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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Introduction & Motivation

- Currently, there's no published calculation inside the Standard Model for $Br(K_L \rightarrow \pi^0\pi^0\mu^+\mu^-)$, although the decay is possible via an off-shell photon.

- serves as a direct probe of chiral perturbation theory to $O(p^4)$ and $O(p^6)$.

- Outside the Standard Model, this decay is possible via the H^0 neutral boson.

- HyperCP first reported this *'potential'* new neutral boson H^0 in an observation of $\Sigma^+ \rightarrow p\mu^+\mu^-$. They determined the following branching ratios:

$$Br(\Sigma^+ \rightarrow p\mu^+\mu^-) = \left(8.6^{+6.6}_{-5.4}(stat) \pm 5.5(syst)\right) x10^{-8},$$
$$Br(\Sigma^+ \rightarrow pH^0 \rightarrow p\mu^+\mu^-) = \left(3.1^{+2.4}_{-1.9}(stat) \pm 1.5(syst)\right) x10^{-8}$$

- Hyper CP gave the mass of the *'potential'* new boson H^0 as: $(214.3 \pm 0.5)\,MeV$

- two groups (Valencia *et al*. and Deshpande *et al*.) have recently computed $Br(K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-)$ in a phenomenological fashion.

Previous Studies

~Theorist Brainstorming~

- Valencia *et al.* and Deshpande *et al.* calculate $Br(K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-)$ following observations made by HyperCP; that is, they assume that the H^0's have small widths, are short lived and do not interact strongly.

- Deshpande *et al.* estimates contraints on scalar and pseudoscalar H^0's.

- finding that pseudoscalar couplings have the largest contribution, they evaluate the branching ratio as:

$$Br(K_L \rightarrow \pi^0\pi^0 H^0_P \rightarrow \pi^0\pi^0\mu^+\mu^-) = 8.02\text{x}10^{-9} \qquad (\textit{Deshpande et al.}, 2005)$$

- *Valencia et al.* has ruled out the possibility of scalar or vector H^0's. Using existing constraints on pseudoscalar or axial vector H^0's, they predict the H^0 contributions to the $K_L \to \pi^0\pi^0\mu^+\mu^-$ decay mode:

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

(*Valencia et al.*, 2005)

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

- there is *no current experimental upper limit* on $K_L \to \pi^0\pi^0\mu^+\mu^-$ or $K_L \to \pi^0\pi^0 H^0 \to \pi^0\pi^0\mu^+\mu^-$.

The Possibility of $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Within The Standard Model

- the decay $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ is feasable within the Standard Model although its' phase space is limited to a paltry 16.35 MeV.

- although there is no current published Standard Model theory for $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$, Heiliger and Sehgal have paper out there on $K_L \rightarrow \pi^0\pi^0 e^+e^-$.

- the amplitude of $K_L \rightarrow \pi^0\pi^0 e^+e^-$ is encompassed in a two piece set, with one piece coming from conversion of a virtual photon in the process $K_L \rightarrow \pi^0\pi^0\gamma^*$ and another with a real photon amplitude $K_L \rightarrow \pi^0\pi^0\gamma$.

- there are two processes which can contribute to the $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ decay topology: $K_L \rightarrow \pi^0\pi^0\gamma^* \rightarrow \pi^0\pi^0\mu^+\mu^-$ and $K_L \rightarrow \pi^0\pi^0 H^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$.

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*

Status of Analysis

- this analysis does/will address the shortcomings of the previous study, such as the following:

  ~identification and estimation of background. ← Complete!

  ~the box has 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. A preliminary Feldman-Cousins analysis using the flux from D. Smith's thesis is underway.

  ~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

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

-Data Selection-

- the data to be used in this study will be from the dimuon trigger of the 1997 (1999 later on) KTeV E799 run. The tapes used were NZL001-NZL130.

- a 'crunch' has been performed on these 130 data storage tapes...these tapes contained approximately *1.73 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 trigger 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*	Data♫	MC ♪
Require 2 tracks	0.700	0.970
$C_{track1} = -C_{track2}$	0.999	0.999
$E_{cl}(track) \leq 2.0$ GeV	0.391	0.913
$E_{cl}(track) / p_{track} \leq 0.9$	0.999	0.999
# γ clusters ≥ 4	0.056	0.636
# hits in μ planes ≥ 1	0.980	1.000
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq 15$ MeV	0.196	0.952
$90.0 \text{ m} \leq Z_{VTX} \leq 160.0 \text{ m}$	0.265	0.985
$p_T^2 \leq 0.06 \text{ GeV}^2/c^2$	0.569	0.802
Total Acceptance	0.00044	0.424

** = cuts listed in chronological order, ♫ = initial # events was ~277 M, ♪ = initial # events was ~1.83M.*

-Notes on Crunch-

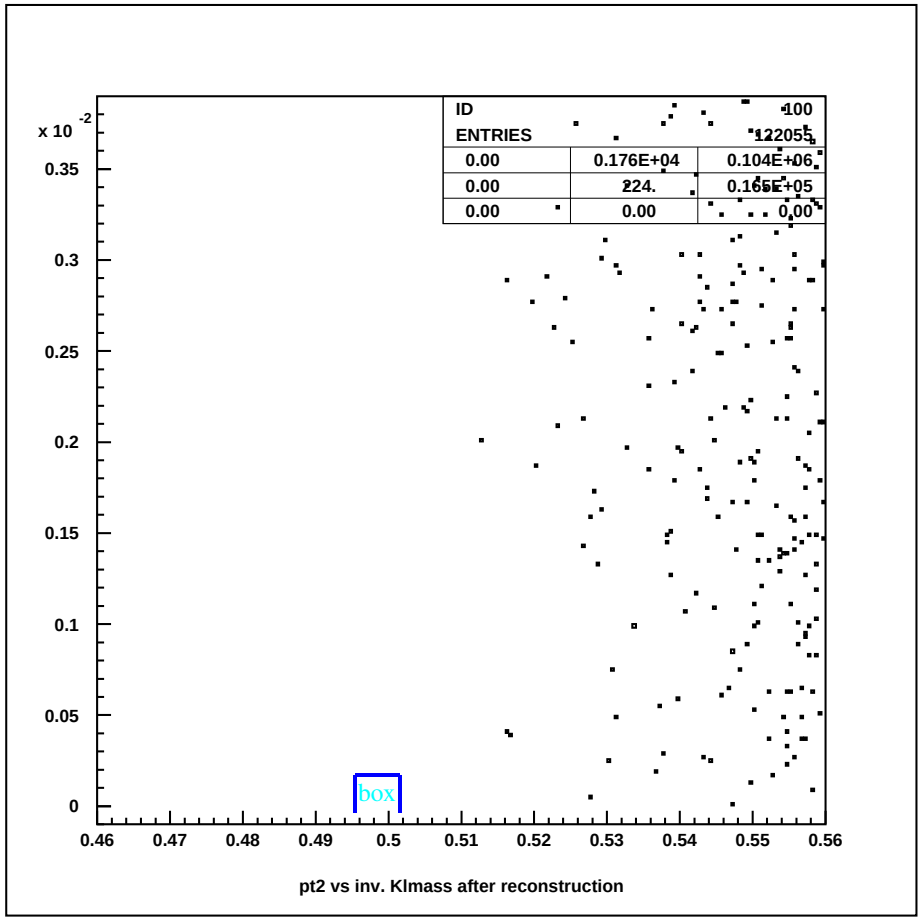
- Runs 10923-10928 (on Tape NZL118) and the last (and only) run on Tape NZL130 were *bad.*

- 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.

Results From Crunch of All Tapes

(P_T^2 vs. Inv. K_L Mass)



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

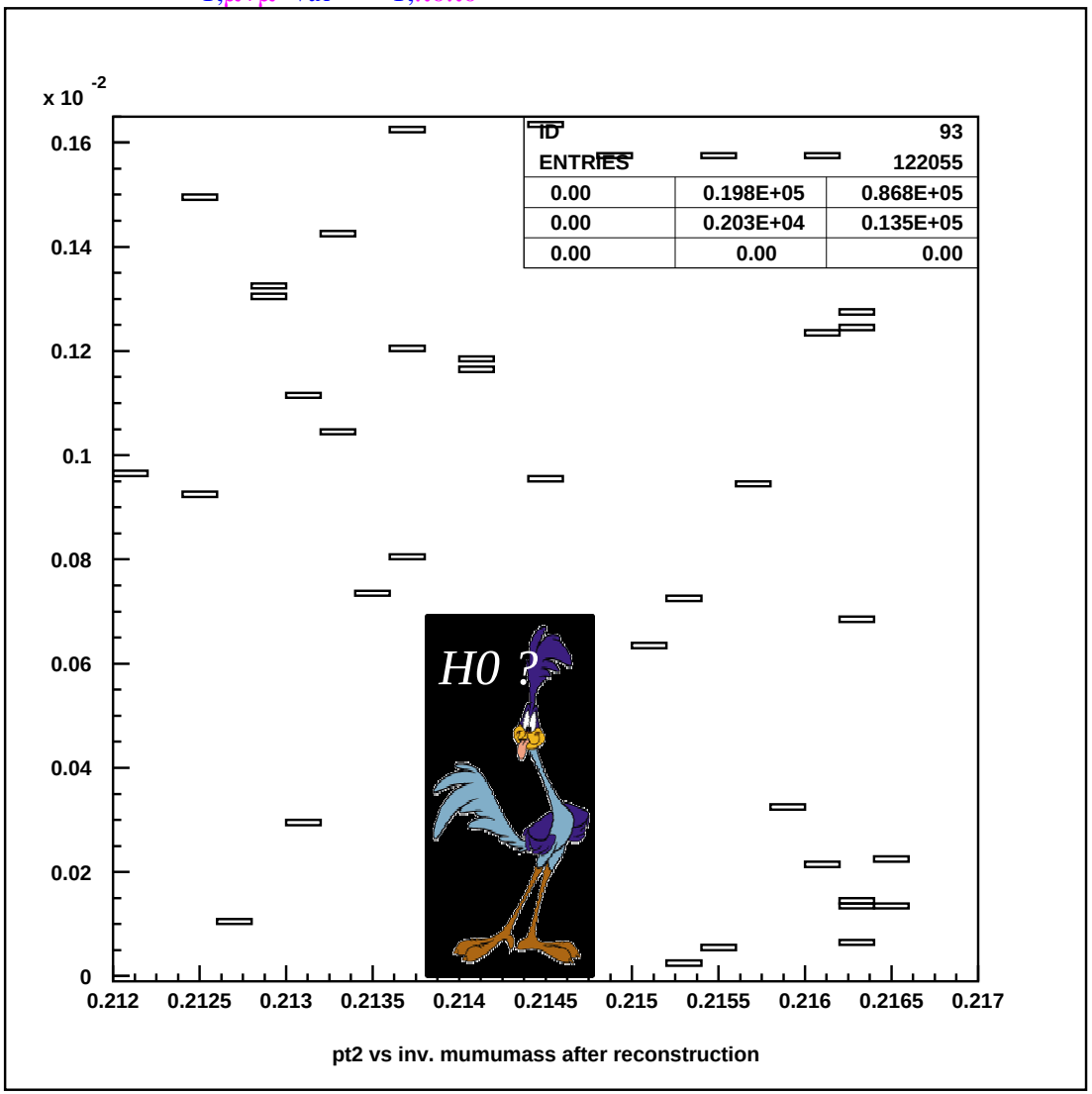
~ Box Dimensions ~

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

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

Results From Crunch of All Tapes

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



$K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *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	H^0 Signal MC	Background MC
$480\ \text{MeV} \leq M_K \leq 520\ \text{MeV}$	0.962	0.966	0.002
$p_T^2 \leq 0.001\ \text{GeV}^2/c^2$	0.982	0.980	0.188
$E_{cl}(\text{track}) \leq 1.0\ \text{GeV}$	0.956	0.955	1.000
$P_{track} \leq 7.0\ \text{GeV}$	0.999	0.999	1.000
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq 9\ \text{MeV}$	0.997	0.997	0.667
$M_{\mu\mu} \leq 232\ \text{MeV}$	0.999	0.999	0.000
$495\ \text{MeV} \leq M_K \leq 501\ \text{MeV}$ & $p_T^2 \leq 0.00013\ \text{GeV}^2/c^2$	0.914	0.891	0.000
$213.8\ \text{MeV} \leq M_{\mu\mu} \leq 214.8\ \text{MeV}$ & $p_{T,\mu\mu}^2 \leq 0.0007\ \text{GeV}^2/c^2$	------	0.953	0.000
Total Acceptance (all inclusive)	0.0314	0.0281	0.000

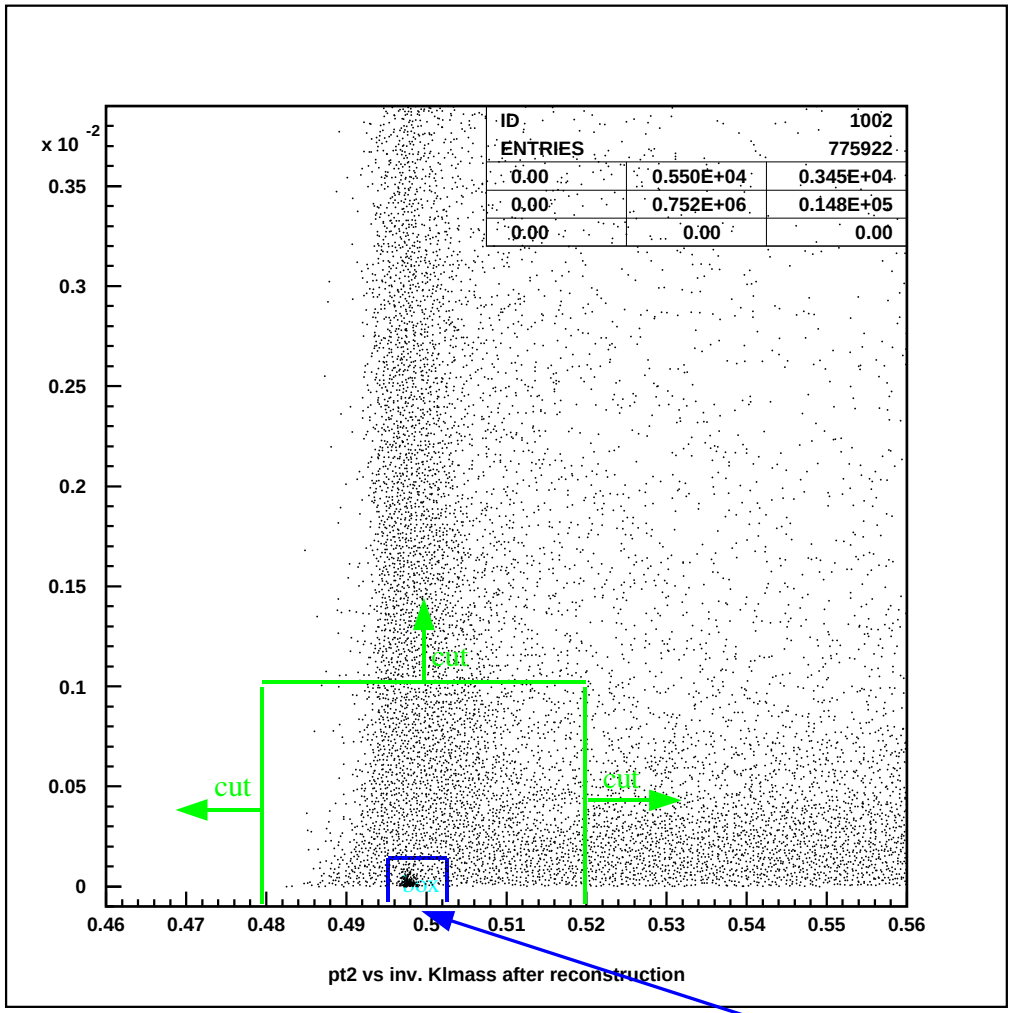
With the exception of $K^0_{\mu 3}$ and $\pi^+\pi^-\pi^0$, more than 5 fluxes were generated!

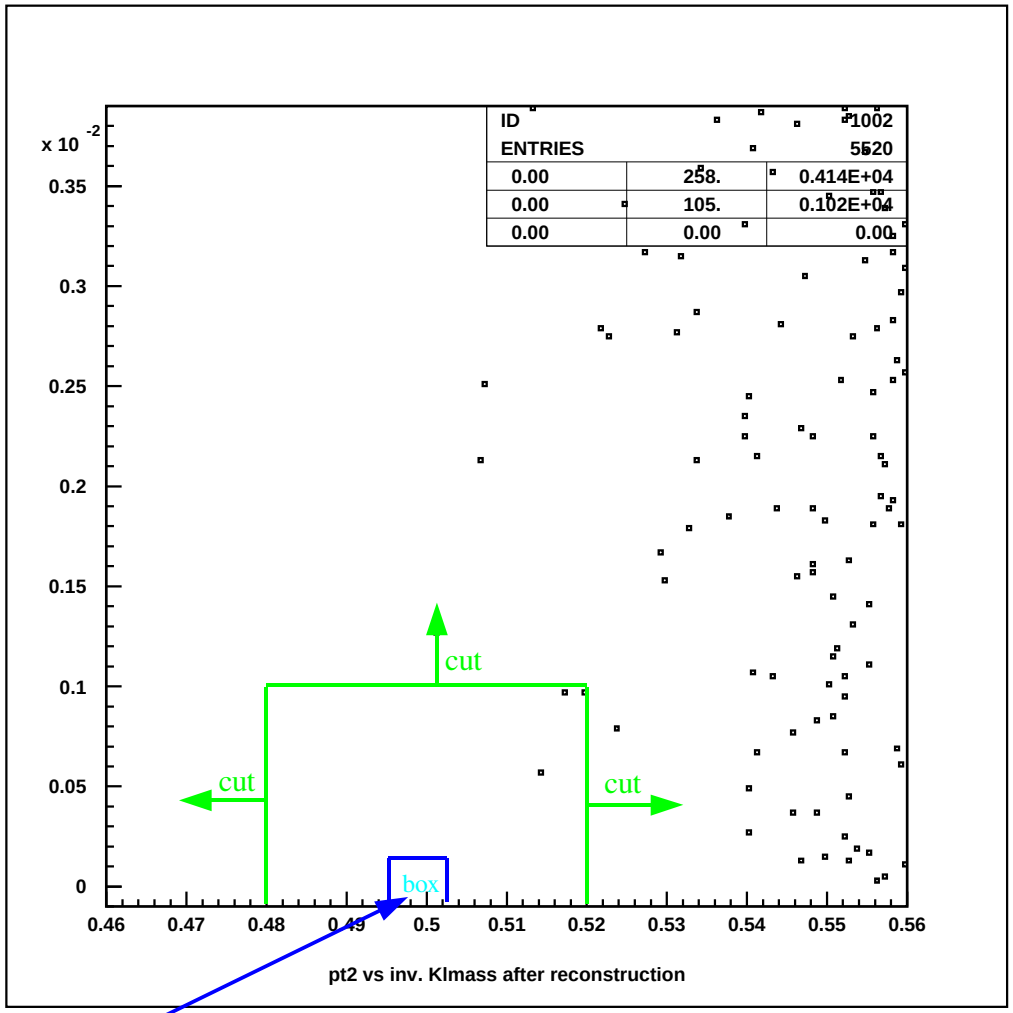
Compare with old 2.74% result

* = *cuts listed in chronological order*

Cut on P_T^2 vs. Inv. K_L Mass

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





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

~ Box Dimensions ~

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

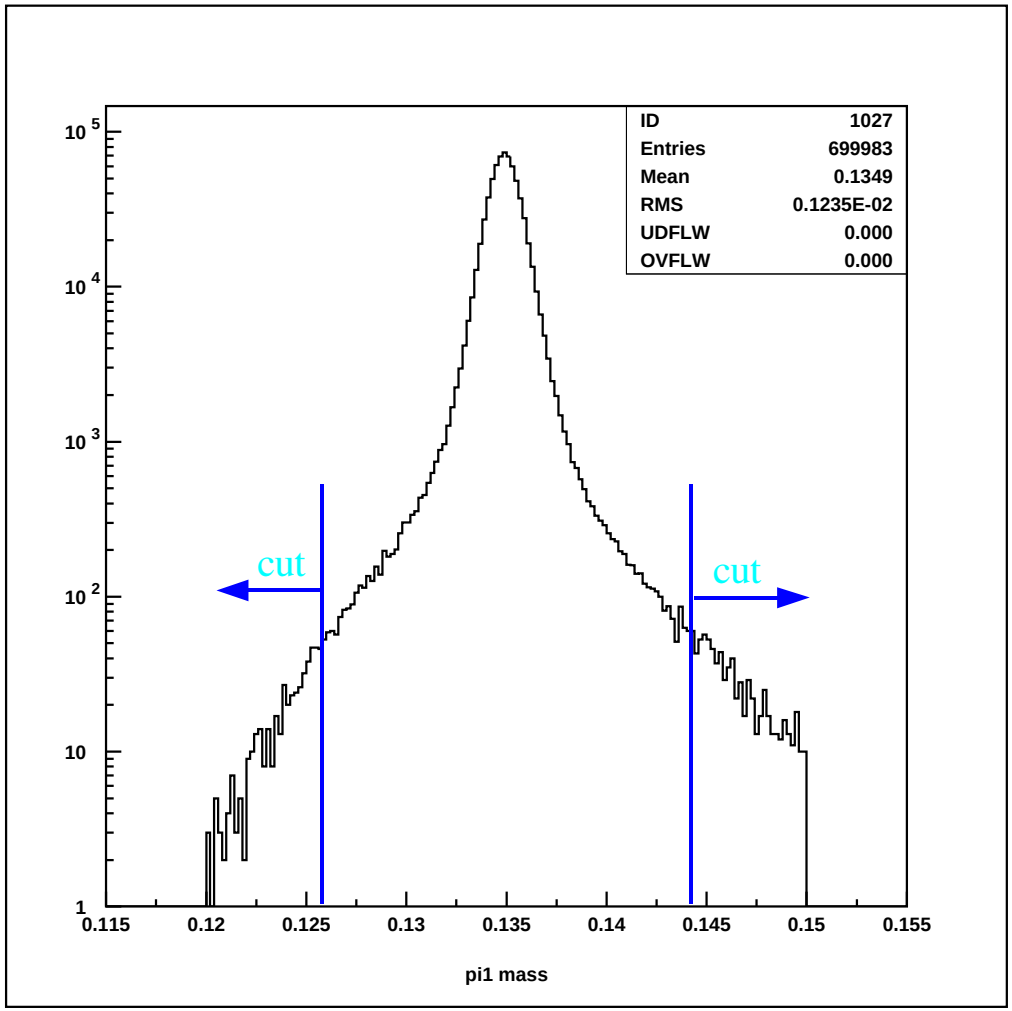
$p_T^2 \leq 130\ \text{MeV}^2$

Closed Signal Box!!

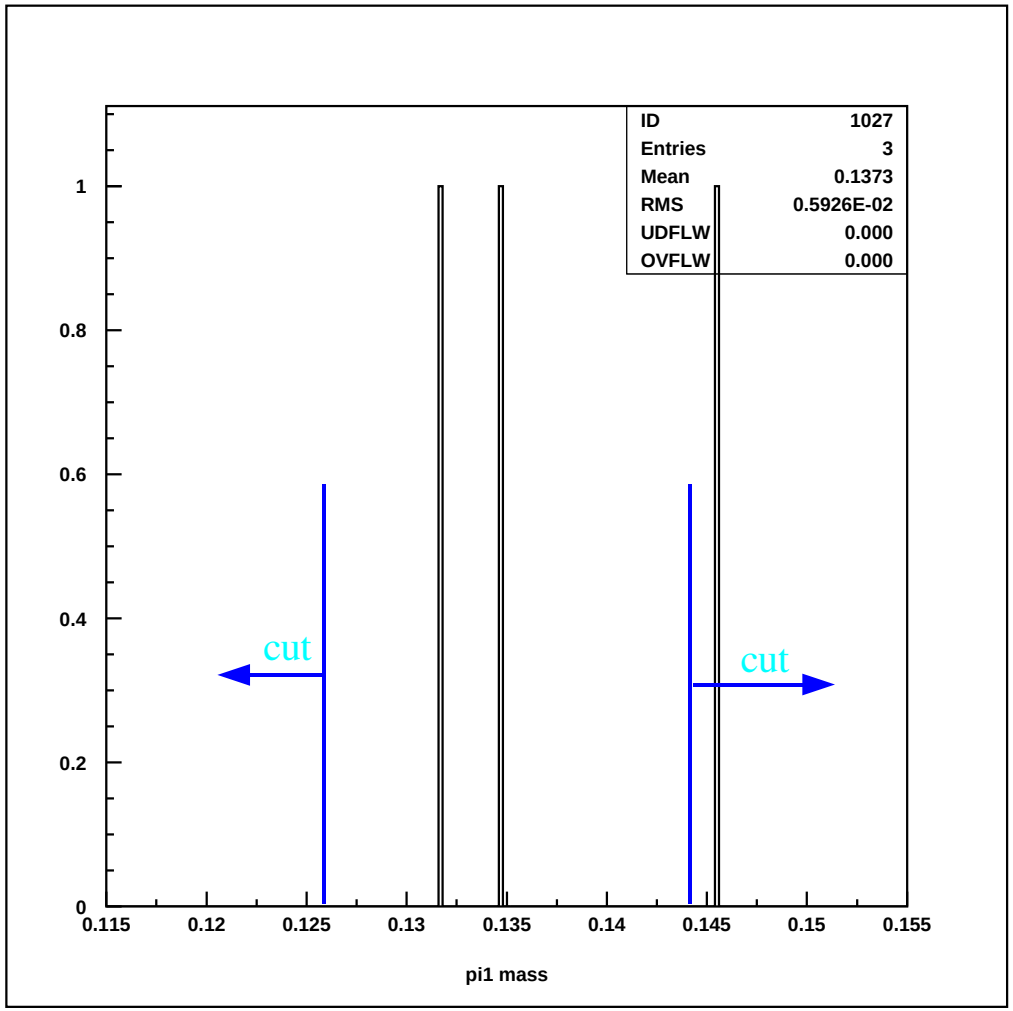
$K^0_{\mu 4}$ *MC Background*

Cut on π^0 Masses

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



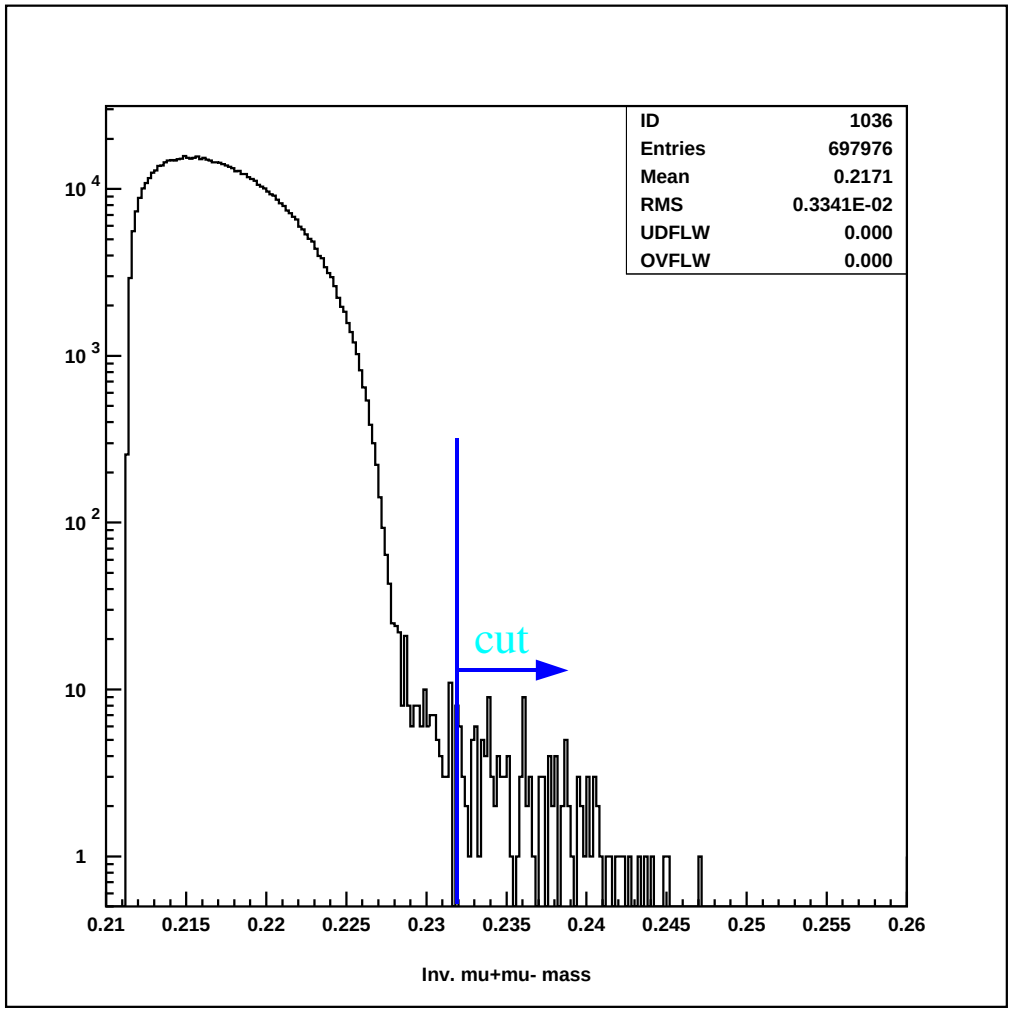
$K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*



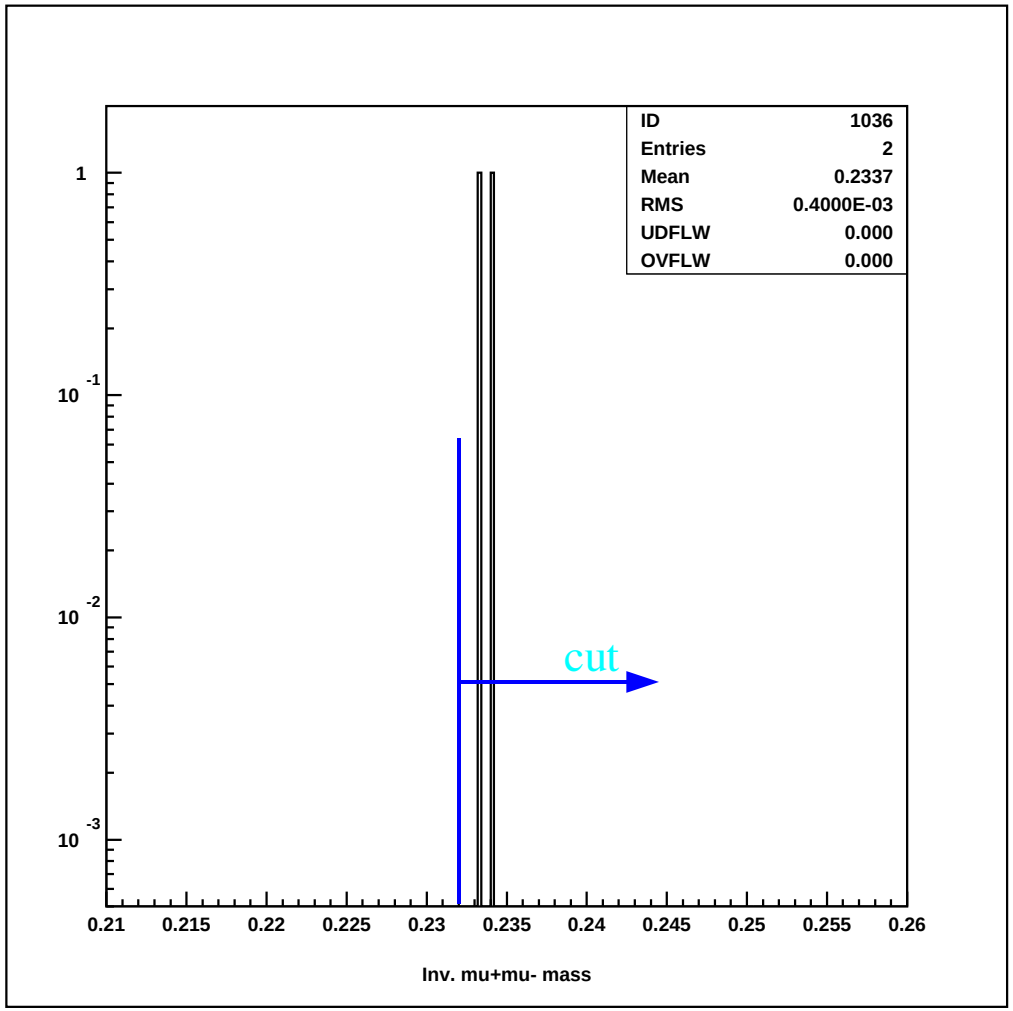
$K^0_{\mu 4}$ *MC Background*

Cut on Dimuon Mass

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

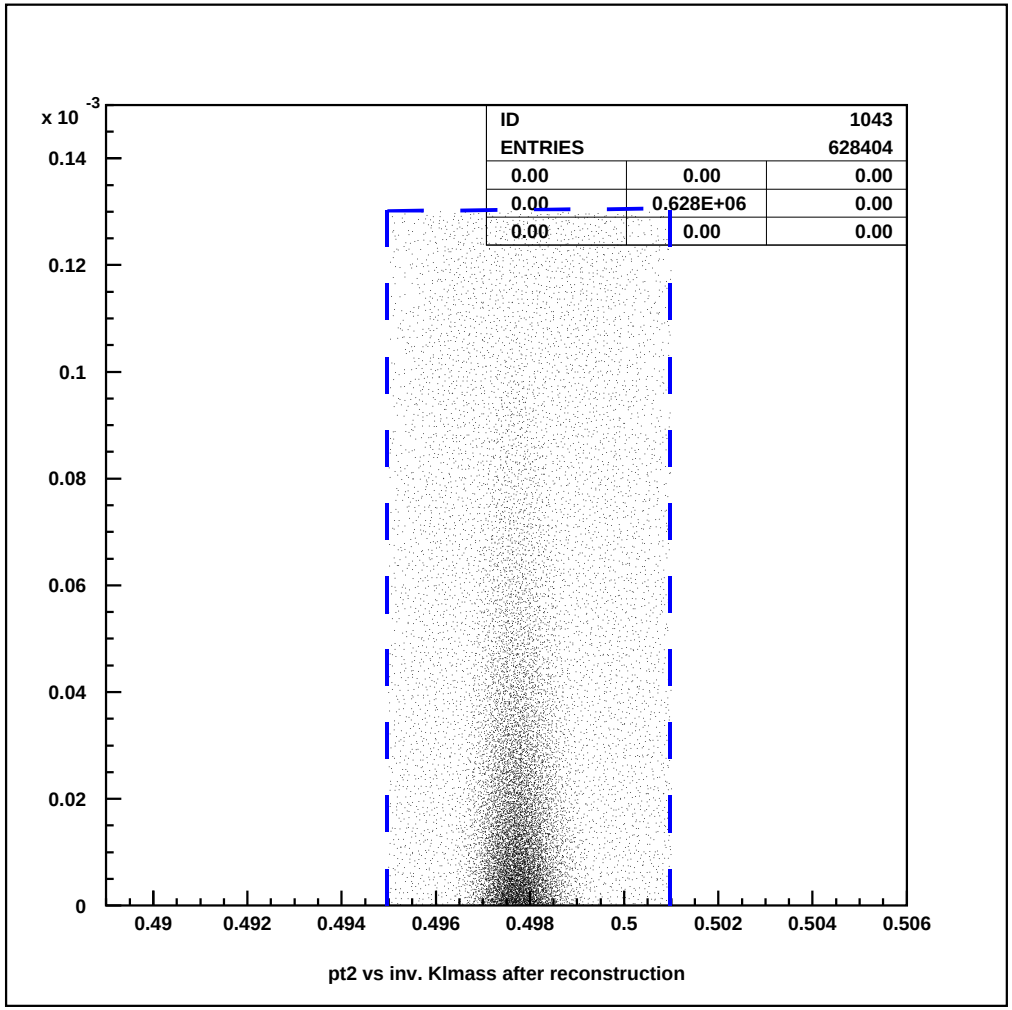


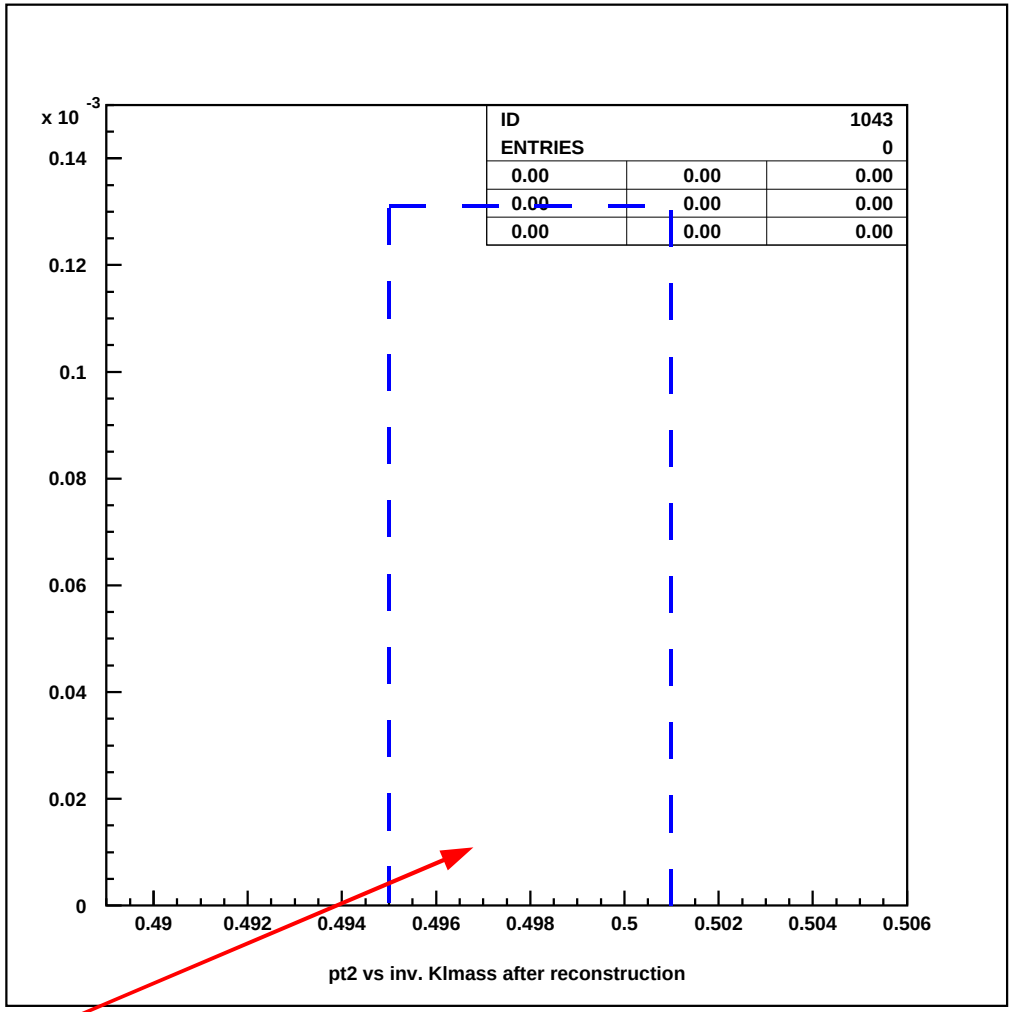
$K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*



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

Opening of the K_L Signal Box!



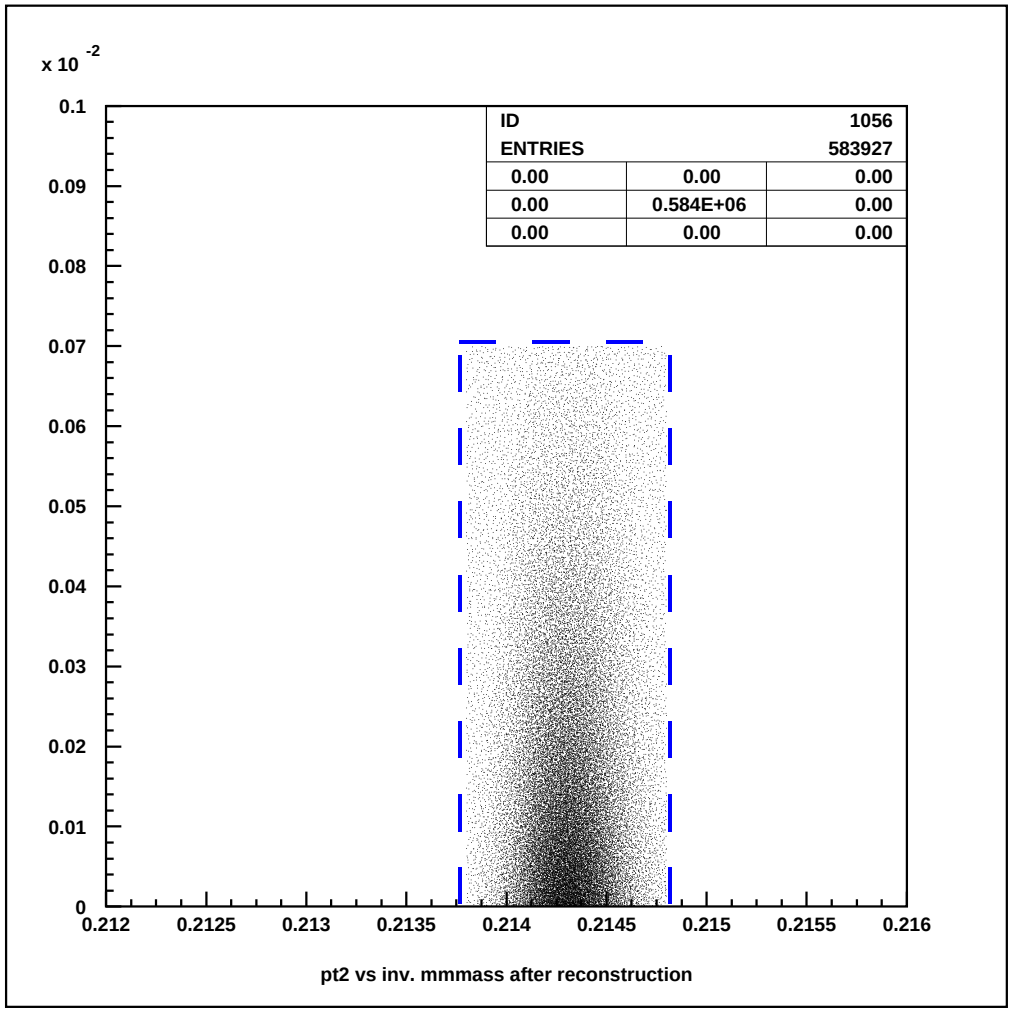


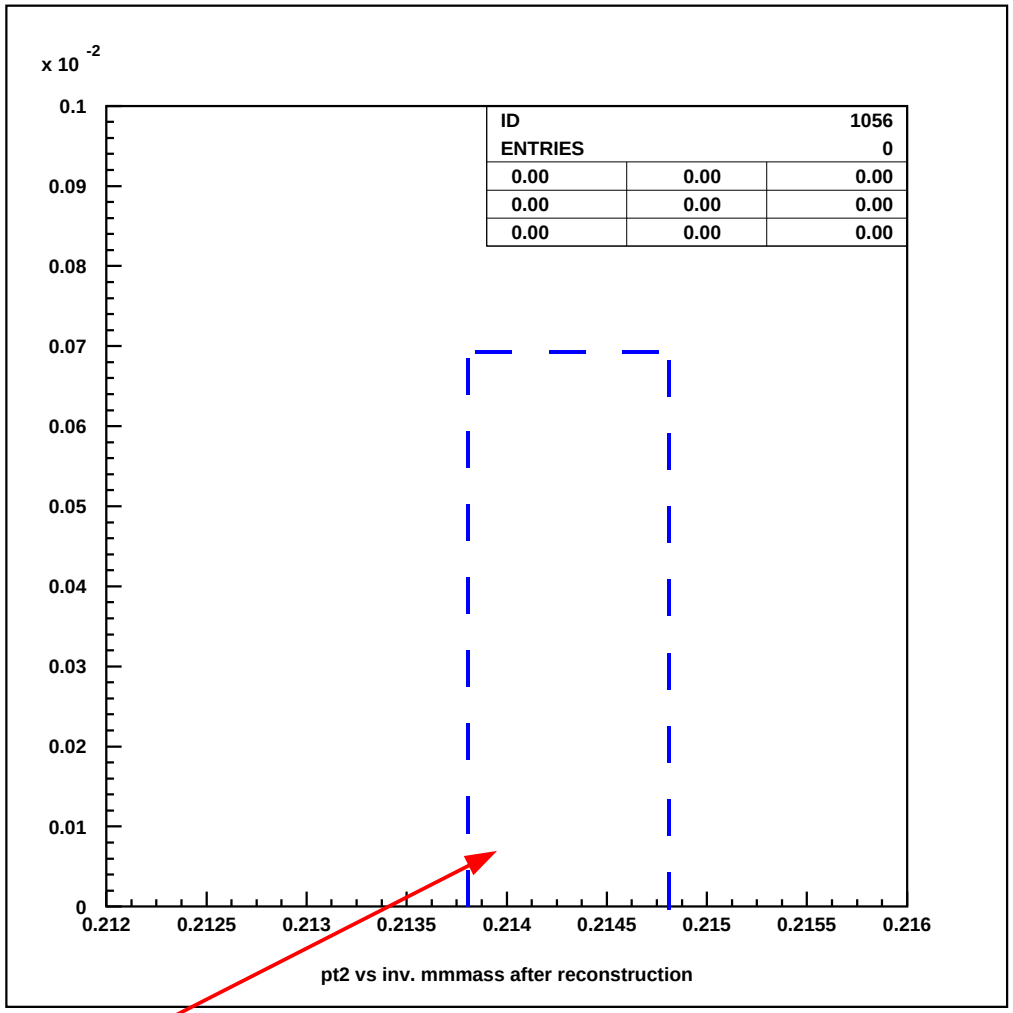
$K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *MC*

K_L Signal Box Opened and is EMPTY!

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

Opening of the H^0 Box!





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

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

H^0 Signal Box Opened and is EMPTY!

Results and Future Plans

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

Compare with old 2.74% result

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

Using $N_K = 2.43 \times 10^{11}$ (D. Smith Thesis), one finds:

SES($K_L \to \pi^0\pi^0\mu^+\mu^-$) = 1.31×10^{-10}

SES($K_L \to \pi^0\pi^0 H^0 \to \pi^0\pi^0\mu^+\mu^-$) = 1.46×10^{-10}

Compare with:

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

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

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

→ *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.

- analysis of 1999 data set has also begun.

- statistics. Need to develop a Feldman-Cousins estimate with zero signal and background events. Does one use F.-C. in such a scenario?