Update on The Search for $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$

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KTeV Collaboration Meeting

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Status of $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Analysis

- this analysis has addressed/will address various issues, such as the following:

  ~identification and estimation of background. ← Complete!

  ~the boxes for 1997 *AND* 1999 have been opened! An SES for virtual photon and H^0 channels has been obtained with a slight improvement over the previous result.

  ~completion of a normalization mode ($K_L \rightarrow \pi^0\pi^0\pi^0_D$) analysis. ← In Progress...

  ~systematics in the sensitivity.

  ~usage of a constant matrix element in the $K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ MC generation. ← Future Work

Previous KTeV Studies

($K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$)

- A short yet incomplete study was performed on this mode in December 2005. The data used in the previous KTeV study was from the 1997 E799 run.

- results from that analysis include:

  ~acceptance of 2.73% $\rightarrow$ single event sensitivity of 1.4×10^{-10}

  ~signal of less than 2.3 events

  90% C.L. $\rightarrow$

  ~partial width for 'new physics' estimated to be $< 4.0 \times 10^{-24}$ *MeV*

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Analysis Strategy

-Data Selection-

- the data to be used in this study will be from the dimuon triggers of the 1997 and 1999 KTeV E799 runs.

- the tapes used for 1997 were NZL001-NZL130. The tapes used for 1999 were UPM001 - UPM059.

- a 'crunch' has been performed on these 189 data storage tapes, which contained approximately *2.65 TeraBytes* of data. KTeVana v6.04 was used on the crunch and KTeVmc v6.04 was used for MC generation.

- some other decays available from the dimuon triggers are: $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$, $K_L \rightarrow \pi^0 \mu^+ \mu^-$, $K_L \rightarrow \mu^+ \mu^- \gamma\gamma$ and $K_L \rightarrow \mu^+ \mu^- \gamma$.

- $K_L \rightarrow \pi^0 \pi^0 \pi^0_D$ has been chosen for the *normalization* mode. This decay channel is located on the 2e-Nclus trigger.

TRIG5[2MU-LD] = GATE*2V*DC12*2MU3*PHVBAR1*2HCY_LOOSE*HCC_GE1 ← *'97 Dimuon Trigger Def'n*

2V = The VV' Trigger Hodoscope has 2 hits in V view and 1 hit in V' view *OR* 2 hits in V' and 1 hit in V.

DC12 = at least 1 paddle hit in each view of DC1 and DC2.

2MU3 = 2 or more hits in the X and Y views of MU3.

PHVBAR1: this is a veto on all RC's (except RC8), all SA's and the CIA. Specifically, this rejects events that deposit ≥ 500 MeVin the RC's and ≥ 400 MeV in the SA's and the CIA.

2HCY_LOOSE: 2+ hits in every y view of the drift chambers (by the hit counting module); however, a missing hit is allowed in the y view of chamber 1 *OR* chamber 2.

HCC_GE1: ≥ 1 hardware cluster.

TRIG1[2E-NCLUS] = GATE*2V*DC12*ET_THR3*!HA_DC*PHVBAR1*!CA*2HCY_LOOSE*HCC_GE4*1HC2X ← *Normalization Mode Trigger Def'n*

ET_THR3 = Minimum threshold of 25 GeV total raw energy in the CsI electromagnetic calorimeter.

!HA_DC = No DC-coupled Hadron Anti threshold.

!CA = No Collar Anti with energy above 14 MeV.

1HC2X = 1 or more hits in the DC2 X view.

HCC_GE4: ≥ 4 hardware clusters.

(logic symbols: & or * = *AND*, | or + = *OR*, ! = *NOT*)

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Event Reconstruction

-Crunch Cuts-

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Crunch Cut*	1997 Data ♫	1997 MC ♪	1999 Data ♫	1999 MC ♪
Require 2 tracks	0.700	0.970	0.483	0.971
$C_{track1} = -C_{track2}$	0.999	0.999	0.999	0.999
$E_{cl}(track) \leq 2.0$ GeV	0.391	0.913	0.436	0.906
$E_{cl}(track) / p_{track} \leq 0.9$	0.999	0.999	0.999	0.999
# γ clusters ≥ 4	0.056	0.636	0.050	0.687
# hits in μ planes ≥ 1	0.980	0.999	0.989	0.999
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq 15$ MeV	0.196	0.952	0.211	0.959
$90.0 \text{ m} \leq Z_{VTX} \leq 160.0 \text{ m}$	0.265	0.985	0.310	0.975
$p_T^2 \leq 0.06 \text{ GeV}^2/c^2$	0.569	0.802	0.700	0.964
Total Acceptance	0.00044	0.0388	0.00048	0.0498

** = cuts listed in chronological order, ♫ = initial # events was ~277 M (1997) and ~148 M (1999), ♪ = initial # events for 1997 and 1999 was ~2.0 M (# generated events was ~20 M).*

-Notes on Crunch-

- Runs 10923-10928 (on Tape NZL118) and the last (and only) run on Tape NZL130 were *bad.*

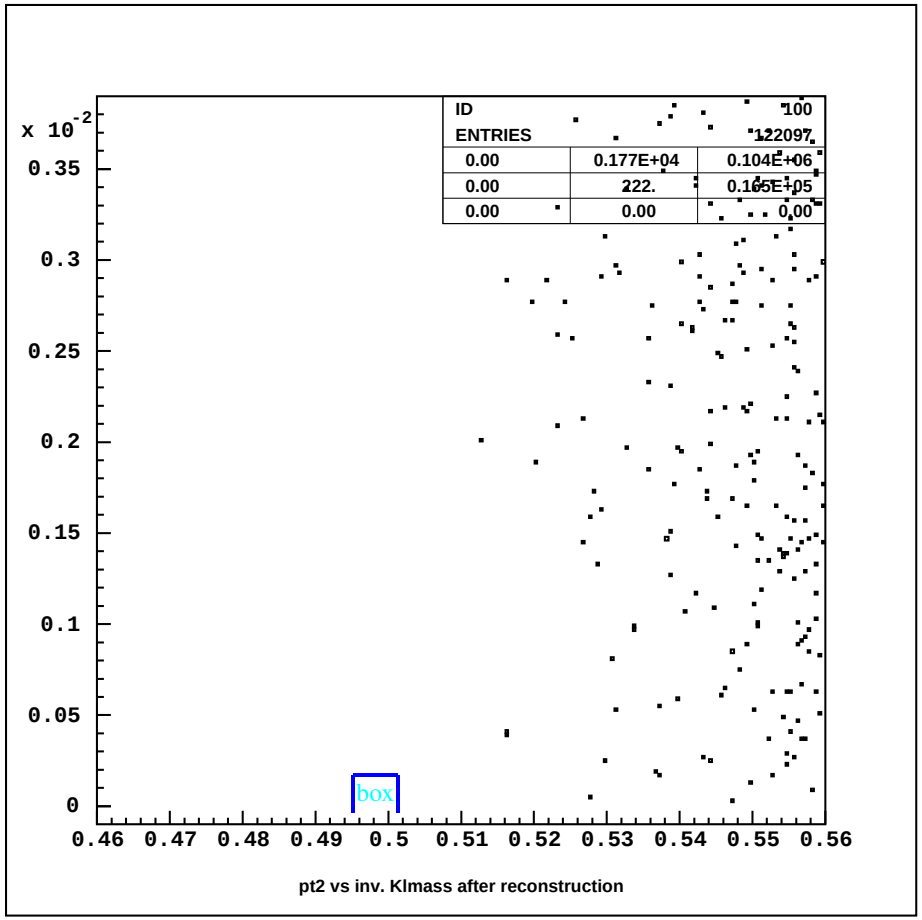
- have refrained from crunching these runs altogether. This only yields a loss of about *0.4%* of the data.

- this change is also reflected in the MC generation.

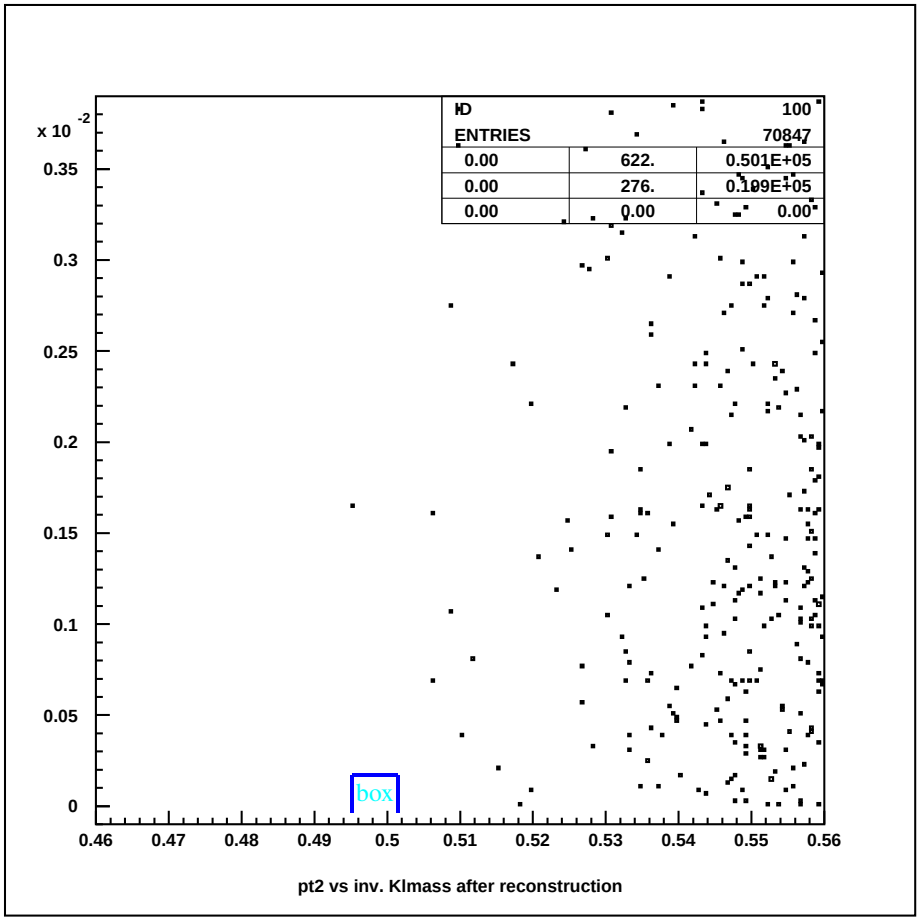
- after the crunch (but before the analysis) a bad spill cut was performed, which reduced the acceptance by ~19% in 1997 data and ~6% in 1999 data.

Results From Crunch of All Tapes

(P_T^2 vs. Inv. K_L Mass)



1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *Data*



1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *Data*

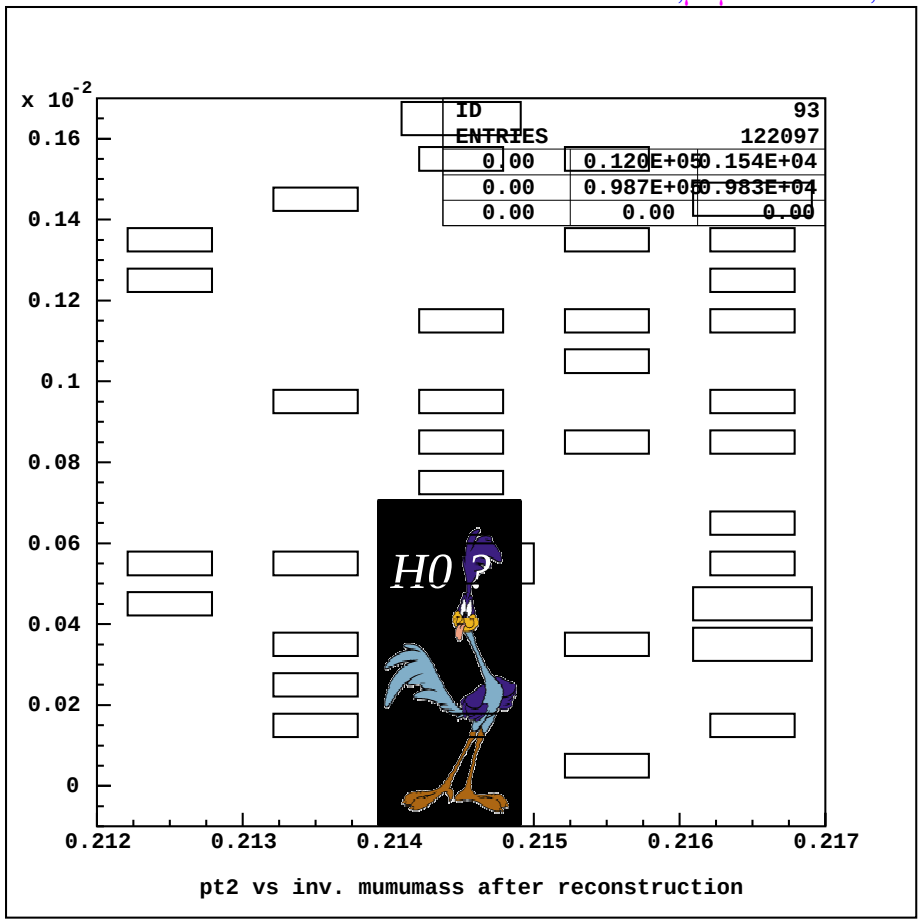
~ Box Dimensions ~

$495 \text{ MeV} \leq M_{\gamma\gamma\gamma\gamma\mu\mu} \leq 501 \text{ MeV}$

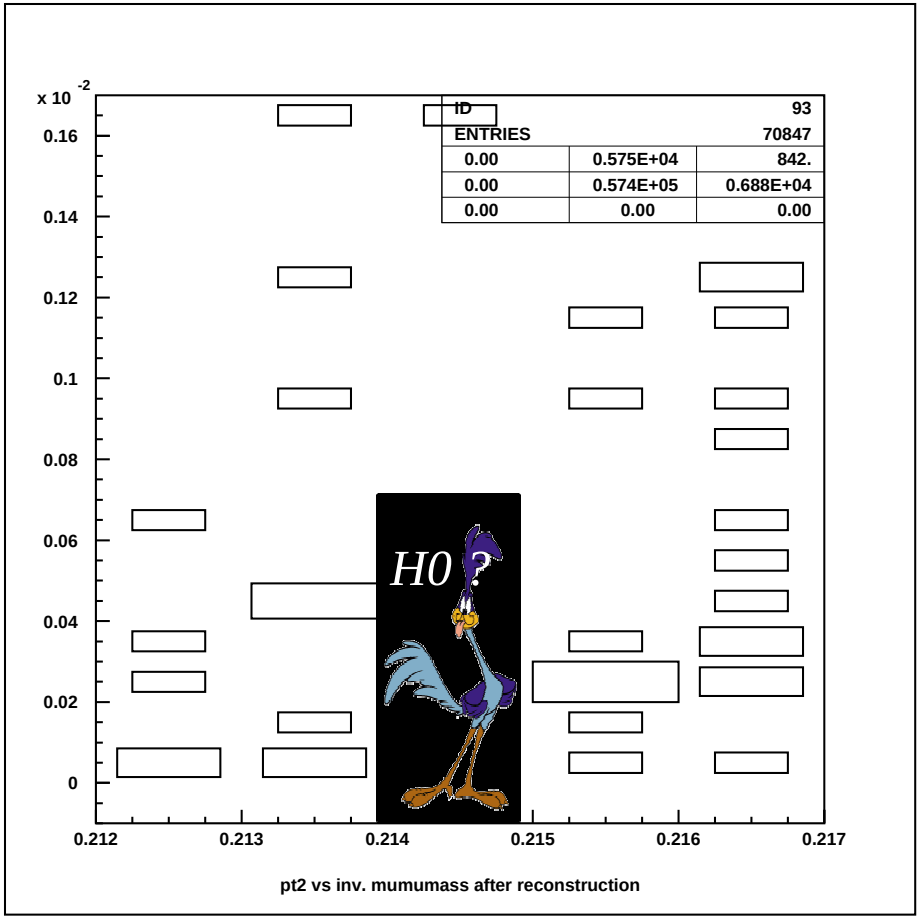
$p_T^2 \leq 130 \text{ MeV}^2$

Results From Crunch of All Tapes

($[P_{T,\mu+\mu-vtx}{}^2 - P_{T,\pi0\pi0}{}^2]$ vs. Inv. $\mu^+\mu^-$ Mass)



1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *Data*



1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *Data*

~ Box Dimensions ~

$213.8 \text{ MeV} \leq M_{\mu\mu} \leq 214.8 \text{ MeV}$

$p_T{}^2 \leq 700 \text{ MeV}^2$

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Analysis

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Analysis Results

-Analysis Cuts-

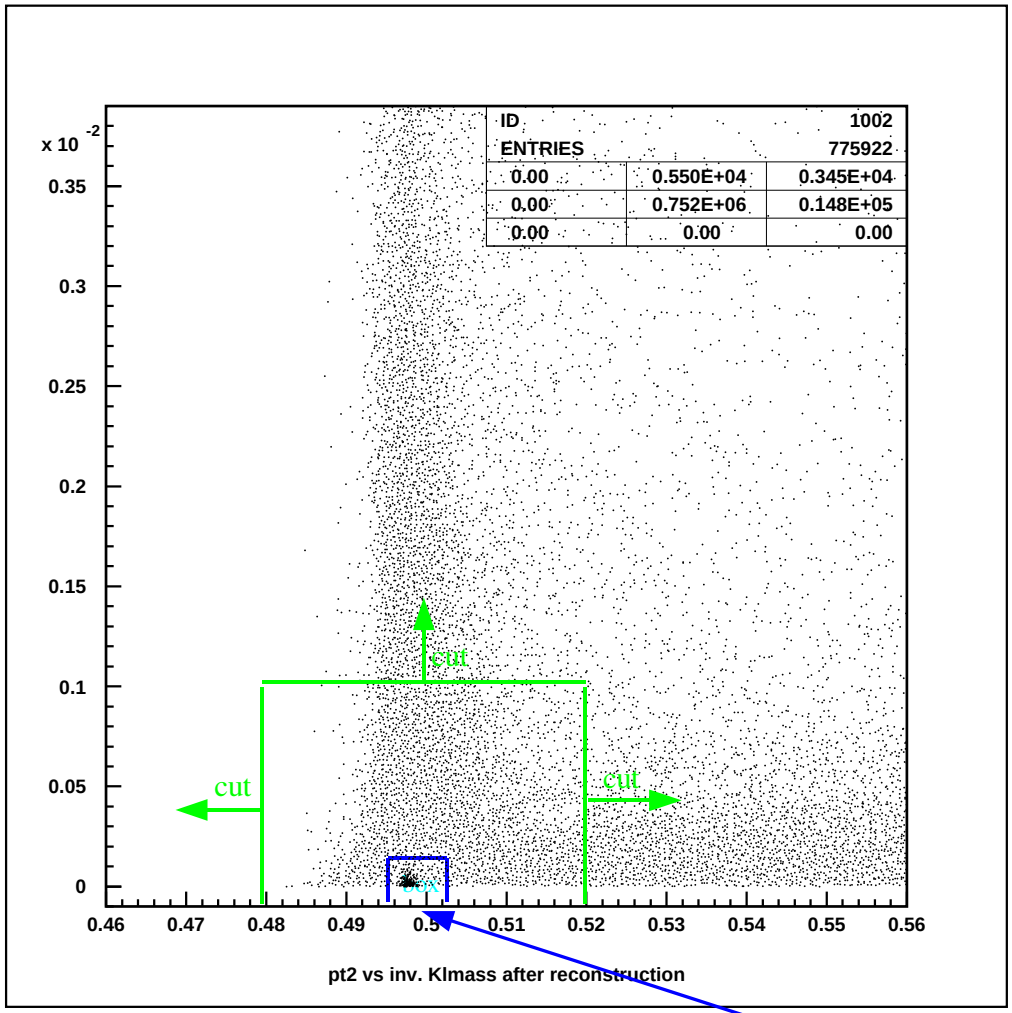
$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Analysis Cut*	γ^* Signal MC (1997)	H^0 Signal MC (1997)	γ^* Signal MC (1999)	H^0 Signal MC (1999)
$480\ \text{MeV} \leq M_K \leq 520\ \text{MeV}$	0.962	0.966	0.964	0.967
$p_T^2 \leq 0.001\ \text{GeV}^2/c^2$	0.982	0.980	0.984	0.983
$E_{cl}(\text{track}) \leq 1.0\ \text{GeV}$	0.956	0.955	0.959	0.959
$P_{track} \leq 7.0\ \text{GeV}$	0.999	0.999	0.994	0.995
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq 9\ \text{MeV}$	0.997	0.997	0.997	0.997
$M_{\mu\mu} \leq 232\ \text{MeV}$	0.999	0.999	0.999	0.999
$495\ \text{MeV} \leq M_K \leq 501\ \text{MeV}$ & $p_T^2 \leq 0.00013\ \text{GeV}^2/c^2$	0.914	0.891	0.794	0.761
$213.8\ \text{MeV} \leq M_{\mu\mu} \leq 214.8\ \text{MeV}$ & $p_{T,\mu\mu}^2 \leq 0.0007\ \text{GeV}^2/c^2$	------	0.953	------	0.945
Total Acceptance (all inclusive)	0.0314	0.0281	0.0356	0.0315

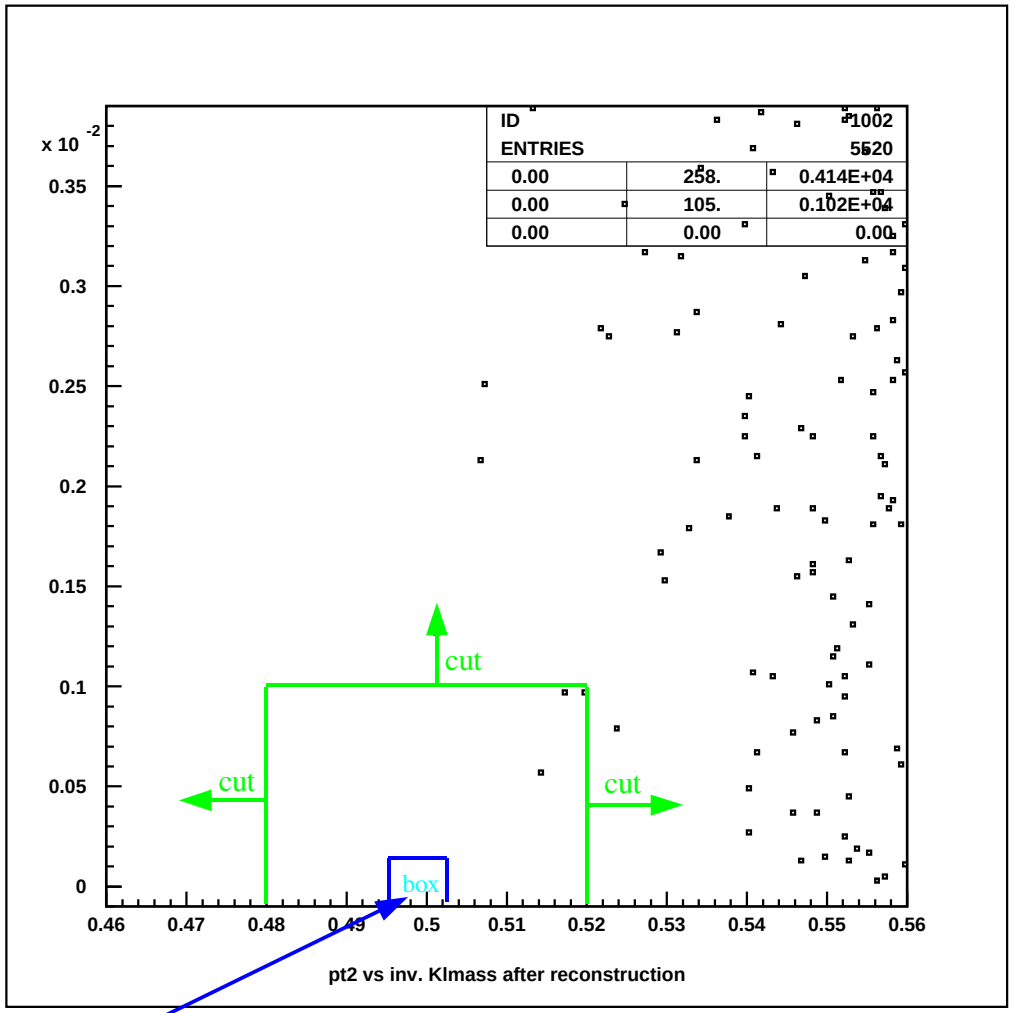
** = cuts listed in chronological order*

Compare with old 2.74% result

Cut on P_T^2 vs. Inv. K_L Mass

(1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Analysis - 1st Cut)





1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*

1997 $K^0_{\mu 4}$ *MC Background*

~ Box Dimensions ~

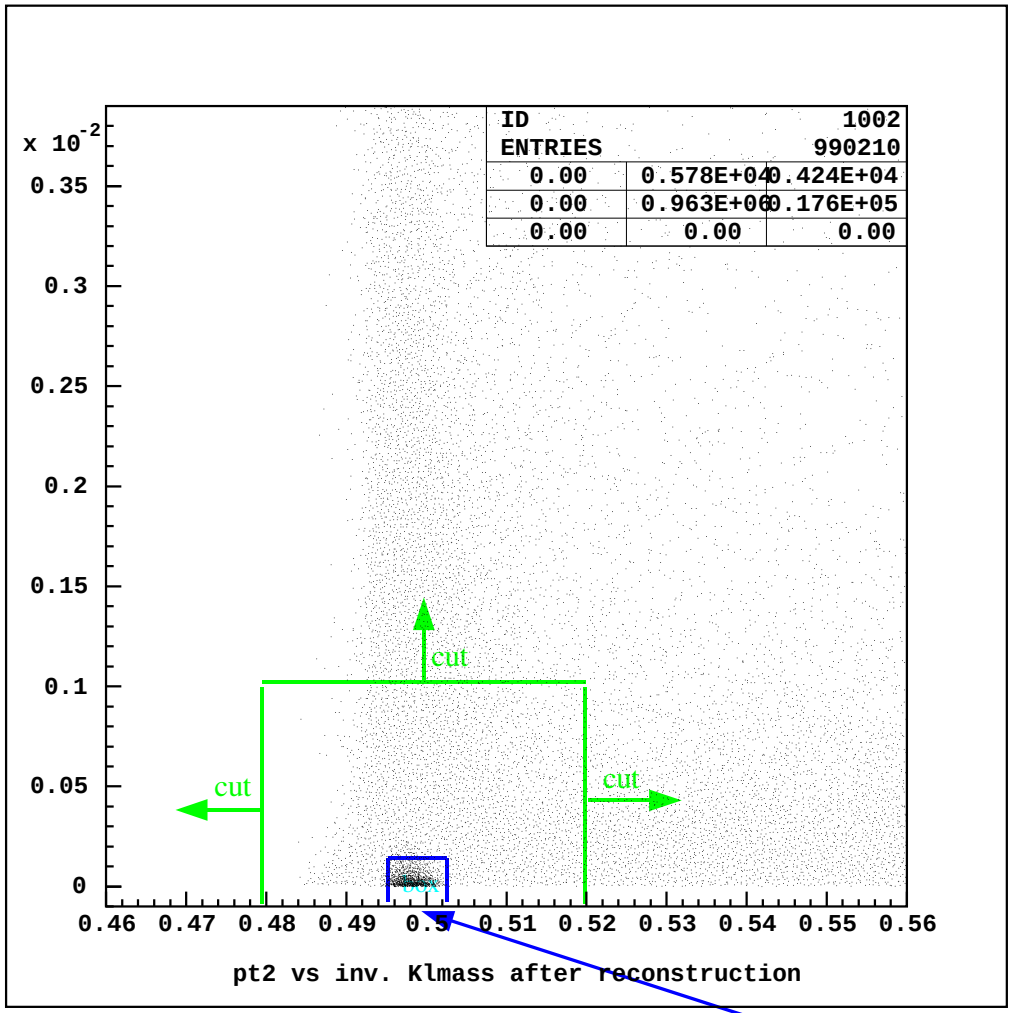
$495 \text{ MeV} \leq M_{\gamma\gamma\gamma\gamma\mu\mu} \leq 501 \text{ MeV}$

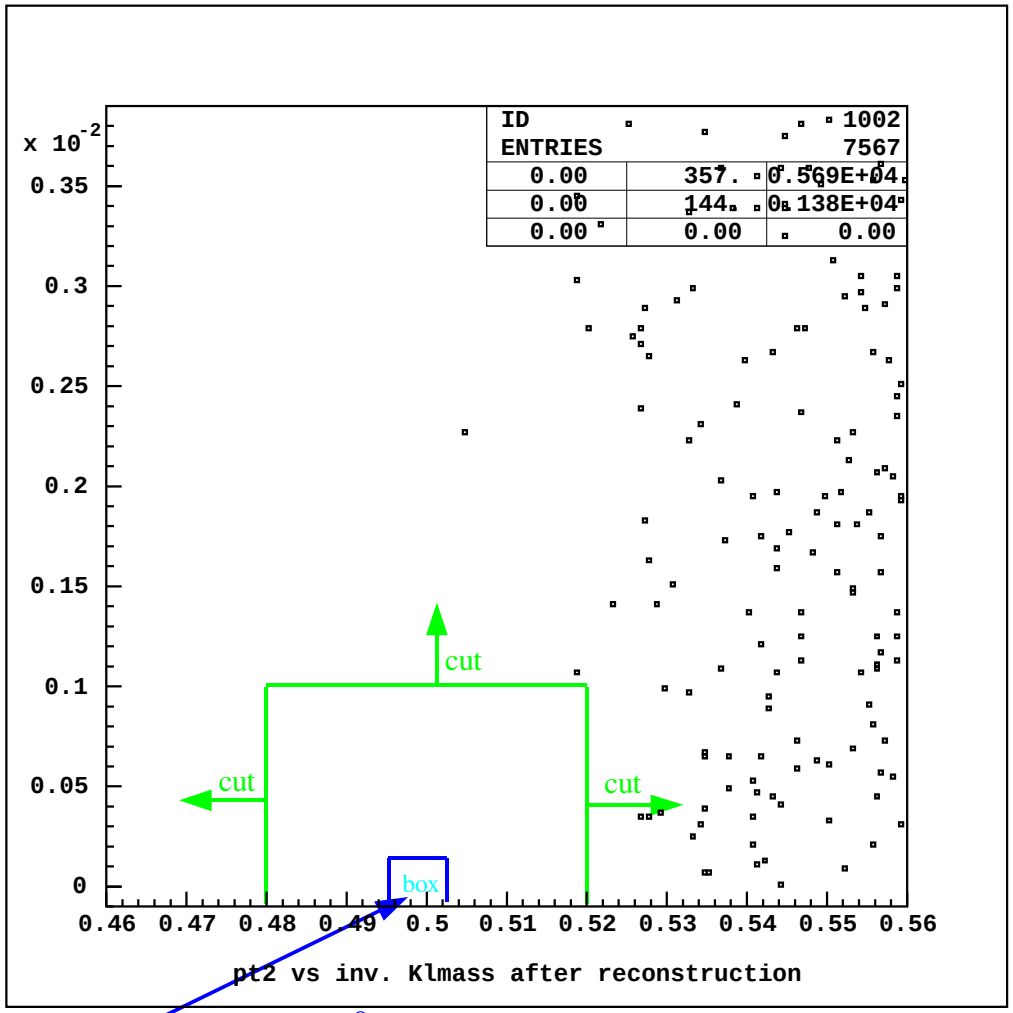
$p_T^2 \leq 130 \text{ MeV}^2$

Closed Signal Box!!

Cut on P_T^2 vs. Inv. K_L Mass

(1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Analysis - 1st Cut)





1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*

1999 $K^0_{\mu 4}$ *MC Background*

~ Box Dimensions ~

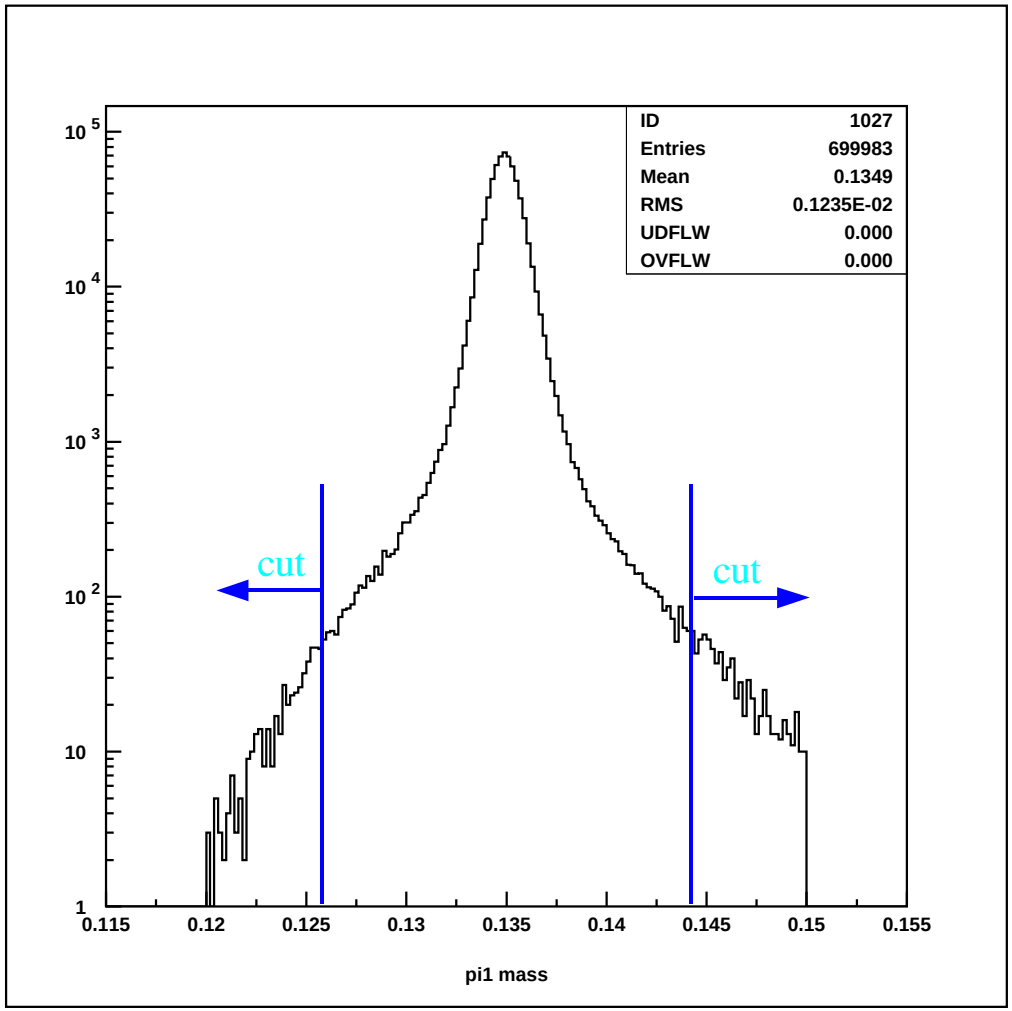
$495 \text{ MeV} \leq M_{\gamma\gamma\gamma\gamma\mu\mu} \leq 501 \text{ MeV}$

$p_T^2 \leq 130 \text{ MeV}^2$

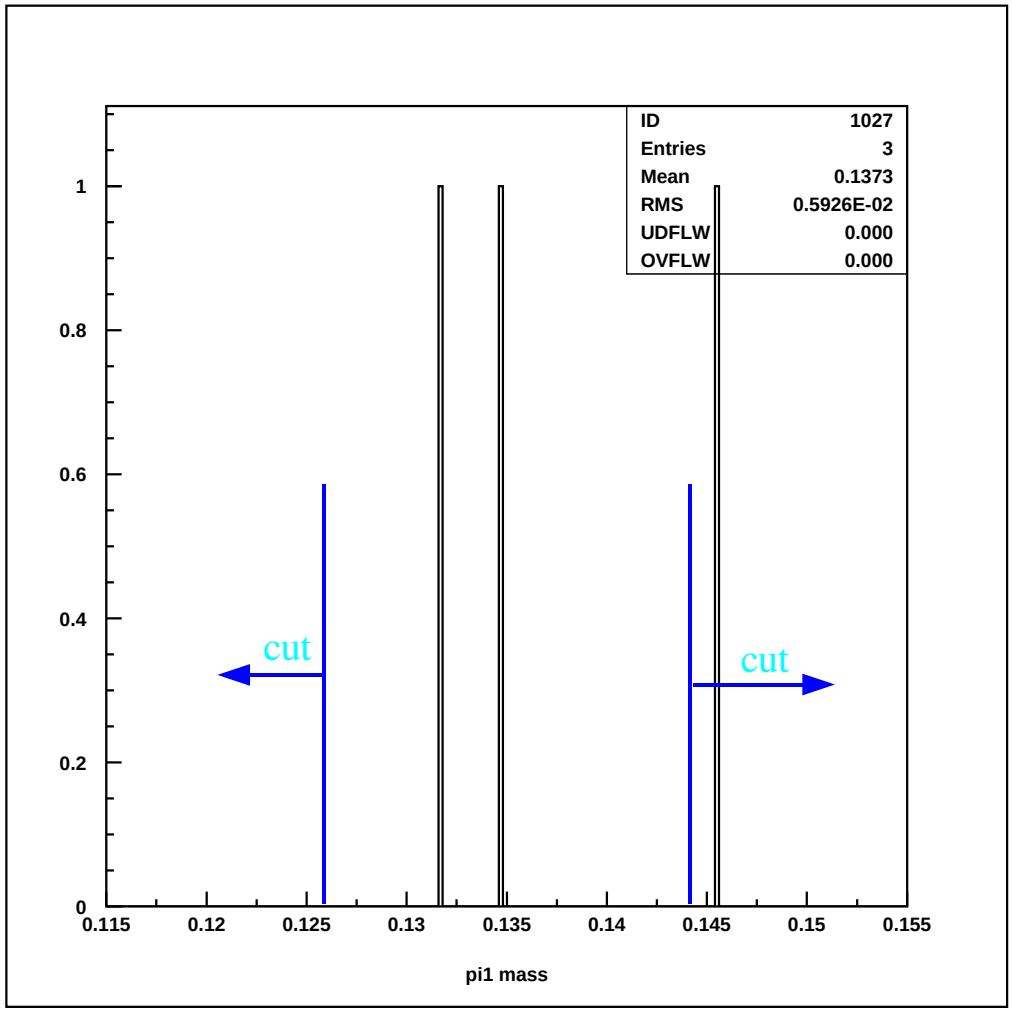
Closed Signal Box!!

Cut on π^0 Masses

(1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Analysis - 4th Cut)



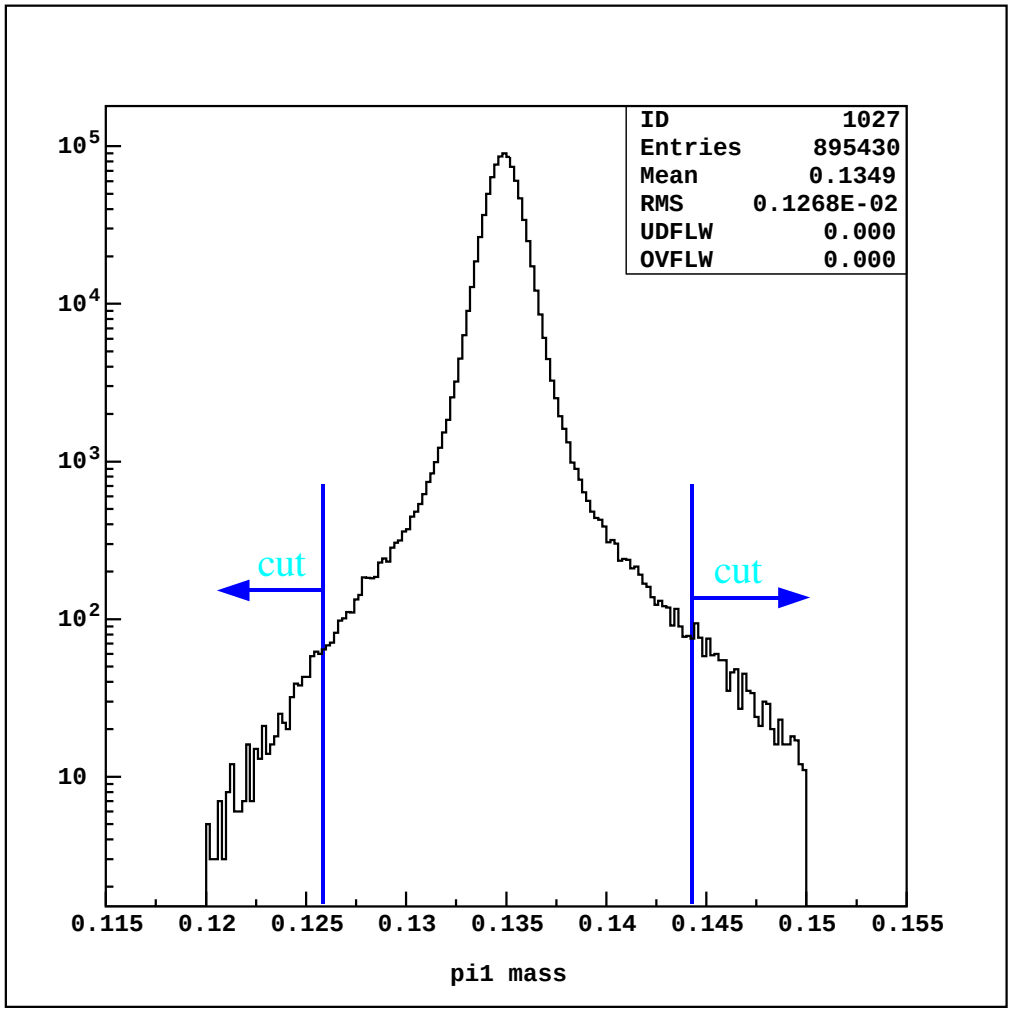
1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*



1997 $K^0_{\mu 4}$ *MC Background*

Cut on π^0 Masses

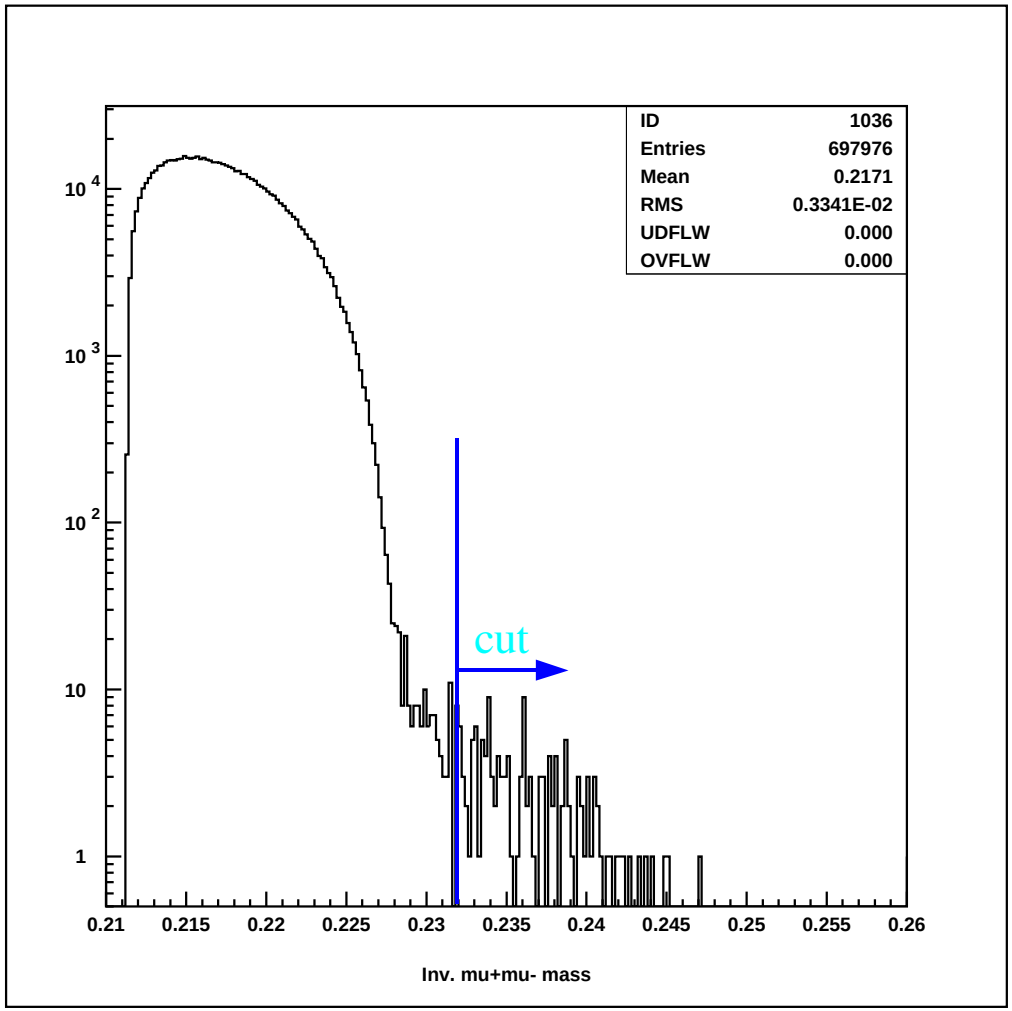
(1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Analysis - 4th Cut)



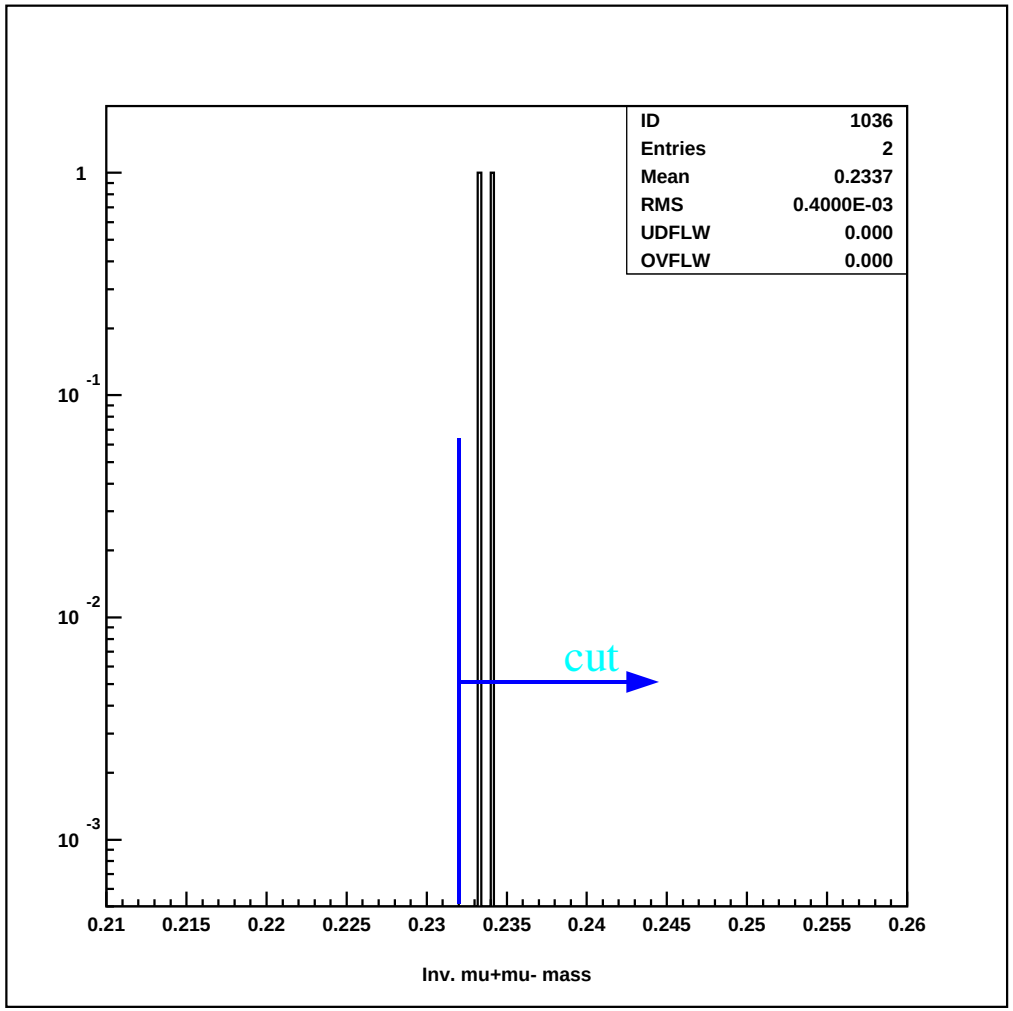
1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*

Cut on Dimuon Mass

(1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Analysis - 5th Cut)



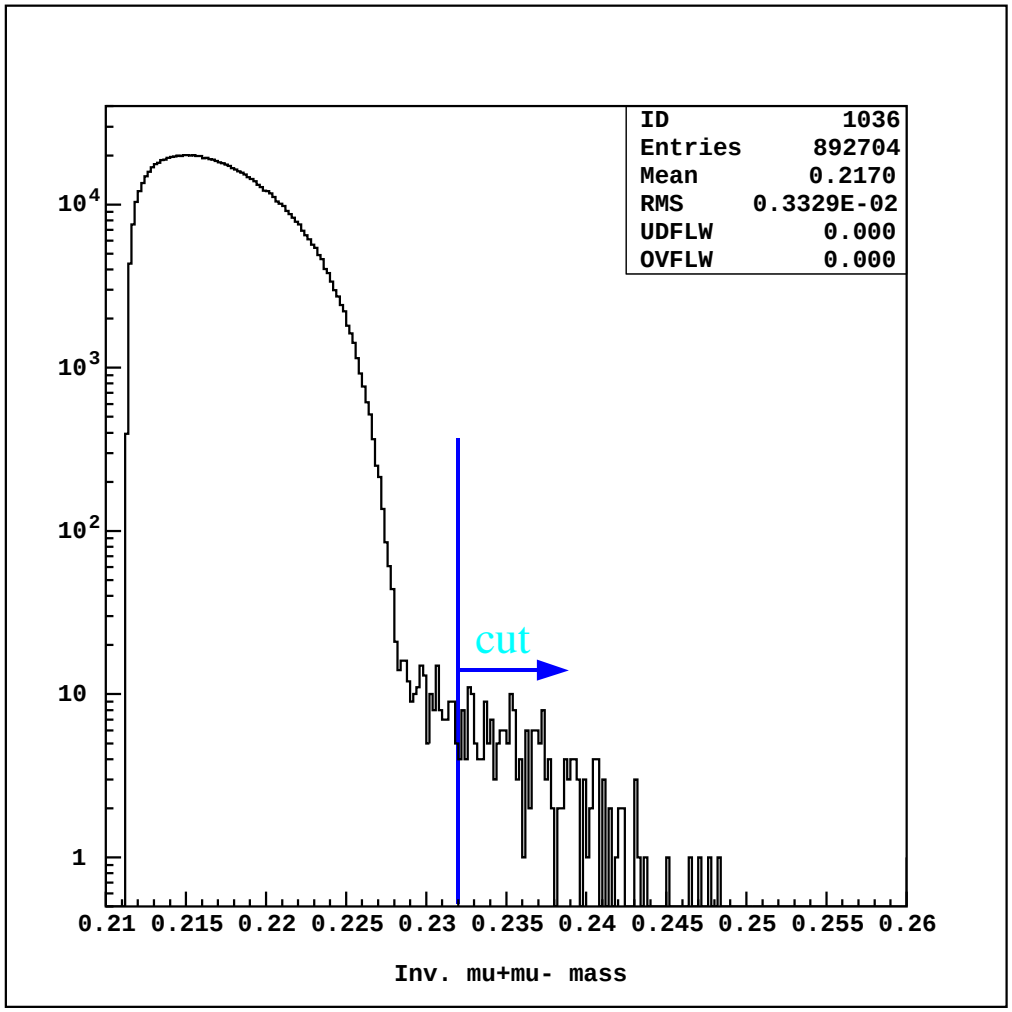
1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*



1997 $K^0_{\mu 4}$ *MC Background*

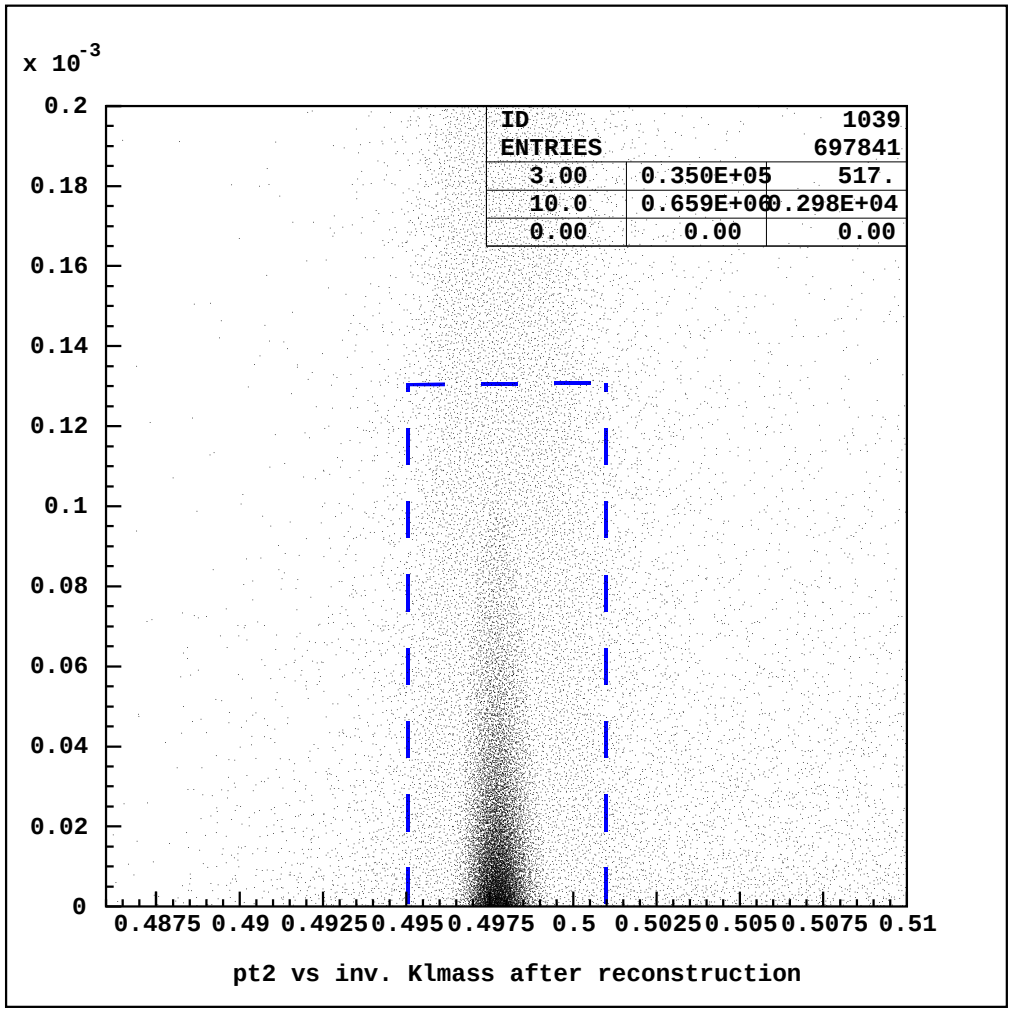
Cut on Dimuon Mass

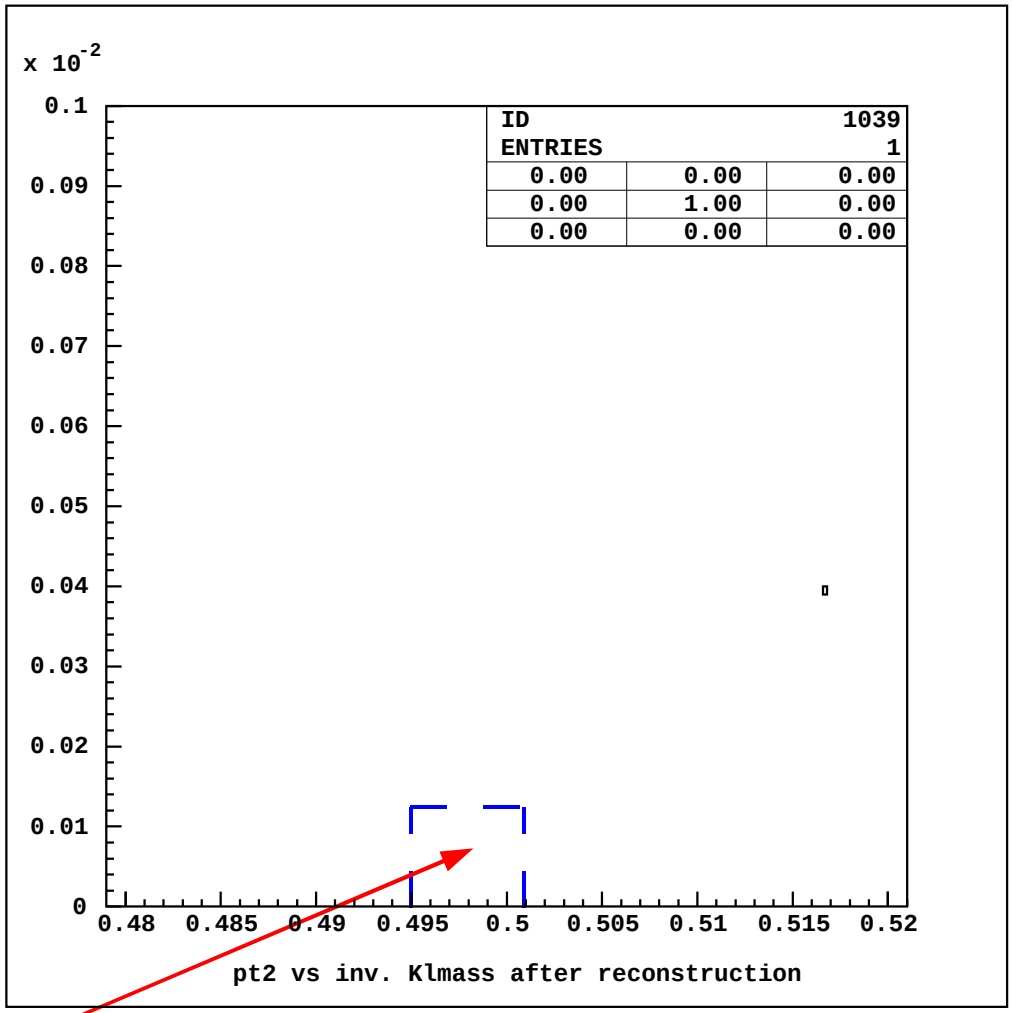
(1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Analysis - 5th Cut)



1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*

Opening of the 1997 K_L Signal Box!



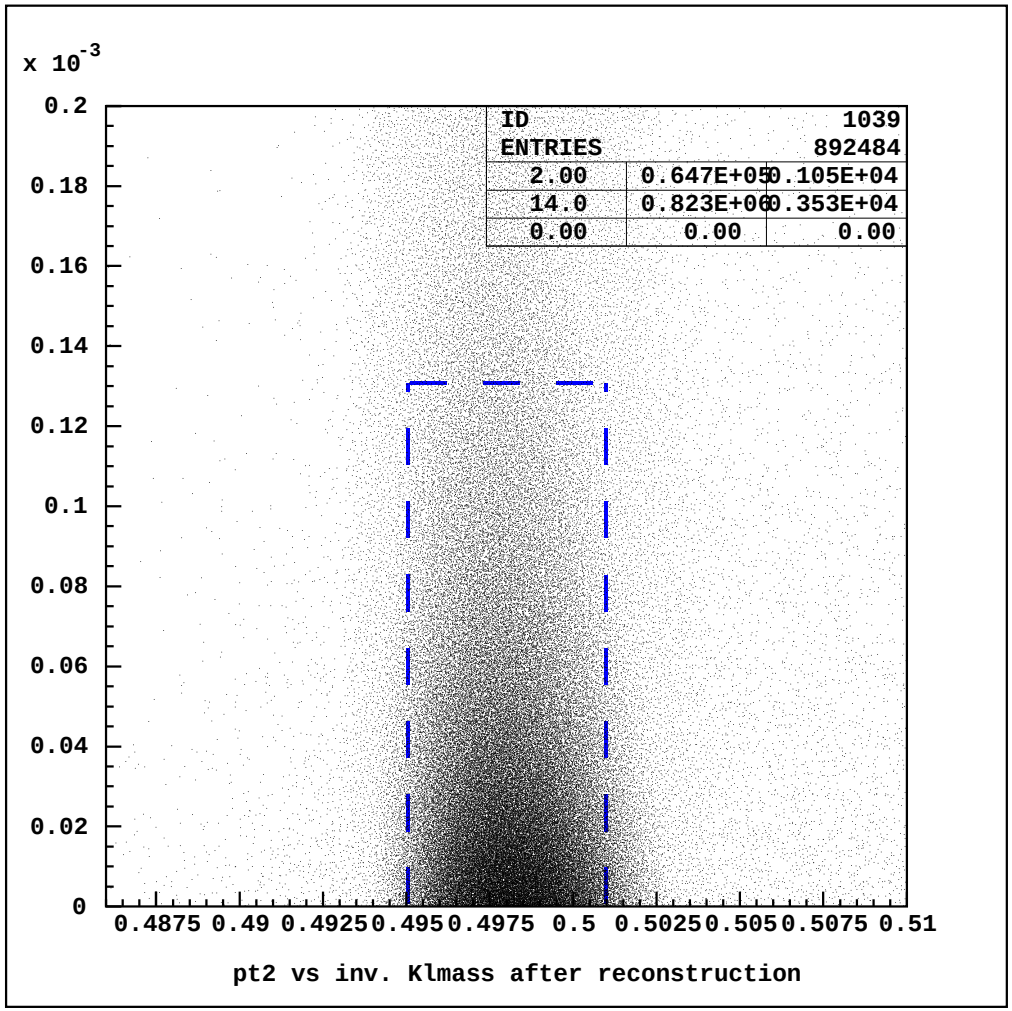


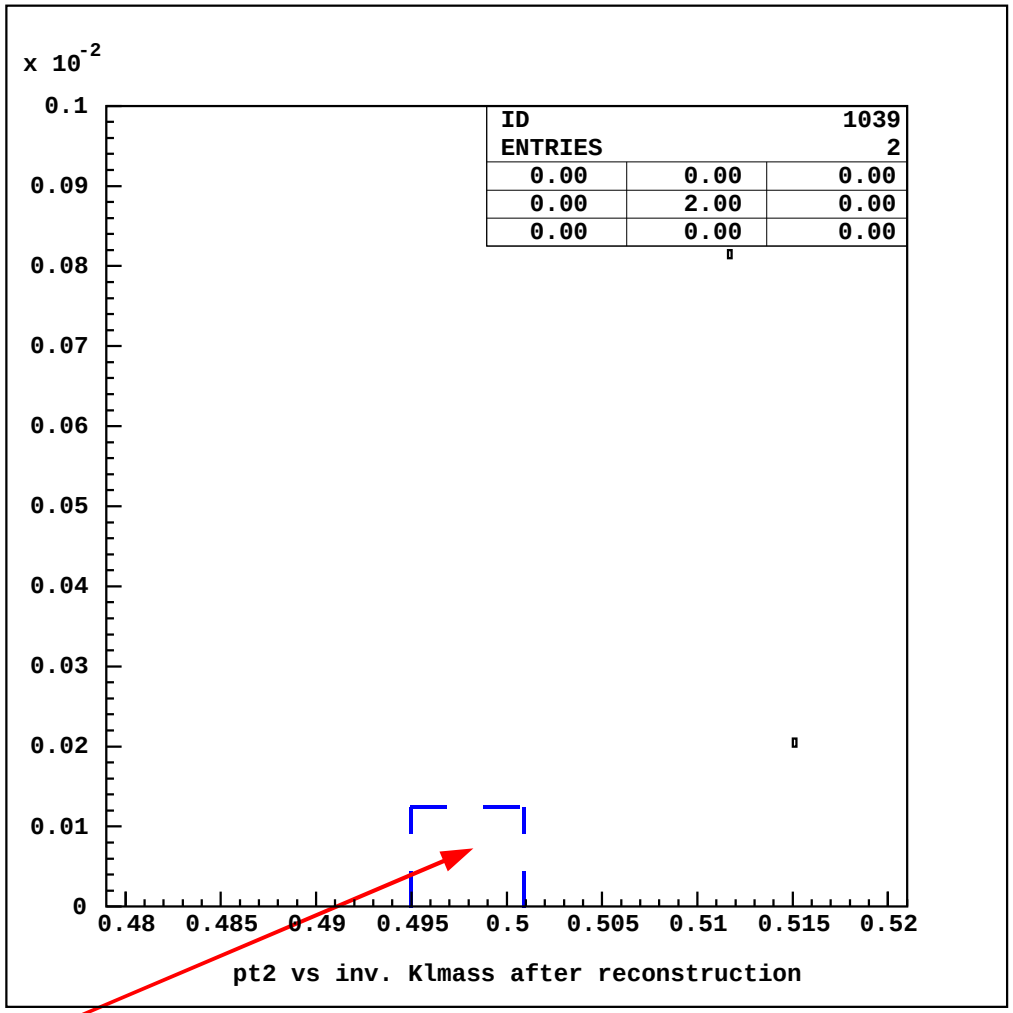
1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*

K_L Signal Box Opened and is EMPTY!

1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *Data*

Opening of the 1999 K_L Signal Box!



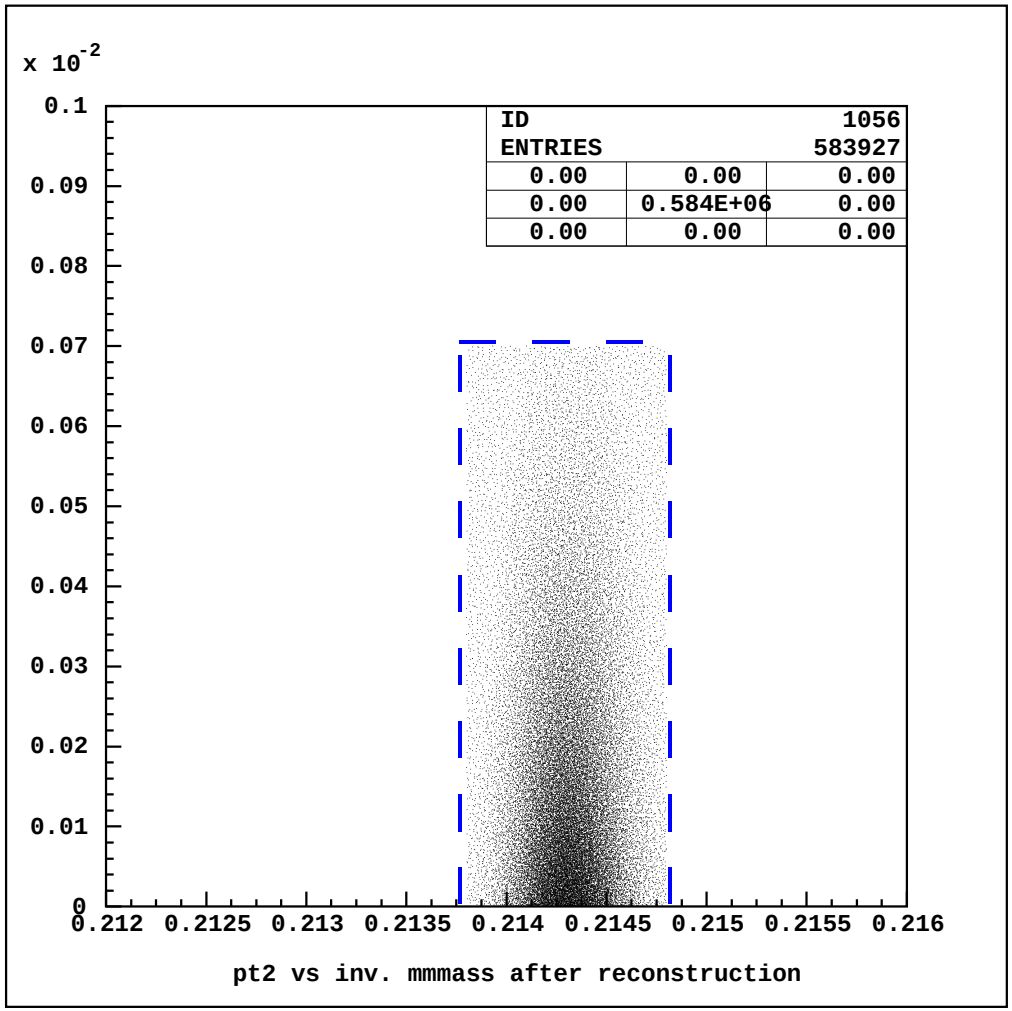


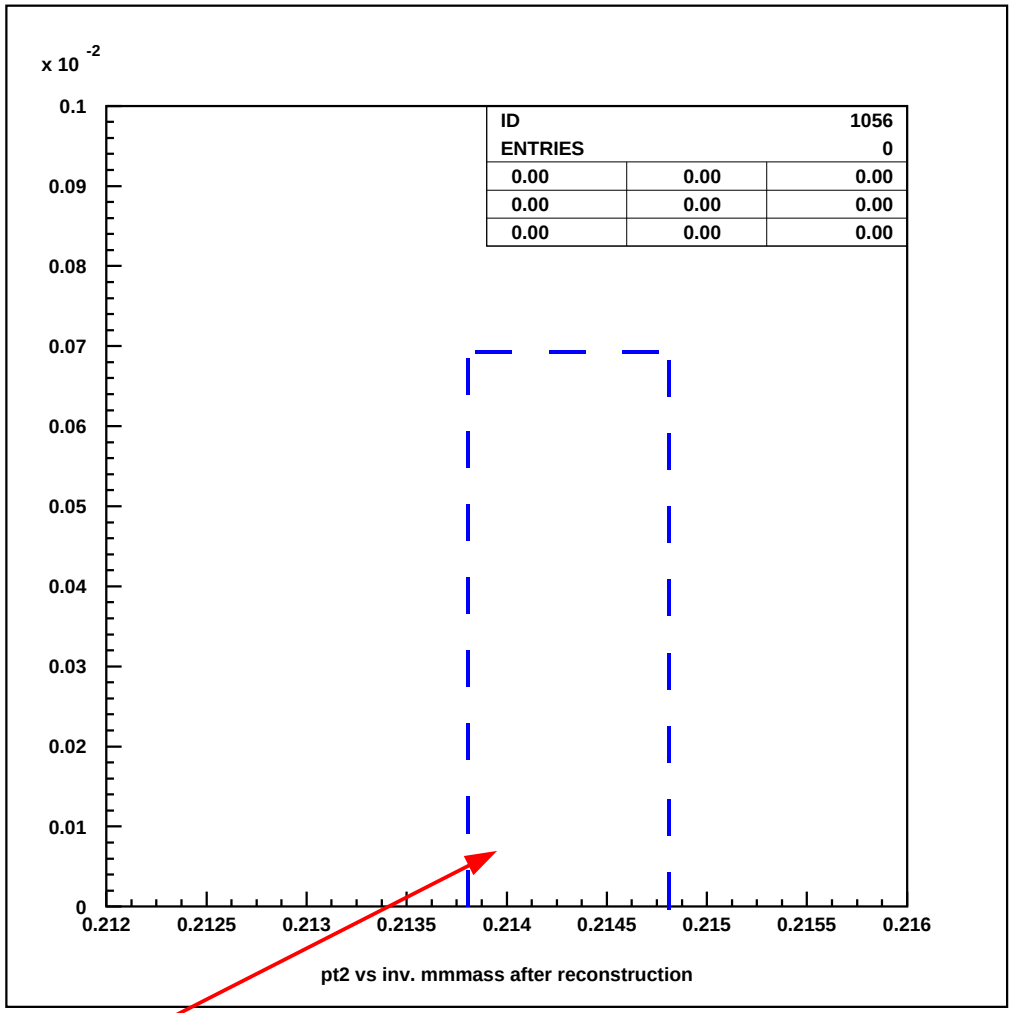
1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*

K_L Signal Box Opened and is EMPTY!

1999 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *Data*

Opening of the 1997 H^0 Box!



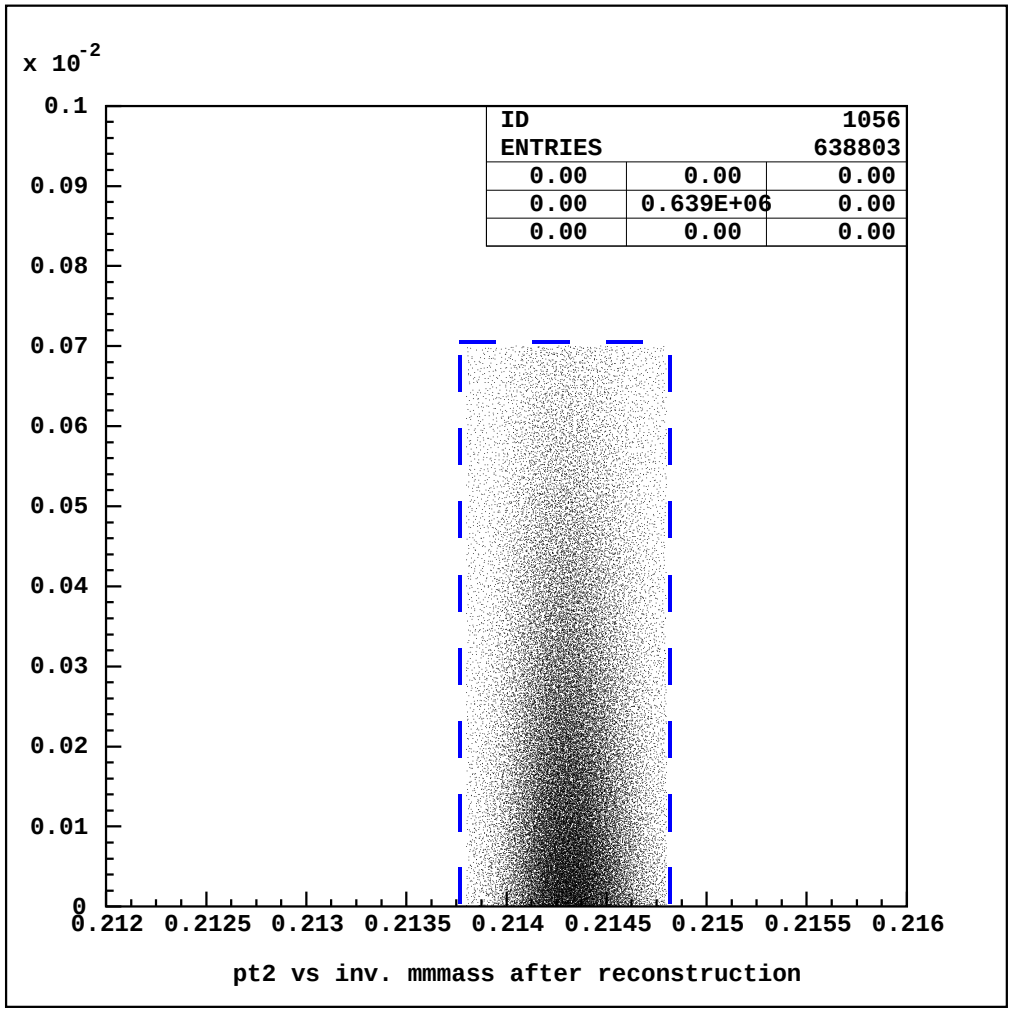


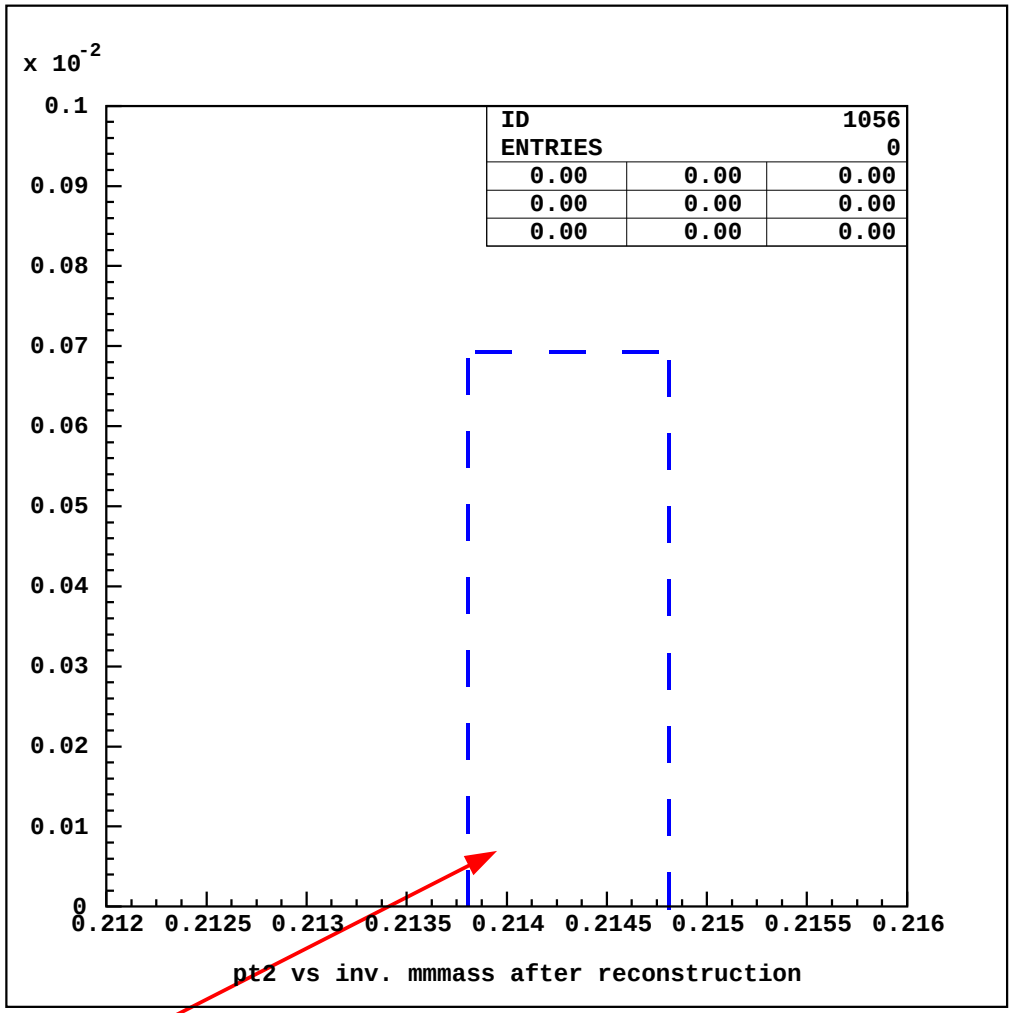
1997 $K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*

1997 $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *Data*

H^0 Signal Box Opened and is EMPTY!

Opening of the 1999 H^0 Box!





1999 $K_L \to \pi^0\pi^0 H^0 \to \pi^0\pi^0\mu^+\mu^-$ *MC*

1999 $K_L \to \pi^0\pi^0\mu^+\mu^-$ *Data*

H^0 Signal Box Opened and is EMPTY!

Summary of Backgrounds

Decay Mode	# '97 MC events generated	# '99 MC events generated
$K^0_{\mu 3}$ (punch through)	~ 2.6 Billion (0.039 *f*)	1,752,020,868 (0.027 *f*)
$K^0_{\mu 3}$ (pion decay = $\pi^{+,-} \to \mu^{+,-}\nu_\mu$)	still need to generate	still need to generate
$K^0_{\mu 4}$ (punch through)	120,066,571 (8.38 *f*)	96,372,292 (6.72 *f*)
$K^0_{\mu 4}$ (pion decay)	93,373,819 (6.51 *f*)	109,831,267 (7.66 *f*)
$K_L \to \pi^+\pi^-\pi^0$ (2x punch through)	1,848,796,492 (0.060 *f*)	1,062,004,339 (0.035 *f*)
$K_L \to \pi^+\pi^-\pi^0$ (2x pion decay)	85,552,978 (0.0028 *f*)	106,912,811 (0.0035 *f*)
$K_L \to \pi^+\pi^-\pi^0$ (punch & decay)	still need to generate	still need to generate
$K_L \to \pi^+\pi^-\gamma$ (2x punch through)	15,125,863 (1.41 *f*)	21,646,250 (2.03 *f*)
$K_L \to \pi^+\pi^-\gamma$ (2x pion decay)	20,304,857 (1.90 *f*)	16,311,114 (1.53 *f*)
$K_L \to \pi^+\pi^-\gamma$ (punch & decay)	14,188,452 (1.33 *f*)	14,599,805 (1.37 *f*)
$K_L \to \pi^+\pi^-$ (2x punch through)	684,036,044 (1.35 *f*)	671,923,195 (1.32 *f*)
$K_L \to \pi^+\pi^-$ (2x pion decay)	8,529,573 (0.017 *f*)	21,840,183 (0.044 *f*)
$K_L \to \pi^+\pi^-$ (punch & decay)	50,916,829 (0.100 *f*)	26,557,616 (0.053 *f*)
$K_L \to \mu^+\mu^-$	1,183,635 (670.0 *f*)	5,240,705 (2967 *f*)
$K_L \to \mu^+\mu^-\gamma$	9,582,978 (109.8 *f*)	119,650,358 (1372 *f*)
$K_L \to \mu^+\mu^-\gamma\gamma$	10,869,003 (4473 *f*)	48,801,465 (20084 *f*)
$K_L \to \pi^0\mu^+\mu^-$	11,042,193	13,008,645

- after all analysis cuts, there were *ZERO* background events found in MC.

- in the case of *ZERO* signal events and *ZERO* background events, the upper limit of the branching ratio (at 90% CL) may be found by:

$$Br = 2.3 * N_K * SES$$

- this result holds for either a Bayesian or a Classical viewpoint [1] and can also be found in the 2008 PDG [2].

[1] W.T. Eadie, D. Drijard, F.E. James, M. Roos and B. Sadoulet, ***Statistical Methods in Experimental Physics,*** American Elsevier, New York, 1971, p. 190-202, 213. Ref. [10] explains the Poisson Upper Limit in this scenario.

[2] C. Amsler *et al.,* **Physics Letters *B667,*** Table 32.3, Chapter 32, p. 23 (2008)

Results and Future Plans

1997 Acceptance ($K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$) = 3.14 %

1997 Acceptance ($K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$) = 2.81 %

1999 Acceptance ($K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$) = 3.56 %

1999 Acceptance ($K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$) = 3.15 %

Compare with old 2.74% result

Using $N_K = 2.43 \times 10^{11}$ (D. Smith Thesis), one finds the following upper limits at *90% CL*:

$Br(K_L \rightarrow \pi^0\pi^0\mu^+\mu^-) < 2.83 \times 10^{-10}$

$Br(K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-) < 3.17 \times 10^{-10}$

Compare with:

$Br(K_L \rightarrow \pi^0\pi^0 H^0_p \rightarrow \pi^0\pi^0\mu^+\mu^-) = (8.3^{+7.5}_{-6.6})\, x10^{-9}$

$Br(K_L \rightarrow \pi^0\pi^0 H^0_A \rightarrow \pi^0\pi^0\mu^+\mu^-) = (1.0^{+0.9}_{-0.8})\, x10^{-10}$

- HyperCP uses a uniform matrix element for $\Sigma^+ \rightarrow pH^0 \rightarrow p\mu^+\mu^-$. Theorists advise against using flat phase space since the K_L decay is momentum dependent.

$\rightarrow$ *must ensure that we use the most effective matrix element in the MC generation!!!*

- *Deshpande et al.* gives the matrix element for $K_L \rightarrow \pi^+\pi^- H^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ (albeit for a pseudoscalar H^0)

- meanwhile, *Valencia et al.* provides the matrix element for the decay K^0**bar**$\rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ (for both pseudoscalar and axial vector H^0's)

- with the tools listed above, we should be able to construct a suitable matrix element for $K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ and compare to flat phase space.

- need to determine the flux using $K_L \rightarrow \pi^0\pi^0\pi^0_D$. Normalization mode crunch (1997 and 1999) is under way.