLUS	Require L3 tag bit
	Vertexing	Require vertex found
	Cluster/track match	Require all tracks match clusters
	E/p	$E/p > 0.9$
	HCC clusters	$N_{HCC} = 5$
	Vertex position	Vertex must be in beam.
	Five γ mass	$m_{5\gamma} > 0.380$
Analysis		
	Tracking	Two opposite signed tracks
	Clustering	Five hardware clusters
	Energy	$30 < ET < 210$
	Trigger counters	VV' verification
	Bad Spills (run<8245)	Reject Mask = 0x1072FFDF
	(run< 8577)	Reject Mask = 0x1073FFDF
	(run< 10000)	Reject Mask = 0x10727FDF
	(run> 10000)	Reject Mask = 0x10727FDB
	E/p	$0.95 < E/p < 1.05$
	Minimum Cluster Energy	$E_{min} > 2.0$
	x, y track separation	DC1 $x, y_{sep} > 0.01$
	π^0 mass (best comb)	$0.130 < m_{\gamma\gamma} < 0.140$
	Decay vertex	$98 < z < 157$
	Collar Anti	$E_{CA} < 12$
	Beam hole cut	$d > 0.015$
	In-time pairs	No extra intime pairs
	Transverse momentum	$p_T > 0.003$

List of Cuts

Stage	Cut	Requirement
Background Reduction		
	Ring counters	$E_{RC} < 0.05$
	Spectrometer Antis	$E_{SA} < 0.1$
	$3\pi^0$ kinematics	$m_{\gamma\gamma\gamma}$ vs pp0kin cut
	Fusion χ^2 cut	FUSE3x3 < 4
	$2\pi^0$ kinematics	$NN > 0.95$
		$m_{e^+e^-\gamma} < 0.115,\ m_{e^+e^-\gamma} > 0.150$
	Track/Cluster distance	$d > 0.0125$
	Kaon mass	$0.490 < m_K < 0.505$

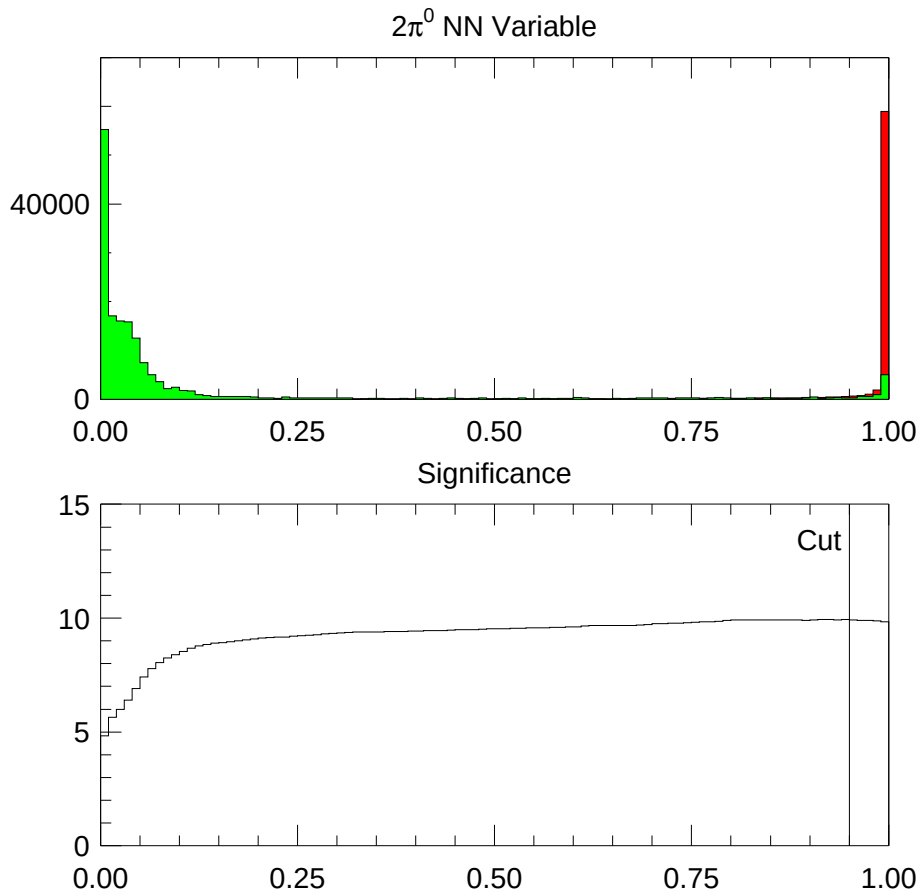
- New cuts to reduce $2\pi^0$ and $3\pi^0$ backgrounds.
- Better understanding of some backgrounds.

$K_L \to \pi^0\pi^0$ Background

- Two sources.
  - Tails of the $e^+e^-\gamma$ mass distribution.
  - Wrong $\gamma\gamma$ combination.
- Use Neural Net to reduce bkg from second source.
  - Input $m_{e^+e^-\gamma}$(2nd), $m_{e^+e^-\gamma}$(3rd), $m_{\gamma\gamma}$(2nd), $m_{\gamma\gamma}$(3rd).
  - Tune on small sample of $2\pi^0$ and $\pi^0 e^+e^-\gamma$ MC.
  - Cut on NN variable.

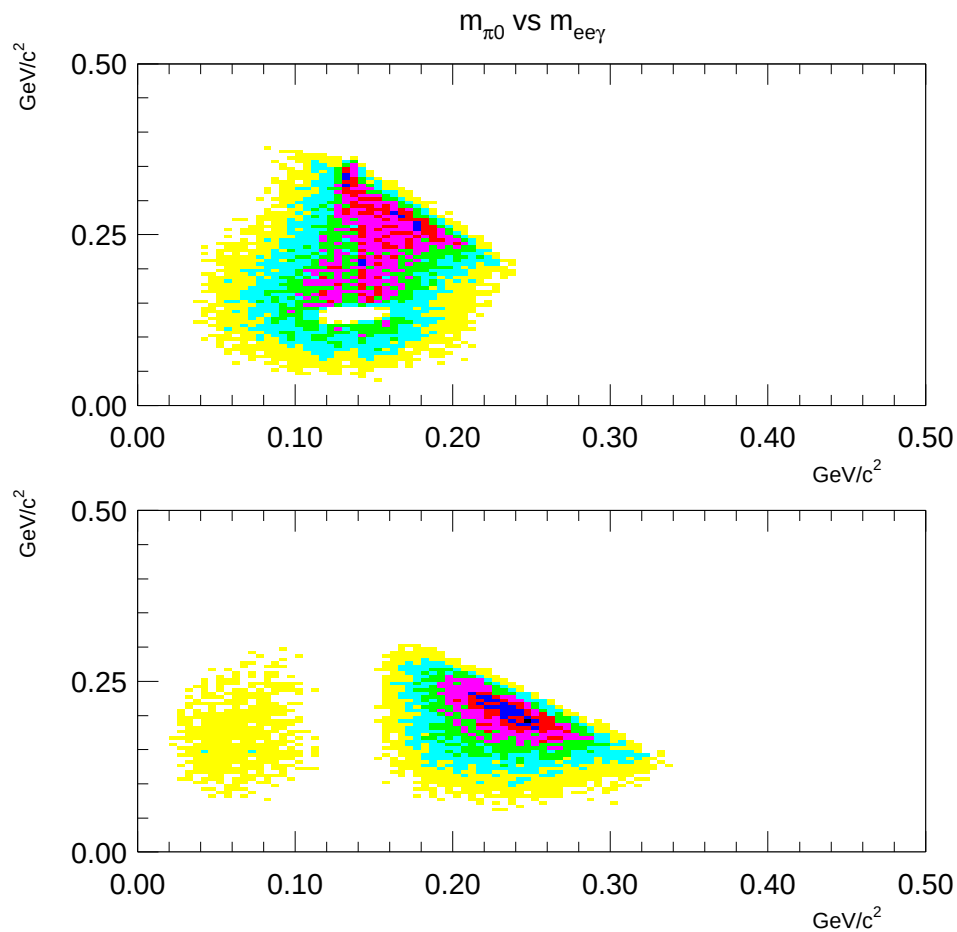
$K_L \to \pi^0\pi^0$ Background

- NN variable for $2\pi^0$ (green) and $\pi^0 e^+ e^- \gamma$ (red) MC.
- Significance
  - $S = \frac{N_{sig}}{\sqrt{N_{sig}+N_{bkg}}}$
  - Cut at point that maximizes significance.
  - Remaining $2\pi^0$ events have poorly reconstructed γ or $e^{\pm}$.



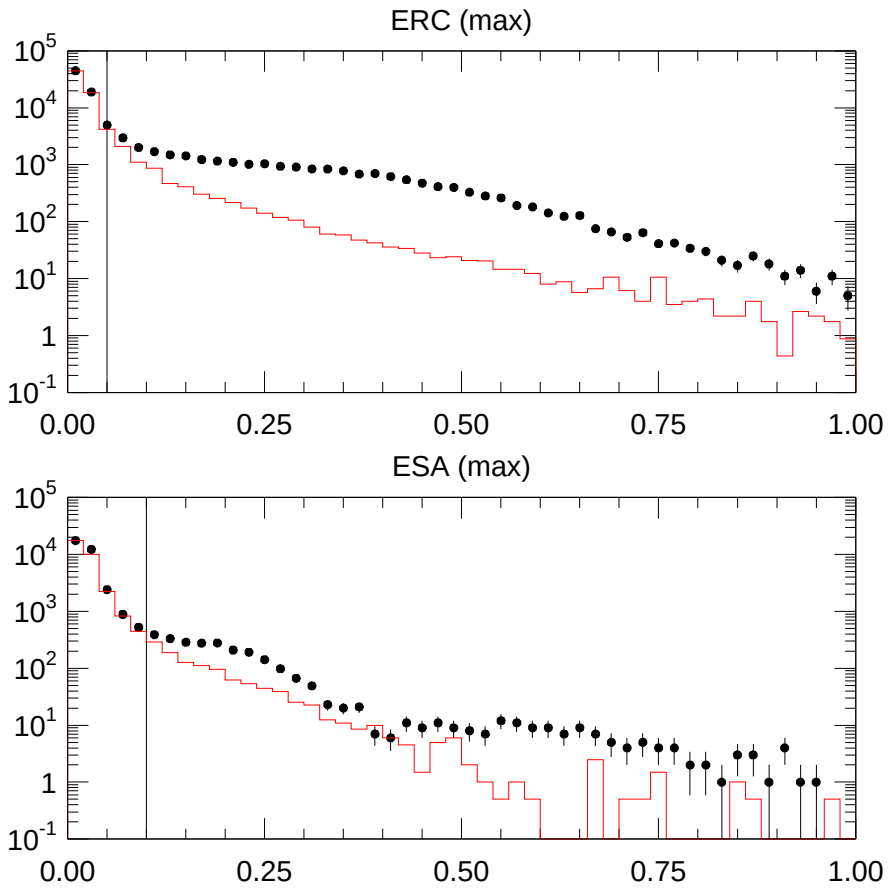
$K_L \to \pi^0\pi^0$ Background

- Effect on $\pi^0\pi^0$ background.
  - Top plot: 2nd best combination.
  - Bottom plot: 3rd best combination.



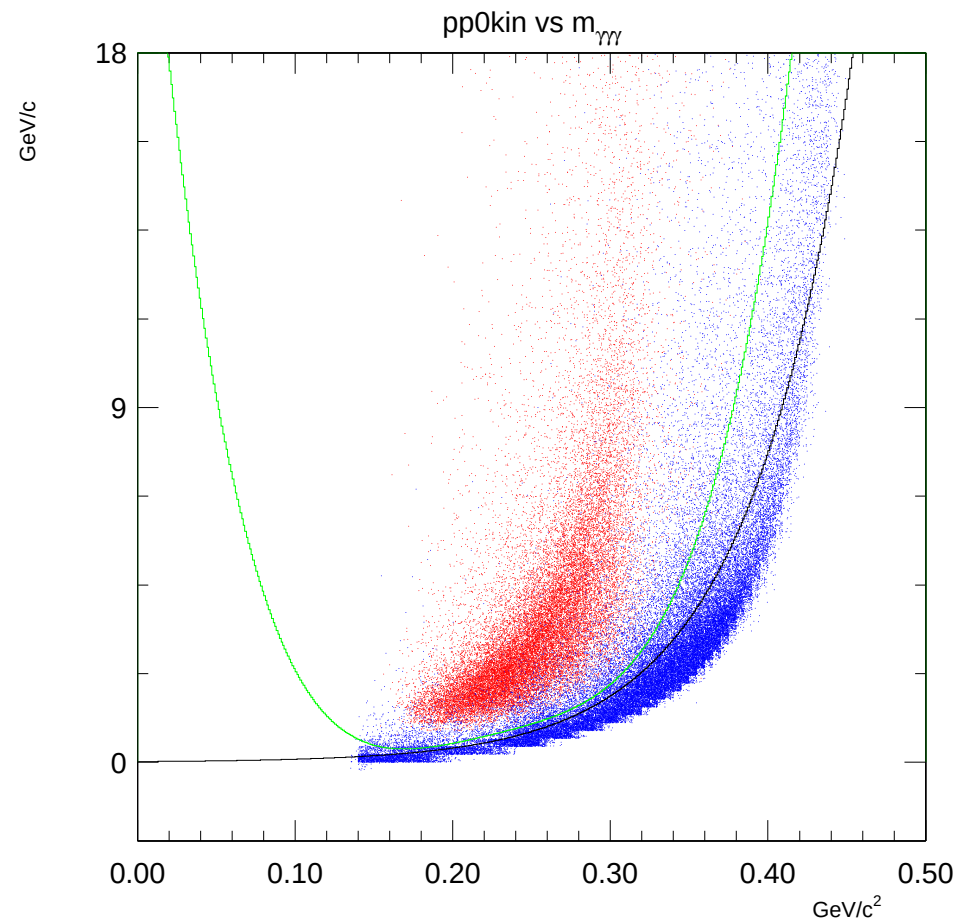
$K_L \to \pi^0\pi^0\pi^0$ Background

- Use RCs and SAs
  - Previous analysis only used RCs.
  - Some extra rejection when using SAs.



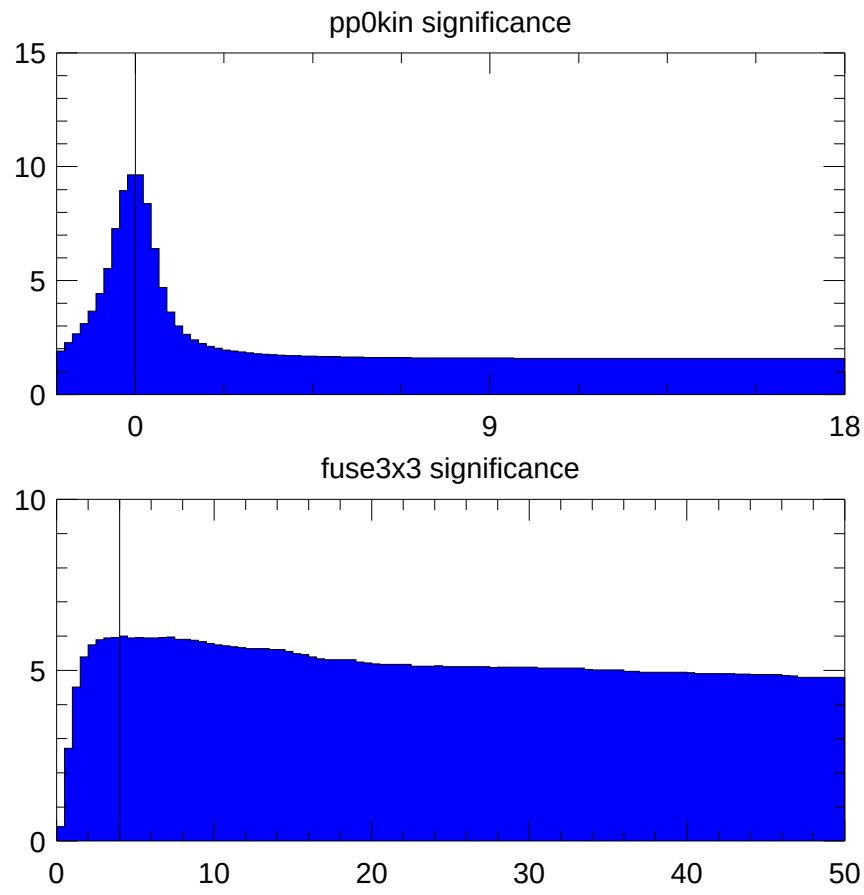
$K_L \to \pi^0\pi^0\pi^0$ Background

- Look at pp0kin vs $m_{\gamma\gamma\gamma}$
- Black line is effective cut from previous analysis.
- Green line is new cut.
  - New cut retains more $\pi^0\pi^0$ (blue) events.



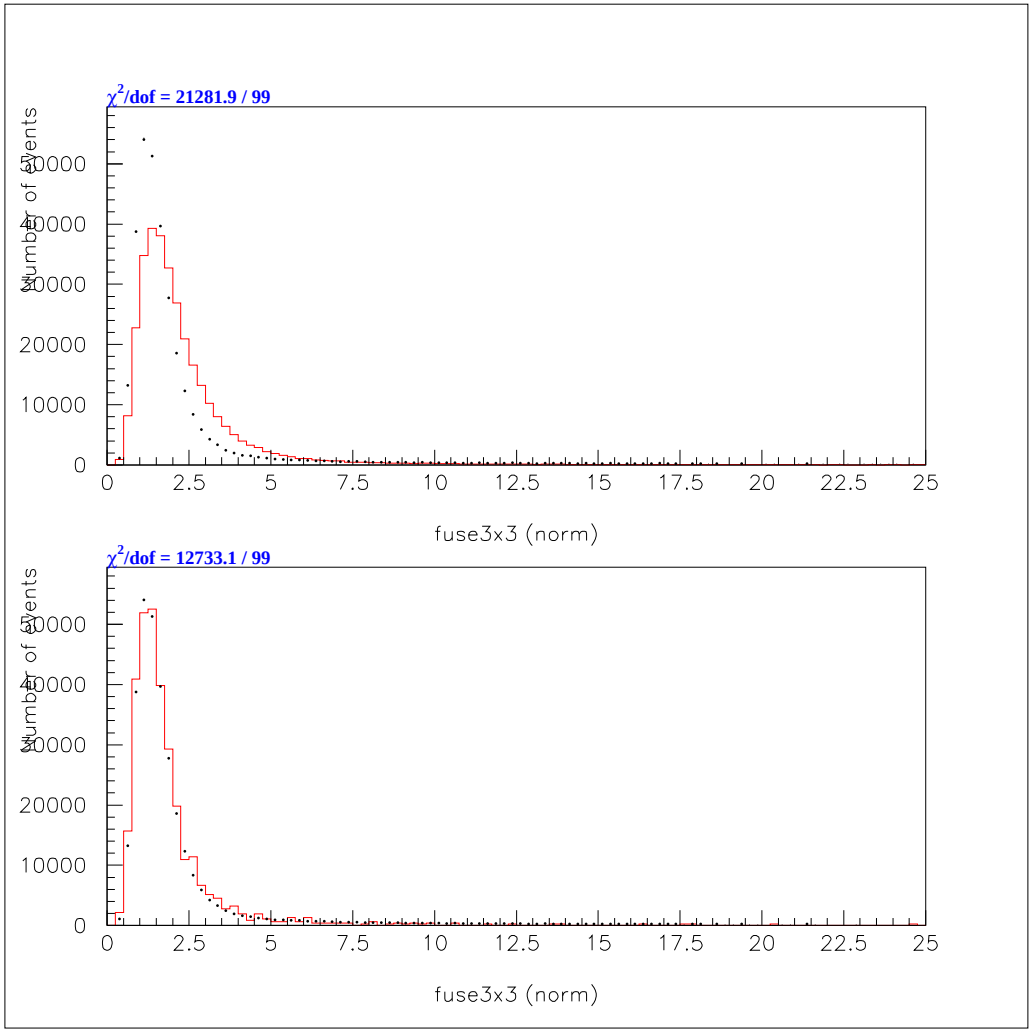
Cut optimization

- Cut optimizaton.
  - Maximize significance for both pp0kin and fuse3x3 cuts.



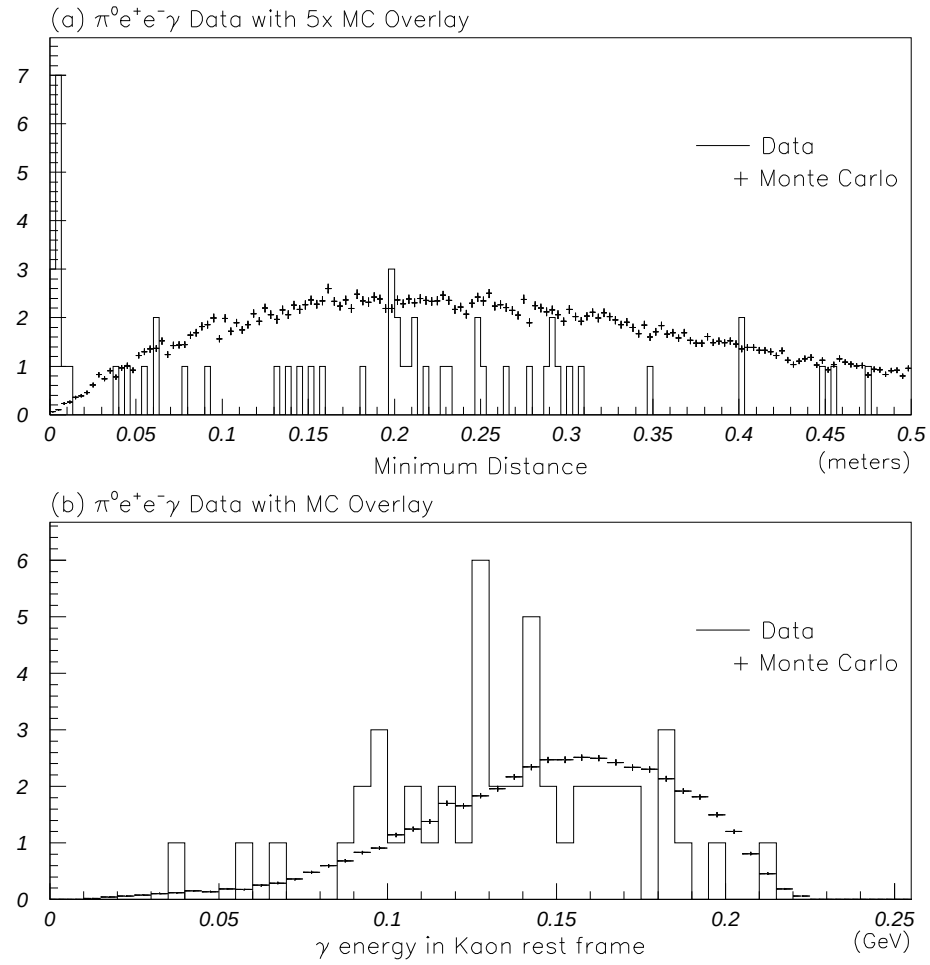
Fusion χ^2

- Use data showers for determining fusion χ^2
  - All other quantities calculated using usual GEANT showers.
  - Better agreement between data and MC.
  - Predicts different shape under peak.

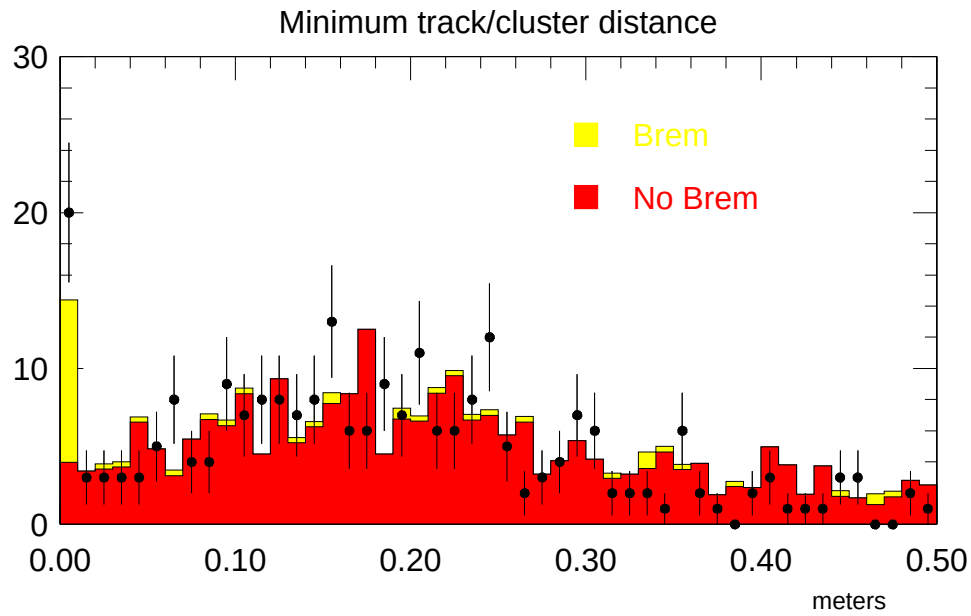


Bremsstrahlung Events

- In PRL result, MC/data discrepancy.
  - Distance between upstream track projection and cluster in CsI.
  - Attributed to $K_L \to e^+e^-\gamma\gamma$ events.
  - Small number of events.



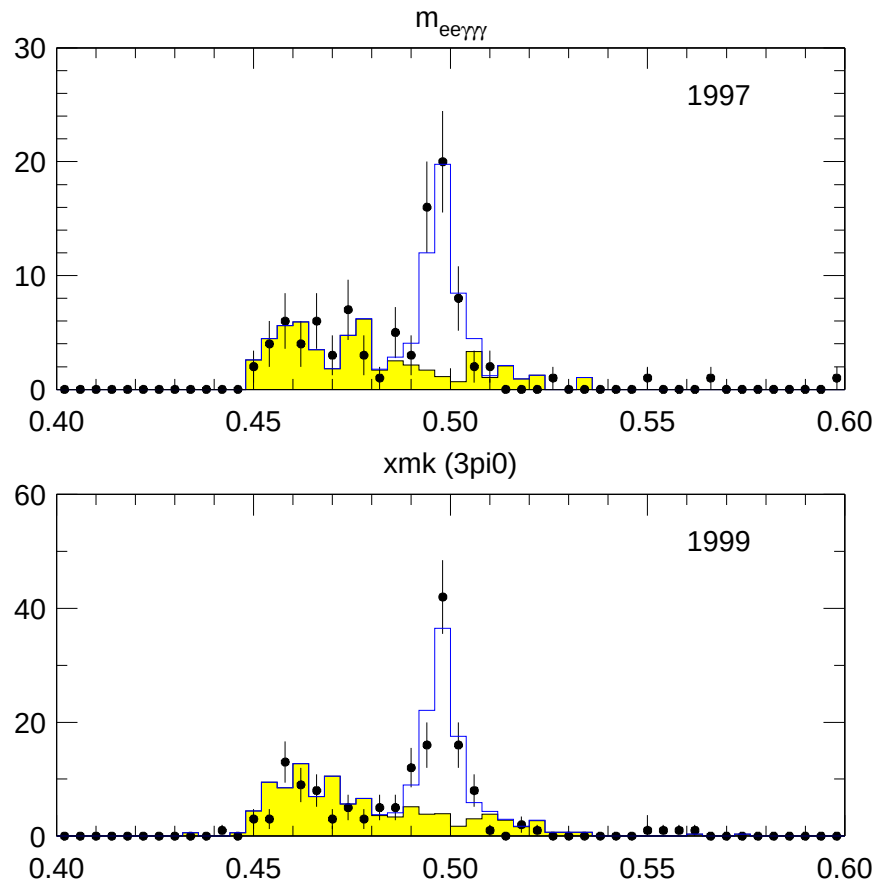
Bremsstrahlung Events



- MC allows at least one missing particle.
  - Signal + bkg MC shows spike at small distances.
  - Suggests that previous result did not allow for missing particles.

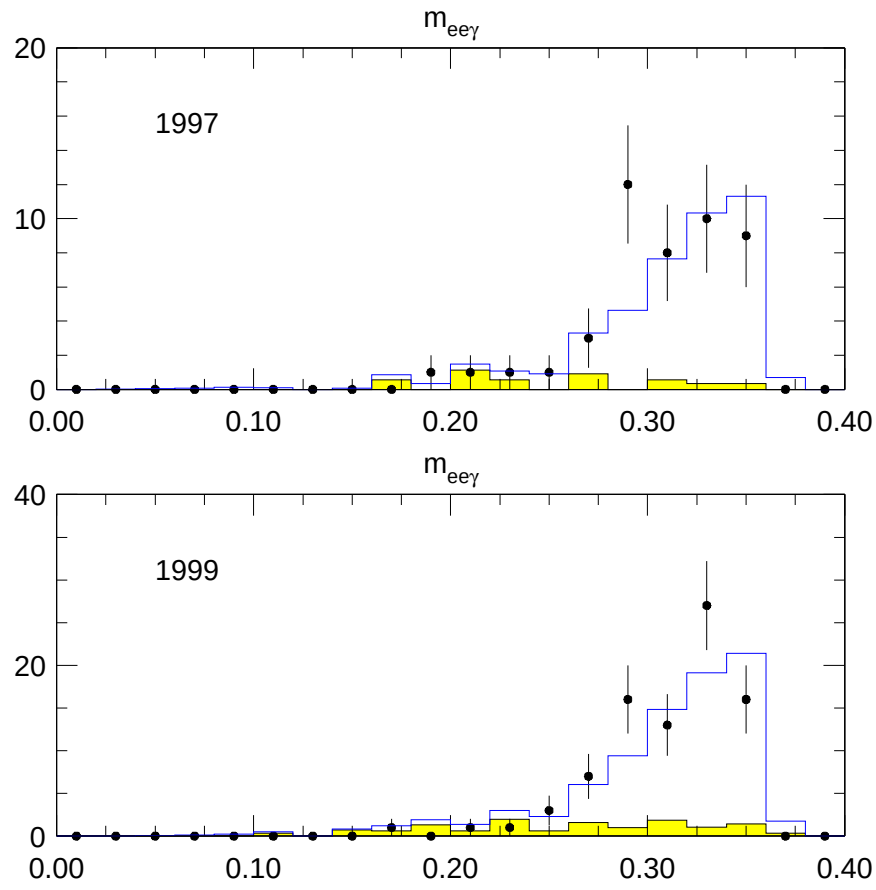
Kaon Mass

- Mass of $e^+e^-\gamma\gamma\gamma$ system.
  - All cuts but kaon mass applied.
  - Somewhat lower background than previous result.



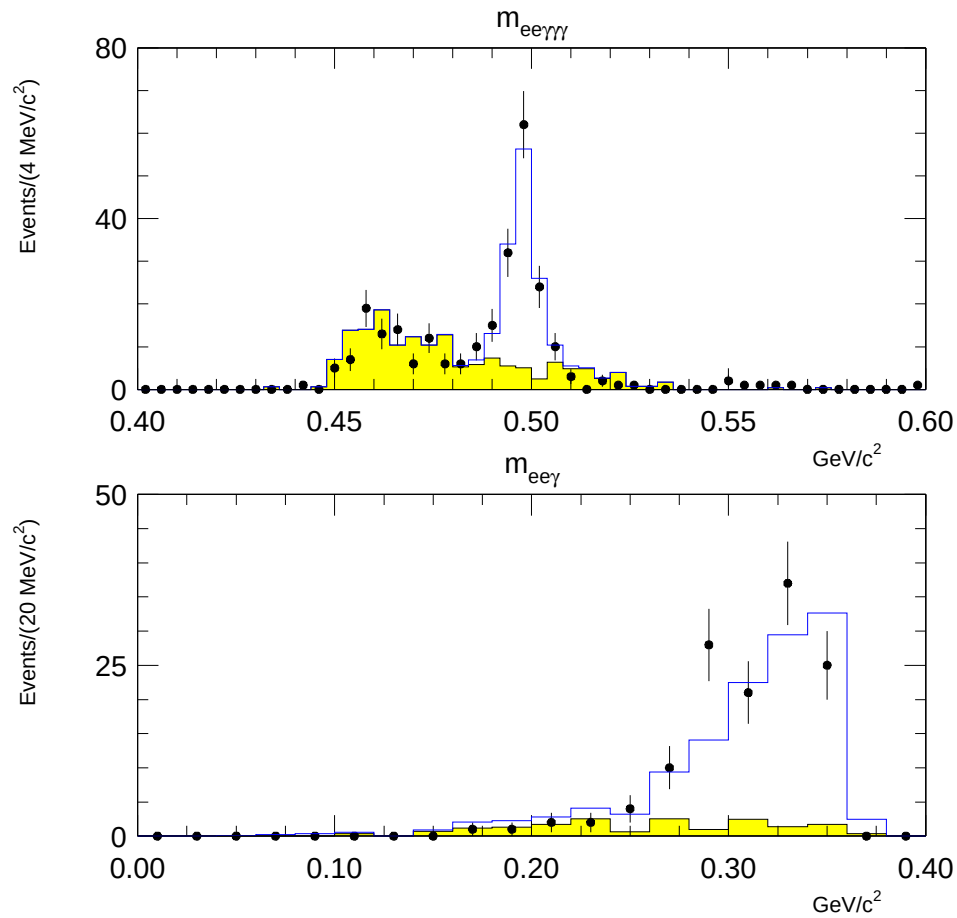
$e^+e^-\gamma$ Mass.

- Final sample.
  - 1997: 46 events.
  - 1999: 85 events.



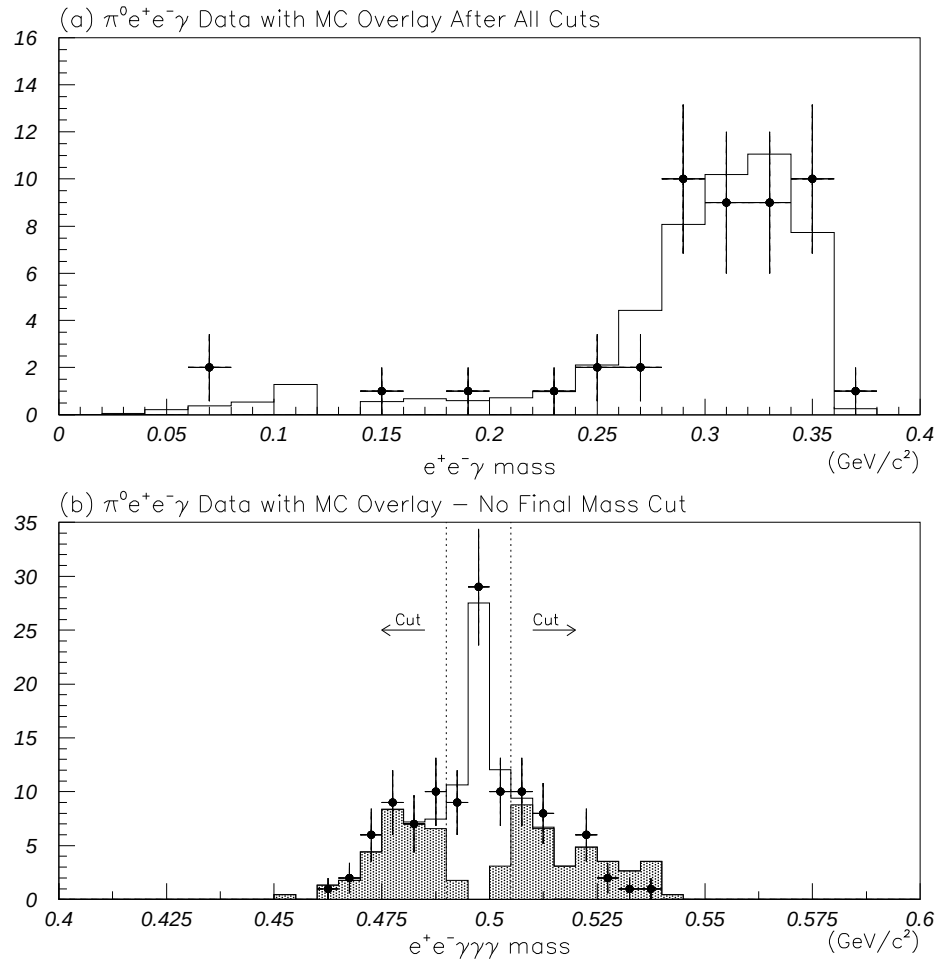
Combined Samples

- 131 candidates.
- 18 background events.
- Little evidence of a tail at low $e^+e^-\gamma$ mass.



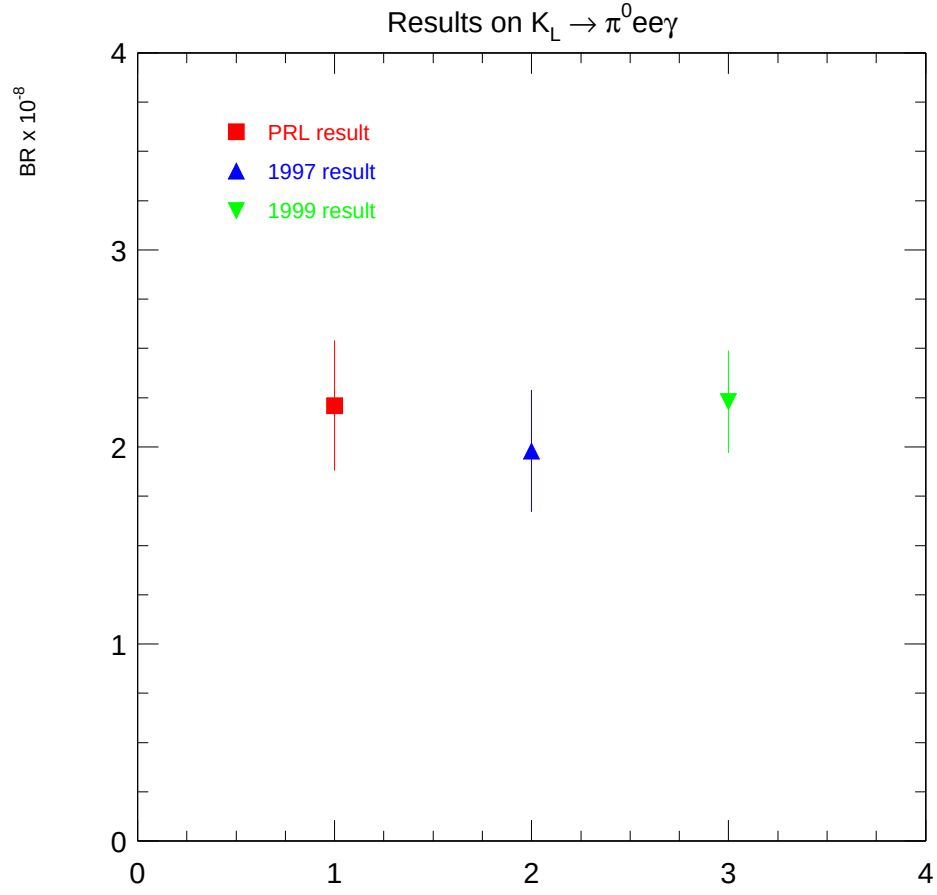
PRL Result

- 48 Events over 3.6 ± 1.1 bkg.
- Somewhat higher background before kaon mass cut.
- Some evidence of a tail at low $e^+e^-\gamma$ mass.



Branching Ratio Results

- PRL: $(2.21 \pm 0.33) \times 10^{-8}$
- 1997: $(1.98 \pm 0.31) \times 10^{-8}$
- 1999: $(2.23 \pm 0.26) \times 10^{-8}$



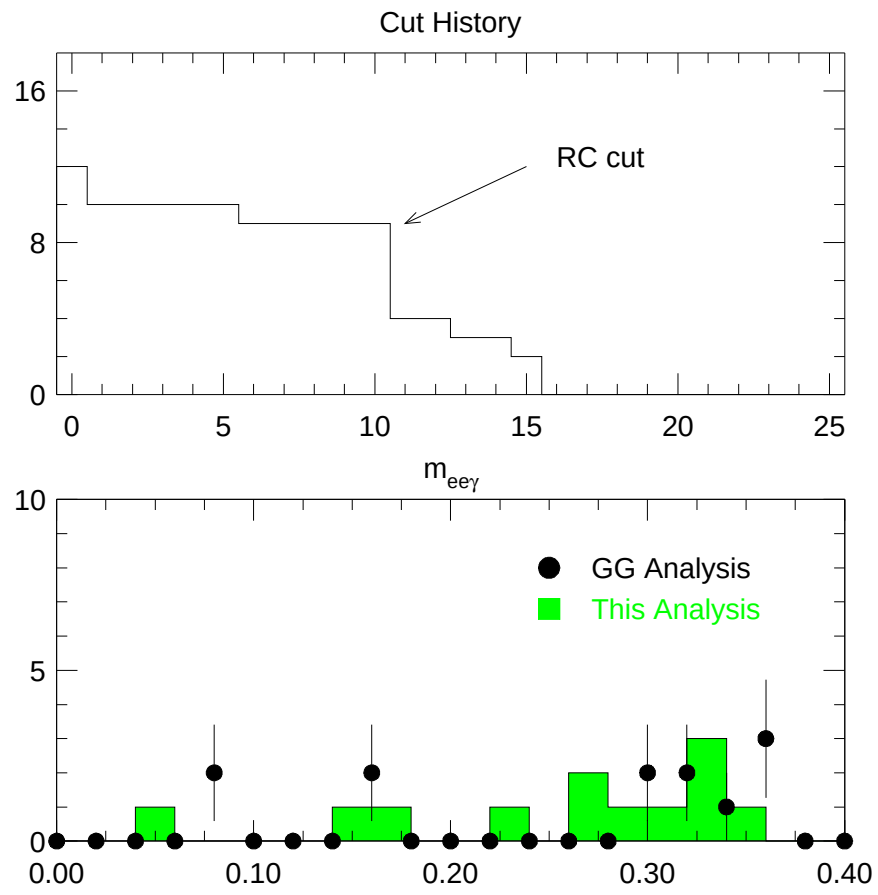
Comparison of Results

	PRL result	1997 Data
Flux	2.80×10^{11}	2.87×10^{11}
Acceptance (%)	0.72	0.73
Signal Events	48	46
Background	3.6 ± 1.1	4.4 ± 1.49
Branching Ratio	2.21×10^{-8}	1.98×10^{-8}

- PRL: 12 exclusive events.
- 1997 new: 13 exclusive events.
- BR difference: $(0.23 \pm 0.23) \times 10^{-8}$.

Comparison of Results

- Of the exclusive events in PRL result.
  - About 40% removed by RC cut.
  - Reconstructed mass very different.
  - $\rightarrow$ Analyses are quite different.



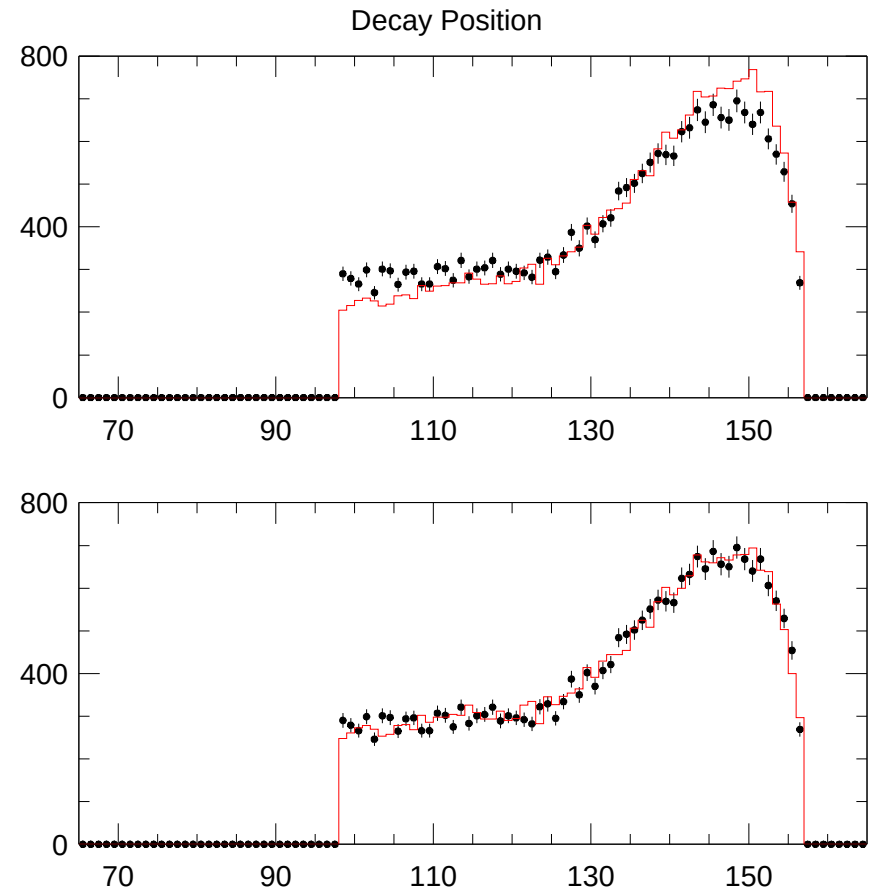
Backgrounds

	1997	1999 Data
$2\pi^0$	1.0 ± 0.6	6.0 ± 1.5
$3\pi^0$	3.4 ± 1.4	7.5 ± 2.2

- Have not broken down into subcomponents.
  - Conversions, fusions, lost photons.

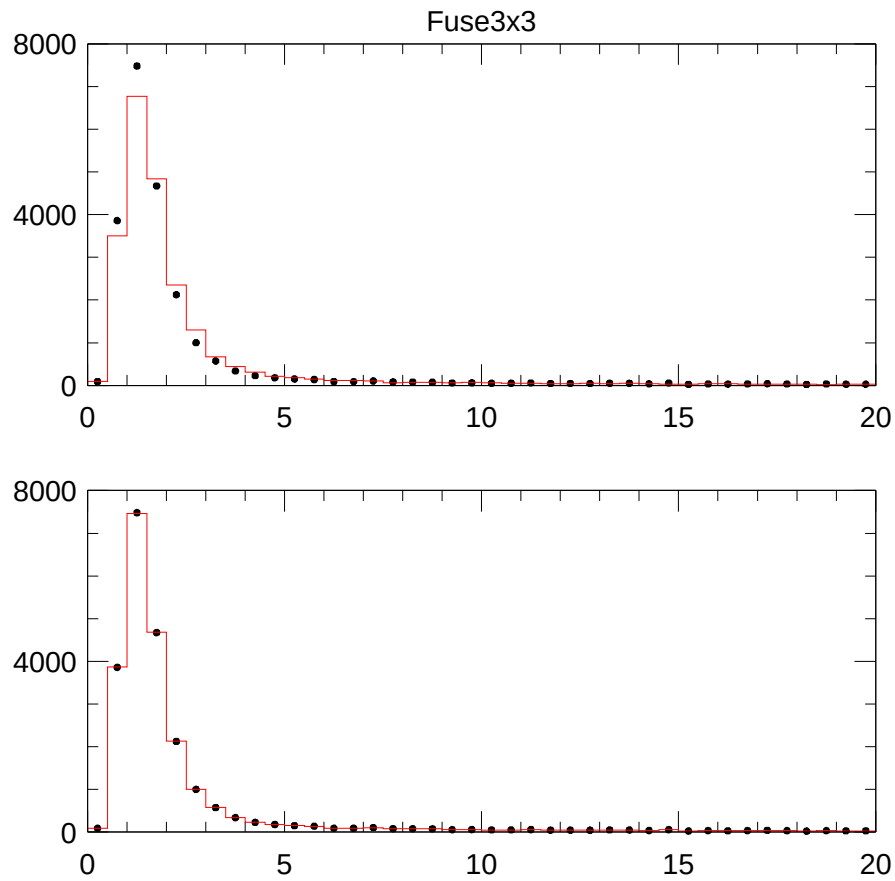
Systematic Studies

- Reweight MC to match data.
  - In some cases use actual data/MC ratio.
  - For $3\pi^0$ decay position, use fit to data/MC ratio.
  - Determine change in background level.
    - Take full change as systematic.
  - For $3\pi^0 z$ we find: 1% change.



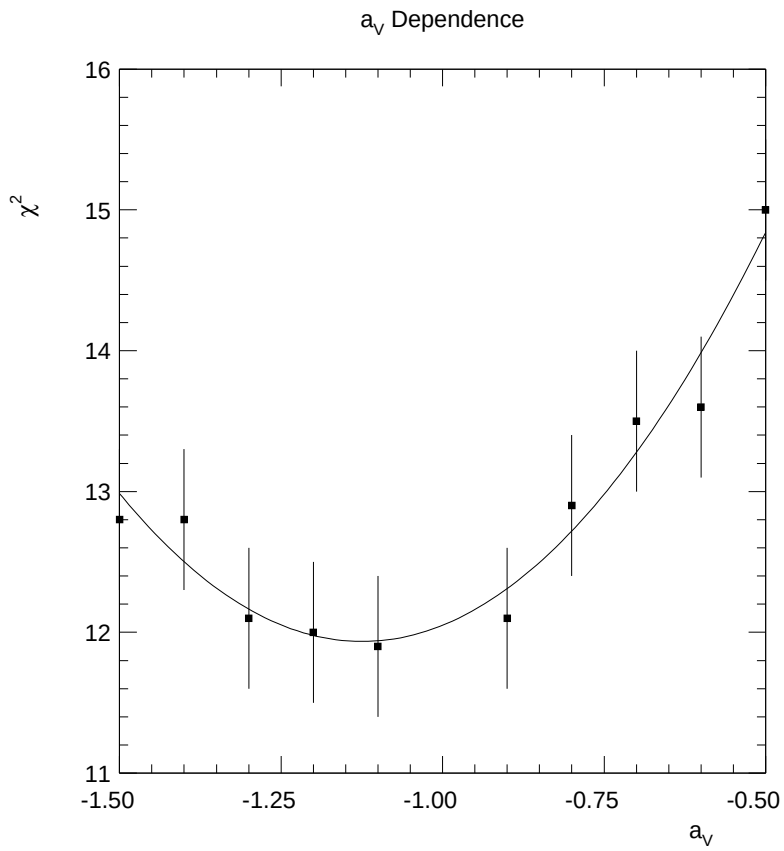
Systematics

- Fuse3x3 variable.
  - $K_L \to \pi^0\pi^0\pi^0$ Data/MC.
  - Still some mismatch below 4 (where we cut).
  - Produces about 1% change in bkg level.



Systematics

- Dependence on a_V parameter.
  - Data prefers a value of $a_V = -1.1$.
    - Varying a_V by 1σ, the acceptance changes by about 6%.
    - This is the largest systematic.
- Plan to look at using y Dalitz variable, also.



Systematics

Systematic	1997 Data	1999 Data
a_V dependence	7.6	5.4
MC Statistics	4.2	3.7
FUSE3x3 cut	1.0	0.5
$3\pi^0$ z	1.0	1.3
$3\pi^0$ normalization	0.0	0.4
pp0kin cut	0.3	0.7
$3\pi^0$ p	0.3	0.4
$2\pi^0$ background	0.3	0.3
apertures	0.4	0.4
$2\pi^0$ z	0.2	0.2
p_T^2 cut	0.1	0.1
Total	8.8	6.8
K_L and π^0 BR	2.8	

Final Result

- Combine results, weighting by combined error.
- BR($K_L \to \pi^0 e^+ e^- \gamma$) = $(2.13 \pm 0.20 \pm 0.13) \times 10^{-8}$
- Compare with $(2.21 \pm 0.33 \pm 0.12) \times 10^{-8}$
- Note on analysis
  - http://kpasa.fnal.gov:8080/private/ktevdoc/e799/kpi0eeg/pi0eeg_97_99.pdf

Things to do

- Work on a_V dependence.
  - Add in y Dalitz variable.
  - Look into more recent theories.
- Background studies.
  - RC TDC information.
  - Try to tune up $2\pi^0$ neural net.
  - Look into vacuum window conversions.
  - Backgrounds from $K_L \to \pi^0\gamma\gamma$.
- More MC?