Notes on the Background Estimation for the 1997 $K_L \to \pi^+\pi^-\gamma$ Analysis

Michael Ronquest
U.Va.
mr7y@virginia.edu

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Contents

1 Introduction **2**

2 Calculation of Kaon Flux From Number of $K_L \to \pi^+\pi^-\gamma$ Decays **2**

3 Background Due to $K_L \to \pi^+\pi^-$ **2**

4 Background Due to $K_L \to \pi^+\pi^-\pi^0$ **3**

5 Background Due to Hyperon Decays **3**
5.1 Estimate of Hyperon Flux 3
5.2 Background Due to $\Lambda \to p\pi$ 4
5.3 Background Due to $\Xi^0 \to \Lambda\pi^0, \Lambda \to p\pi$ 4

6 Background Due to $K_L \to \pi\mu\nu$ **5**

7 Background Due to $K_L \to \pi e\nu$ **6**
7.1 Background Due to $K_L \to \pi e\nu\gamma$ 6

8 Remaining Background **7**

References

[1] Rick Kessler. $K_L \to \pi^+\pi^-\gamma$ level 3,crunch and mc. Jan 2003.

[2] John Shields. *The Search for the Emission of a CP–Violating E1 Photon in the $K_L \to \pi^+\pi^-\gamma$ Decay.* PhD thesis, University of Virginia, 2004.

[3] Steven Bright. *First Measurement of Form Factors of the Beta Decay of the Neutral XI Hyperon.* PhD thesis, University of Chicago, 2000.

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[5] T. Alexopoulus et al. Measurements of the branching fractions and decay distributions for $k_L->\pi\mu\nu\gamma$ and $k_L->\pi e\nu\gamma$. *Physical Review D*, **71**:012001, 2005.

1 Introduction

This note describes the determination of the background composition of the 1997 $K_L \to \pi^+\pi^-\gamma$ analysis. All backgrounds were estimated using PDG branching ratios and acceptances from KTEVMC v6.03 with default parameters, except when mentioned otherwise. All kaon decays were generated within the ranges 115m< Z Vertex <160m, and 18GeV/c<P_K<162GeV/c except when stated otherwise. All events were subjected to the normal crunch cuts detailed in [1], except when stated otherwise.

John Shields [2] estimated that the background under the mass peak in this decay mode is between 618 and 789 events, using exponential fits to the wing region of the $M_{\pi\pi\gamma}$ distribution.

2 Calculation of Kaon Flux From Number of $K_L \to \pi^+\pi^-\gamma$ Decays

In order to estimate the number of background events from first principles, it is necessary to first determine the kaon flux for this data sample. Using the analysis cuts used in the $K_L \to \pi^+\pi^-\gamma$ analysis [2], the total acceptance for $K_L \to \pi^+\pi^-\gamma$ is found to be .06093 for events with $E_\gamma>$ 20MeV, 115m<Z Vertex<160m, and 18GeV/c<P_K<162GeV/c. The 2004 PDG quotes a value of 4.39×10^{-5} for the $K_L \to \pi^+\pi^-\gamma$ branching ratio, when $E_\gamma>$ 20MeV. The final number of events in the data after all cuts including background is 112,140. This leads to an estimate of 4.193×10^{10} kaon decays with 115m< Z Vertex <160m, and 18GeV/c<P_K<162GeV/c.

3 Background Due to $K_L \to \pi^+\pi^-$

As $K_L \to \pi^+\pi^-$ is related to $K_L \to \pi^+\pi^-\gamma$, the expectation is that this is a possible source of background. In order to pass all analysis cuts, this mode must coincide with an accidental photon. The strongest cut against this mode, beside $M_{\pi\pi\gamma}$ and P_T^2 cuts which will depend on the accidental photon, is the $\pi\pi$ mass cut, which for this analysis is set at .492 GeV. After generating nearly an entire flux of $\pi\pi$ events, John estimates the background will consist of only 1.25 ± 1.25 non–IB $\pi^+\pi^-$ events. Clearly, the low branching ratio, along with the $\pi\pi$ mass cut, prevents this mode from having a significant contribution to the background.

4 Background Due to $K_L \to \pi^+\pi^-\pi^0$

Owing to its large branching ratio, $K_L \to \pi^+\pi^-\pi^0, \pi^0 \to \gamma\gamma$ may be a major background. Aside from $M_{\pi\pi\gamma}$ and P_T^2 cuts, the major suppression of this mode will be from the so-called 'pp0kine' cut-or hypothetical squared longitudinal π^0 momentum cut. No cut was made on the presence of reconstructed π^0s.

Using the 2004 PDG value of .1259 for the branching ratio, a full flux of $\pi^+\pi^-\pi^0$ would be 5.27×10^9 – too large a sample to generate easily. In order to save time and resources, 1.53% of the expected flux was generated, and all cuts were applied, except $M_{\pi\pi\gamma}$, P_T^2 and pp0kine cuts. A mass plot was then generated in order to predict the distribution of events on the invariant mass plot. The $P_T^2$and pp0kine cuts were applied together to obtain the amount of suppression that these cuts perform on this decay mode. This suppression factor was then applied to the mass plot to yield a estimate for the $\pi^+\pi^-\pi^0$ background. The calculation was done using the numbers in Table 1.

Cuts Applied	**Events Remaining**
All Except Mass, P_T^2 and $P_{\pi^0}^2$	9134
All Except Mass	18

Figure 1: Major Cuts on $\pi^+\pi^-\pi^0$ with 1.53% of the total yield. All nominal crunch cuts were made, except for pp0kine, and the $M_{\pi\pi\gamma}$ cut, which was lowered to .20 GeV. The B02 overlaps did not receive any pp0kin crunch cut.

After all cuts, except the final P_T^2 , $M_{\pi\pi\gamma}$ and pp0kine cuts, there are 9134 events remaining. Applying the P_T^2 and $M_{\pi\pi\gamma}$ cuts results in 18 events, leading to a efficiency of $(1.97 \pm .46) \times 10^{-3}$ for these final two cuts. Applying this scaling factor to the mass plot before final cuts results in $133 \pm 31 \to \pi^+\pi^-\pi^0$ decays after ALL cuts—for a full flux of $\pi^+\pi^-\pi^0$ decays.

5 Background Due to Hyperon Decays

5.1 Estimate of Hyperon Flux

In order to estimate the hyperon background, the Λ and Ξ yields must first be calculated. This is tricky, as E832 used extra beam absorbers which will invalidate the hyperon flux data from E799, where the hyperon modes were studied. To the best of my knowledge, an estimate of the relative hyperon yield for E832 has never been attempted.

To start, I must first determine the number of kaons to lambdas to cascades in E799. The origin of this number is cloudy, and its value dependent on source. The most popular number seems to be 500:10:1 for the ratio of kaons to Λ to Ξ. The most explicit measurement I could find is from Steven Bright's thesis [3]. In it he quotes a Λ flux of 2.0×10^9, and a Ξ flux of 1.14×10^8. He also quotes a Kaon flux of 1.06×10^{11} for 230GeV $>E_K>$20GeV and 158m> Z Vertex >95m. Using these numbers, the ratio between kaon and hyperon fluxes is 929:17.5:1

for kaons, lambdas and cascades respectively. However, this appears to contradict the 'classic' 500:10:1 ratio, which predicts slightly more Λ, and approximately double the number of Ξ. *In order to be conservative, I chose to use the 'classic' 500:10:1 ratio—for E799.*

E832 used additional absorbers in the beam [4] which will modify the relative hyperon rate from that of E799. Using the numbers given in the reference, the kaon transmission in E832 should be 0.421 times that of E799, while the hyperon transmission should be 0.288 times that of E799, assuming that hyperons and neutrons have similar cross sections in the absorbers. This means that the kaon to hyperon ratio in E832 should increase by a factor of 1.462 relative to that in E799, leading to an expected ratio of 730:10:1 for E832. My quoted kaon flux in section 2 is for a different range in kaon momentum and z vertex. However, the above ratio is only valid for 230GeV>E_K>20GeV and 158m> Z Vertex >95m. In order to properly generate the correct number of hyperons, I must determine the expected kaon flux for the above ranges. By generating $K_L \to \pi^+\pi^-\gamma$ Monte Carlo over the wider range, I found that the acceptance for $K_L \to \pi^+\pi^-\gamma$ is .0388 for $E_\gamma > 20MeV$, $230GeV > E_K > 20GeV$ and $158m >$ Z Vertex$> 95m$. This leads to a kaon flux of 6.584×10^{10}, and thus 9.019×10^8 and 9.019×10^7 for Λ and Ξ respectively.

5.2 Background Due to $\Lambda \to p\pi$

Since protons appear similar to πs in the calorimeter, the hyperon decay $\Lambda \to p\pi$ can fake $K_L \to \pi^+\pi^-\gamma$ when accompanied by an accidental photon. As a Λ mass cut was not made, the primary cuts against this mode are the $P_K$cut, as well as $P_T^2$and $M_{\pi\pi\gamma}$. Once again, only part of a flux was generated—this time, 0.555 of the total flux, or 5.763×10^8 $\Lambda \to p\pi$ events.

Cuts Applied	**Events Remaining**
All Except Final Mass,$P_T^2$and P_K	4102
All Except Final Mass and P_T^2	91
All Except Final Mass and P_K	387
All Except $P_T^2$and P_K	579

Figure 2: Major Cuts on $\Lambda \to p\pi$ with 0.555 of the total yield.

By applying the cuts one by one as in Table 2, we can see that each cut has a efficiency of $.0222 \pm .0023$, $.094 \pm .0048$ and $.1412 \pm .0059$ for the final P_K, $P_T^2$and $M_{\pi\pi\gamma}$cuts respectively. Applying the effect of all cuts on the 4102 events, and scaling up to a full flux leads to an estimate of (2.17 +/- .27) $\Lambda \to p\pi$ decays in this data sample. It should be pointed out that due to assumptions that were made about the hyperon flux from E799, and the effect of the beam absorbers, this may be an *overestimate.*

5.3 Background Due to $\Xi^0 \to \Lambda\pi^0, \Lambda \to p\pi$

This decay is similar to $\Lambda \to p\pi$, except in this decay, accidental photons are not required, as two photons are supplied in the π^0 decay. The dominant cuts here are the same as those for the Λ decay-P_K, $M_{\pi\pi\gamma}$and P_T^2.

For this mode, 0.5689 of the full sample of 8.98×10^7 decays was generated. The Λ and π^0 were not forced to decay into pπ or 2γ. Once again applying the final cuts separately results in relative cuts of .2971$\pm$.0103, .0294$\pm$.0032 and .1182$\pm$.0065 for P_K, $P_T^2$and $M_{\pi\pi\gamma}$cuts respectively, as shown in Table 3.

Cuts Applied	**Events Remaining**
All Except Final Mass,$P_T^2$and P_K	2793
All Except Final Mass and P_T^2	830
All Except Final Mass and P_K	82
All Except $P_T^2$and P_K	330

Figure 3: Major Cuts on $\Xi^0 \to \Lambda\pi^0$ with 0.5689 of the total yield.

Multiplying the effect of all three final cuts on the 2793 events that survive after all other cuts and scaling up to a full flux results in $5.1 \pm .65$ $\Xi^0 \to \Lambda\pi^0$ events remaining in the final data sample. Again, due to assumptions that were made about the hyperon flux from E799, and the effect of the beam absorbers, this may be an *overestimate*.

6 Background Due to $K_L \to \pi\mu\nu$

Owing to the large branching ratio of this mode, the possibility that it contributes to the background must be explored. Most of this mode will be suppressed by the muon vetoes, except for low momentum muons that are absorbed in the steel in front of mu2. Thus, the strongest cut should be the cut on track momentum, as well as the normal $M_{\pi\pi\gamma}$and P_T^2cuts. Using the 2004 PDG branching ratio of 27.19%, 3.83% of a full flux was generated. Using this reduced sample, all cuts except for the track momentum, $M_{\pi\pi\gamma}$, and P_T^2cuts were applied. Then, each of the remaining cuts was applied singly to obtain the factor by which each reduces the size of the $\pi\mu\nu$ sample.

Cuts Applied	**Events Remaining**
All Except Final Mass,$P_T^2$and track momentum	17760
All Except Final Mass and P_T^2	20
All Except Final Mass and track momentum	284
All Except $P_T^2$and track momentum	5259

Figure 4: Major Cuts on $\pi\mu\nu$ for 0.0383 of the total yield. All nominal crunch cuts were made, except for the P_T^2cut, which was effectively removed, and the $M_{\pi\pi\gamma}$cut, which was widened to 0.4-0.6GeV

Table 4 shows that the $M_{\pi\pi\gamma}$, $P_T^2$and track momentum cuts suppress $\pi\mu\nu$ by factors of .2961$\pm$ .0041, $.016 \pm .001$ and $.00113 \pm .00025$ respectively. Combining these three together, applying the overall factor to the 17,760 events left before final cuts, and scaling up to a full flux leads to an estimate of $2.5 \pm .6$ $\pi\mu\nu$ events in the final data sample.

7 Background Due to $K_L \to \pi e \nu$

The last of the large charged modes that are likely to contribute to the background is $\pi e \nu$. Obviously, the best cut here will be E/p, followed by the usual $M_{\pi\pi\gamma}$and P_T^2cuts. Using the 2004 PDG branching ratio of 38.81%, 3.1% of a full flux was generated. Then, all cuts except for the E/p, $M_{\pi\pi\gamma}$, and P_T^2cuts were applied, and finally each cut was applied singly to get its effect on the $\pi e \nu$ yield.

Cuts Applied	**Events Remaining**
All Except Final Mass,$P_T^2$and E/p	365600
All Except Final Mass and P_T^2	376
All Except Final Mass and E/p	14310

Figure 5: Major Cuts on $\pi e \nu$ with 0.031 of a total yield. All nominal crunch cuts were made, with the exception of E/p, which was removed, and $M_{\pi\pi\gamma}$, which was widened to 0.4-0.6GeV.

Table 5 implies that E/p and P_T^2cuts suppress Ke3 by a factor of $(1.02 \pm .05) \times 10^{-3}$ and $.0391 \pm .0003$ respectively. Taking the $M_{\pi\pi\gamma}$plot from the sample without the $P_T^2$and E/p cuts, and scaling it by the factors for these cuts, while also scaling up to a full flux, results in an estimated $\pi e \nu$ mass spectrum that can be used to model the background of the $M_{\pi\pi\gamma}$distribution. By counting the number of events in the kaon mass region, an estimate of 120 ± 6 $\pi e \nu$ events is found.

7.1 Background Due to $K_L \to \pi e \nu \gamma$

When the $K_L \to \pi e \nu$ MC events were generated, no radiative corrections were applied. To compensate for this, it was necessary to separately generate $K_L \to \pi e \nu \gamma$ events to ensure that the presence of a gamma will not allow this mode to contribute significantly to the background.

I generated 22,542,940 $K_L \to \pi e \nu \gamma$ decays, which works out to 2.8% of a full yield when the most recent KTeV branching ratio[5] for this mode is used to calculate the expected flux.

Then, all cuts except for the E/p, $M_{\pi\pi\gamma}$, and P_T^2cuts were applied, and finally each cut was applied singly to get its effect on the $\pi e \nu \gamma$ yield.

Cuts Applied	**Events Remaining**
All Except Final Mass,$P_T^2$and E/p	31058
All Except Final Mass and P_T^2	31
All Except Final Mass and E/p	2082
All Except $P_T^2$and E/p	7897

Figure 6: Major Cuts on $\pi e \nu \gamma$ with 2.8% of a full yield. All nominal crunch cuts were made, with the exception of E/p, which was removed, and $M_{\pi\pi\gamma}$, which was widened to 0.4-0.6GeV.

Table 6 implies that the E/p and P_T^2cuts suppress $\pi e \nu$ by a factor of $(1.0 \pm .2)\times^{-3}$ and $.0670 \pm .0015$ respectively, while the mass cut would scale this mode by $.2543 \pm .0029$. These

factors, along with the number of events before these cuts, imply that a full sample of background $\pi e \nu \gamma$ decays would consist of 19 ± 3 events

8 Remaining Background

The only significant backgrounds appear to come from $\pi e \nu$ and $\pi^+\pi^-\pi^0$ decays. These two combined yield a background of only 253 events-not nearly enough to match the background level that John estimated. There is still a large amount of remaining background that is unaccounted for.

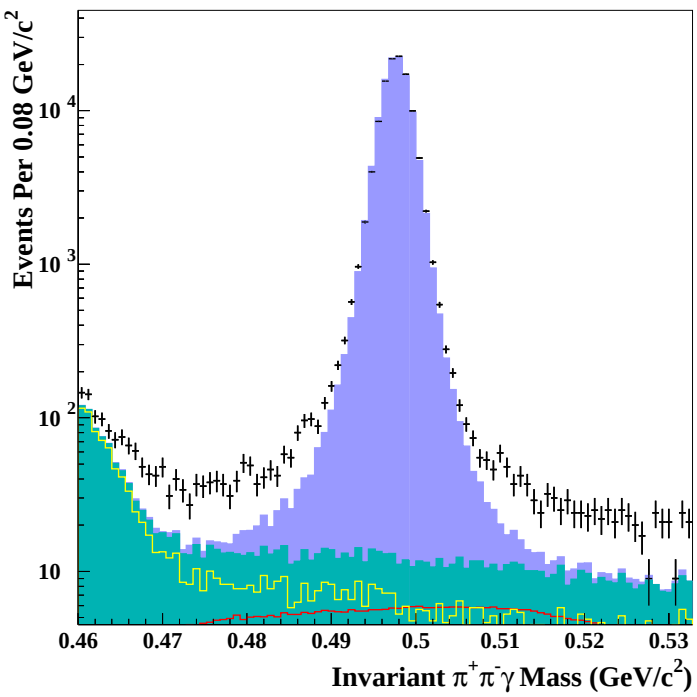

Figure 7: $M_{\pi\pi\gamma}$Plot. Points are data. Blue histogram is total MC prediction. Green histogram is total background Monte Carlo. Yellow histogram is $\pi^+\pi^-\pi^0$ Monte Carlo. Red histogram is $\pi e \nu$ Monte Carlo.

One possibility is that the acceptance predicted from the MC is not quite right for either $\pi e \nu$ or $\pi^+\pi^-\pi^0$. It is highly unlikely that the acceptance for $\pi^+\pi^-\pi^0$ is incorrect, as this mode dominates at $M_{\pi\pi\gamma} <$ 0.46GeV. If the acceptance was off, the data-MC agreement in this region would be poor. This leaves $\pi e \nu$. E/p is the dominant cut for this mode, and any remaining events are way out in the tail of the E/p distribution, which is very hard to simulate correctly. If we look at $M_{\pi\pi\gamma} >$ 0.515GeV, we should avoid any stray $K_L \to \pi^+\pi^-\gamma$ events, and minimize the amount of $\pi^+\pi^-\pi^0$. By doing this, we can try to identify the source of the remaining background.

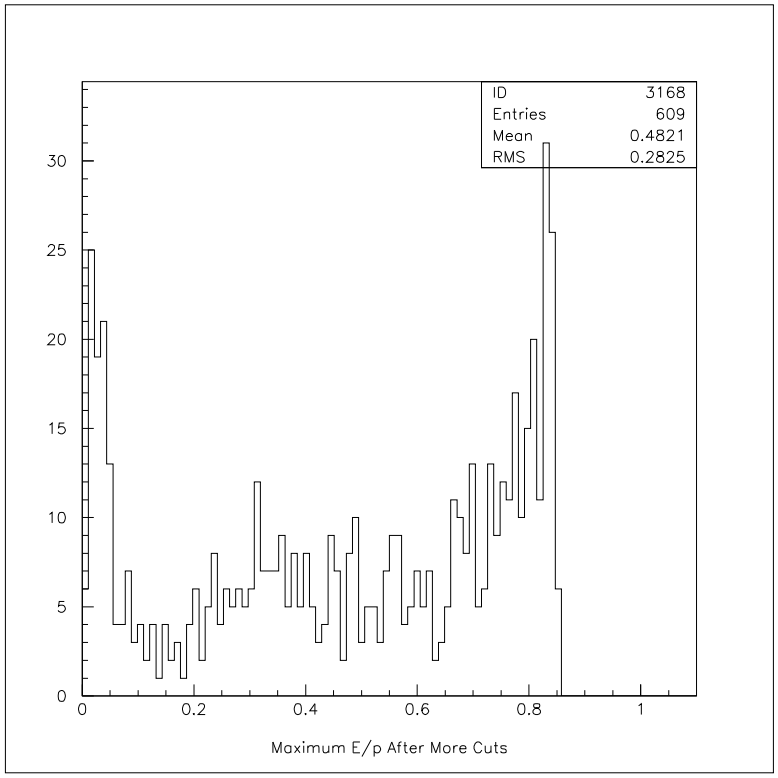

Figure 8: Maximum E/p per event for data ($M_{\pi\pi\gamma}$> 0.515GeV). The rising tail at high E/p indicates the presence of electrons in these data.

Figure 8 indicates that electrons are present in the data at high $M_{\pi\pi\gamma}$. This suggests that the additional background produces electrons. Figure 9 reveals that the data at high $M_{\pi\pi\gamma}$ also have a unique $\cos\theta$ distribution, which is shared by $\pi e\nu$, as shown in Figure 10. The $\cos\theta$ plot for $K_L \to \pi^+\pi^-\gamma$ looks quite different, as shown in Figure 11. Finally, Figure 12 shows that the data at high $M_{\pi\pi\gamma}$ pile up at high $\pi\pi$ mass. Figure 13 indicates that $\pi e\nu$ behaves similarly at high $M_{\pi\pi\gamma}$, as does $K_L \to \pi^+\pi^-\gamma$. The lack of any significant events in this region for Figure 14 reveals that the presence of $\pi^+\pi^-\pi^0$ isn't significant here, as expected.

Given the above evidence, it appears that the majority of the high $M_{\pi\pi\gamma}$ background appears to consist of $\pi e\nu$. Scaling up this mode by a factor of 4.47 results in an acceptable fit, as shown in Figure 15. This results in a total background estimate of 671 $\pm$ 41 events, the majority of which is $\pi e\nu$.

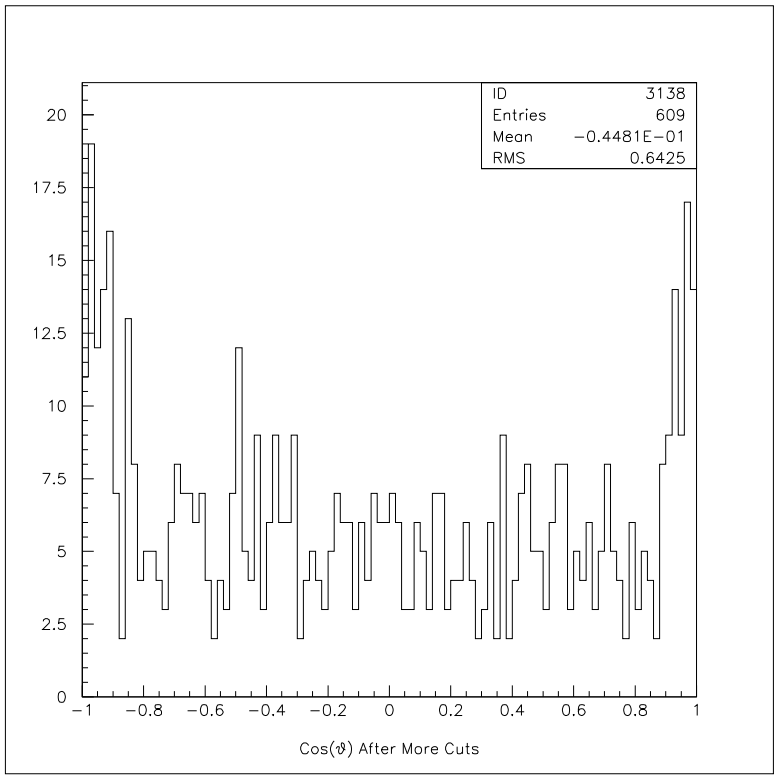

Figure 9: $\cos\theta$ for data ($M_{\pi\pi\gamma}>$ 0.515GeV). The maxima at $\pm$ 1 are a unique feature in this region. θ is the angle between the positive particle and the γ in the $\pi\pi$ rest frame.

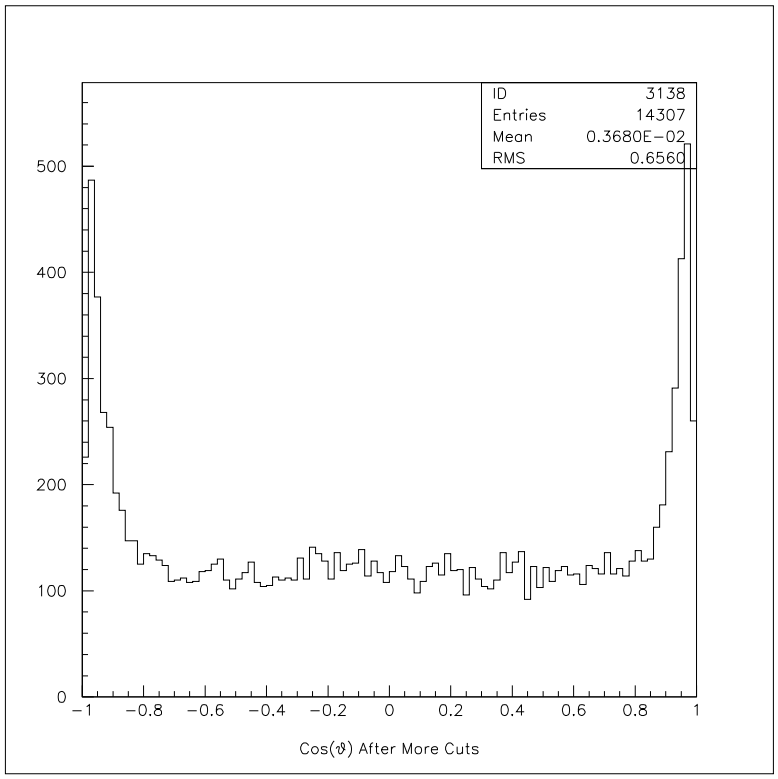

Figure 10: $\cos\theta$ for $\pi e\nu$ MC after P_T^2cut. This plot looks very similar to Figure 9. The $\cos\theta$ plot for $\pi\mu\nu$ does not.

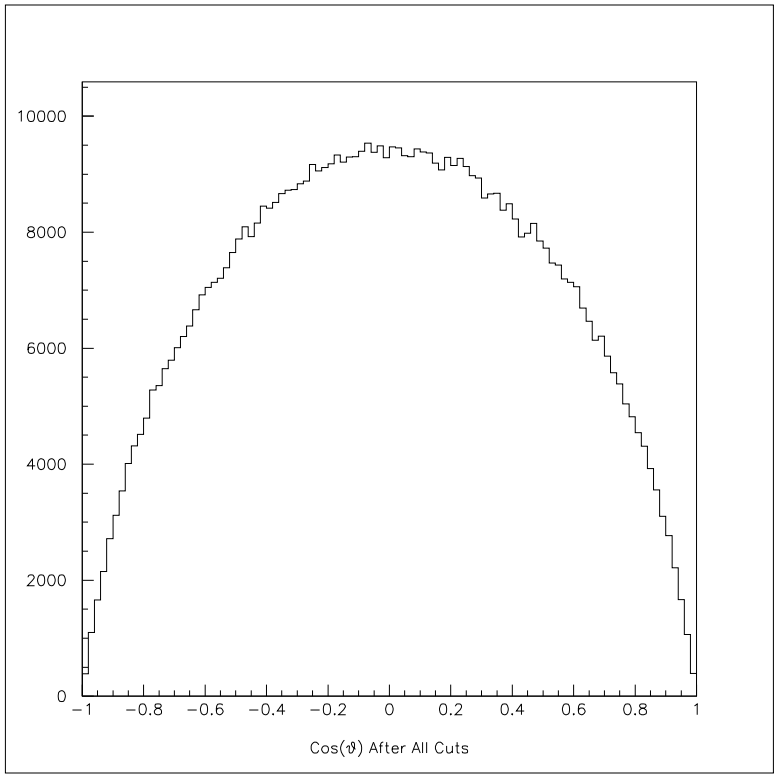

Figure 11: $\cos\theta$ for $K_L \to \pi^+\pi^-\gamma$ MC (Nominal Cuts).

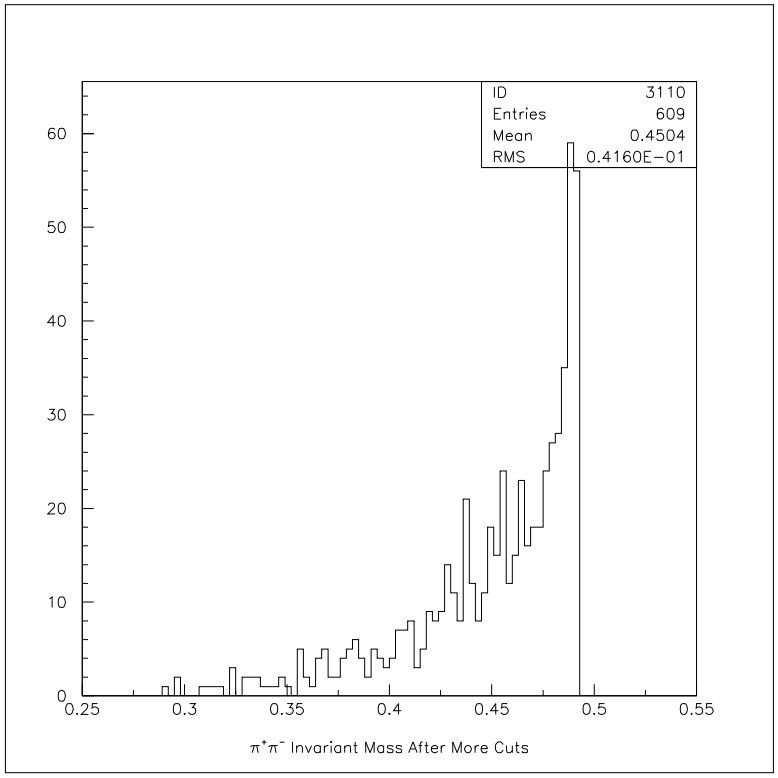

Figure 12: $M_{\pi\pi}$ for data($M_{\pi\pi\gamma}$> 0.515GeV).

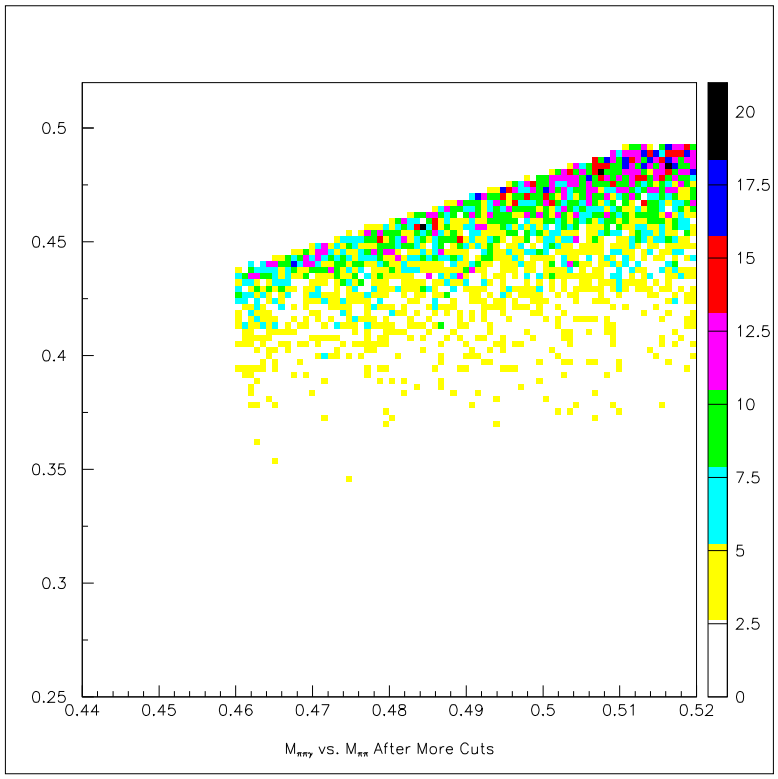

Figure 13: $M_{\pi\pi}$ vs. $M_{\pi\pi\gamma}$for $\pi e\nu$ after the P_T^2 cut. This plot indicates that high $M_{\pi\pi\gamma}$events pile up at high $M_{\pi\pi}$.

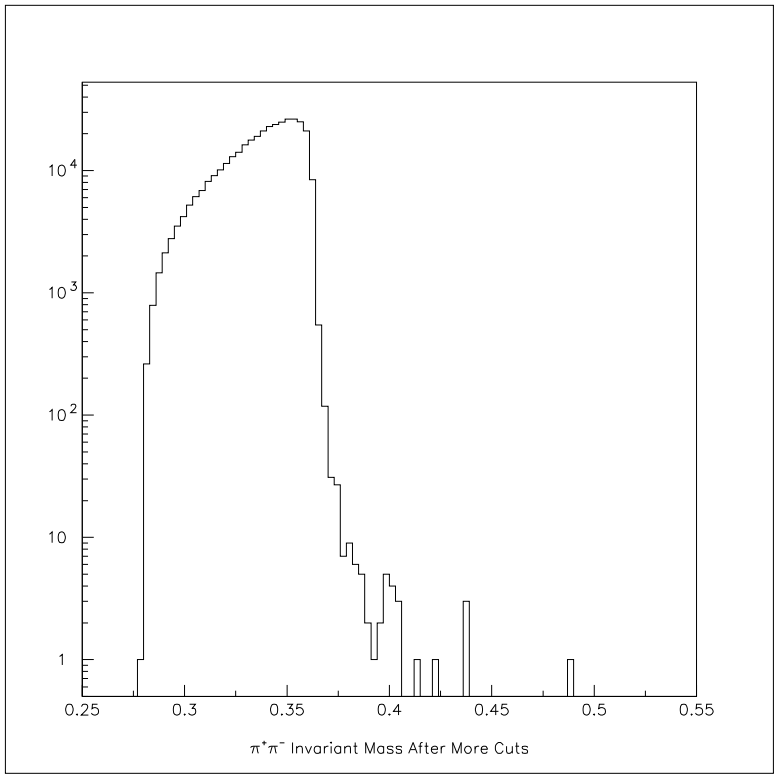

Figure 14: $M_{\pi\pi}$ for $\pi^+\pi^-\pi^0$ before P_T^2 and pp0kine cuts. Note the lack of high $M_{\pi\pi}$ events.

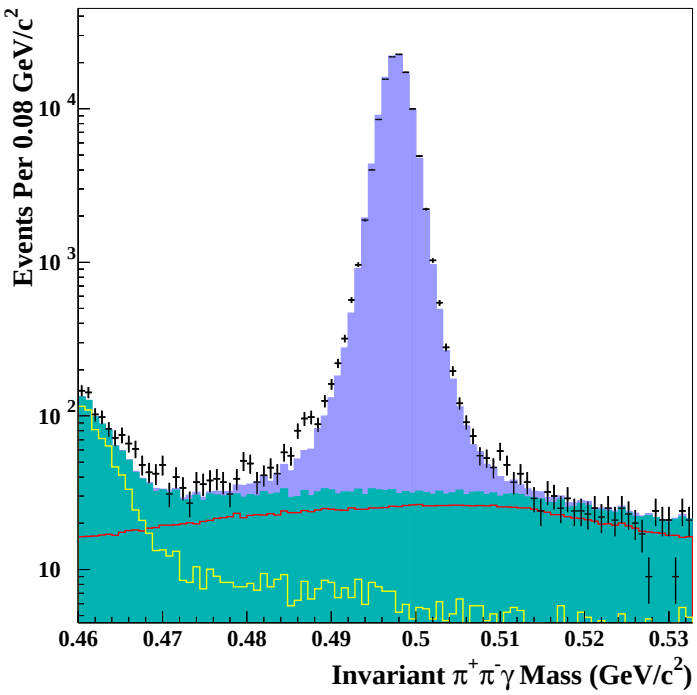

Figure 15: $M_{\pi\pi\gamma}$Plot. $\pi e\nu$ is scaled up by a factor of 4.47. Points are data. Blue histogram is total MC prediction. Green histogram is total background Monte Carlo. Yellow histogram is $\pi^+\pi^-\pi^0$ Monte Carlo. Red histogram is $\pi e\nu$ Monte Carlo.