KTEV
Kaons at the Tevatron

Search for the Rare Decay $K_L \to \pi^0\pi^0\mu^+\mu^-$

David G. Phillips II

2009 Kaon International Conference

June 11, 2009

KTeV Institutions

Fermi National Accelerator Laboratory (Batavia, Illinois)

University of Virginia (Charlottesville, Virginia)

The Enrico Fermi Institute, The University of Chicago (Chicago, Illinois)

University of Arizona (Tucson, Arizona)

University of California at Los Angeles (Los Angeles, California)

Universidade Estadual de Campinas (Campinas, Brasil)

University of Colorado (Boulder, Colorado)

Elmhurst College (Elmhurst, Illinois)

Osaka University (Toyonaka, Osaka, Japan)

Rice University (Houston, Texas)

Universidade de Sao Paolo (Sao Paolo, Brasil)

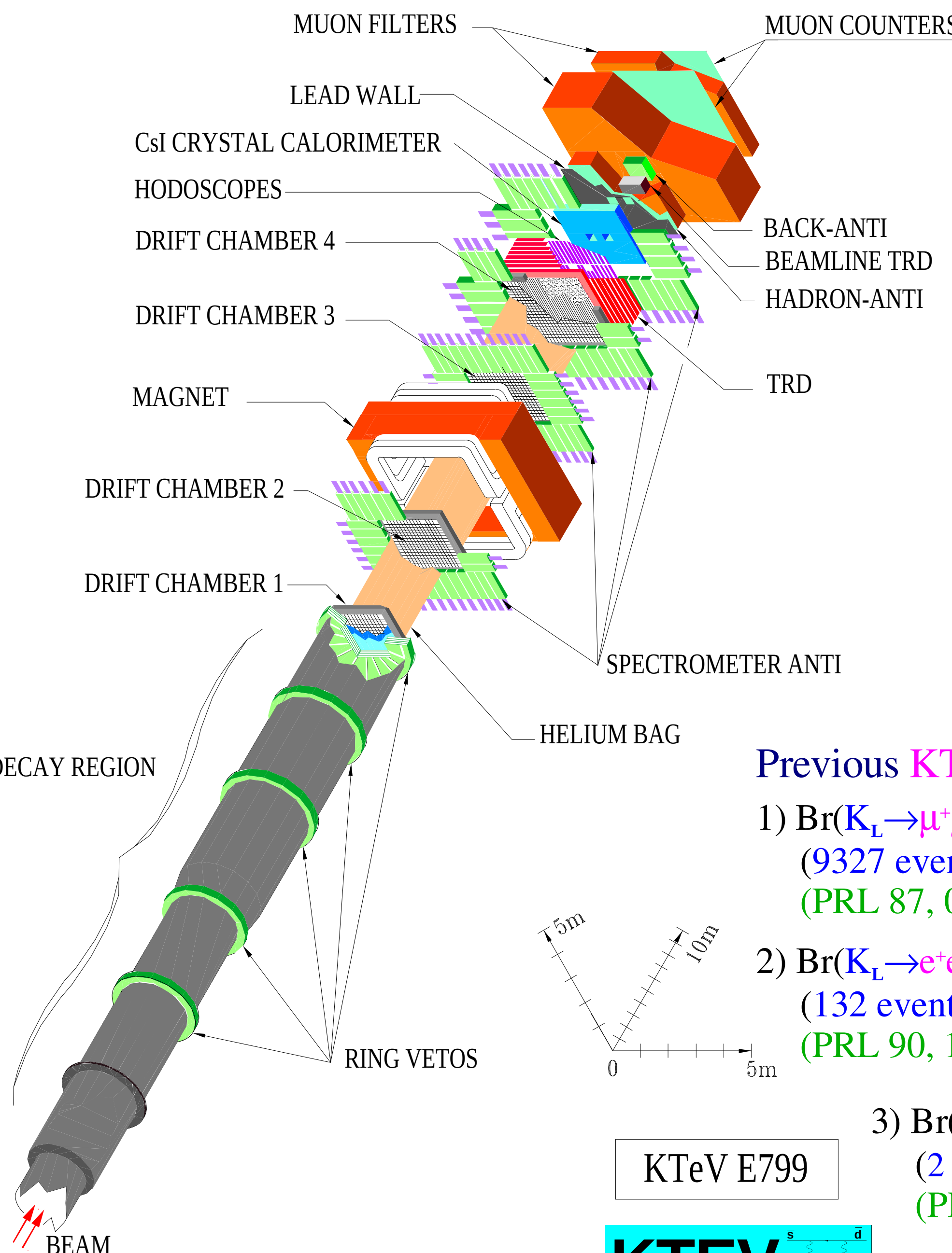
University of Wisconsin (Madison, Wisconsin)

The KTeV Detector

<u>KTeV's coordinate system is:</u>

1) right-handed

2) defined such that the target is at the origin.



KTeV E799

Previous KTeV Dimuon Results:

1) $Br(K_L \to \mu^+\mu^-\gamma) = (3.62 \pm 0.04_{stat} \pm 0.08_{syst}) \times 10^{-7}$
(9327 events)
(PRL 87, 071801 (2001))

2) $Br(K_L \to e^+e^-\mu^+\mu^-) = (2.69 \pm 0.24_{stat} \pm 0.12_{syst}) \times 10^{-9}$
(132 events)
(PRL 90, 141801 (2003))

3) $Br(K_L \to \pi^0\mu^+\mu^-) < 3.8 \times 10^{-10}$
(2 events obs.; 0.87 ± 0.15 bkgd. events)
(PRL 84, 5279-5282 (2000))

KTEV Kaons at the Tevatron

Motivation for the Study of $K_L \to \pi^0\pi^0\mu^+\mu^-$

- There's no published calculation within the Standard Model for Br($K_L \to \pi^0\pi^0\mu^+\mu^-$), but Heiliger and Sehgal have a paper on $K_L \to \pi^0\pi^0 e^+e^-$. (Phys. Lett. B307, 182-186 (1993))

- HyperCP reported evidence of the *'hypothetical'* neutral boson X^0 in a claimed observation of $\Sigma^+ \to p\mu^+\mu^-$. They determined the following branching ratios:

$$Br(\Sigma^+ \to p\mu^+\mu^-) = \left(8.6^{+6.6}_{-5.4}(stat) \pm 5.5(syst)\right) x10^{-8},$$

(PRL 94, 021801 (2005))

3 events observed!

$$Br(\Sigma^+ \to pX^0 \to p\mu^+\mu^-) = \left(3.1^{+2.4}_{-1.9}(stat) \pm 1.5(syst)\right) x10^{-8}$$

- HyperCP determined the mass of the X^0 to be: $(214.3 \pm 0.5)\, MeV$

- Outside the Standard Model, this decay is possible via the same hypothetical X^0 neutral boson, which will be described in the coming slides.

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

Theoretical Estimates for $K_L \to \pi^0\pi^0\mu^+\mu^-$

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

- Valencia *et al.* and Deshpande *et al.* calculate $Br(K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-)$ assuming that X^0 couples to $\bar{d}s$ (and $\mu^+\mu^-$). They also assume that the X^0's are short lived, do not interact strongly and possess a mass of 214.3 MeV.

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

- finding that pseudoscalar couplings have the largest contribution, they find:

$$Br(K_L \to \pi^0\pi^0X^0_P \to \pi^0\pi^0\mu^+\mu^-) = 8.0 \times 10^{-9}$$ (Phys. Lett. B 632 (2006) 212-214)

- Valencia *et al.* take things a step further and consider scalar, pseudoscalar, vector and axial vector particle possibilities for the X^0 state.

- the decay $K^+ \to \pi^+\mu^+\mu^-$ places serious constraints on scalar and vector particle possibilities. The branching ratio for $K^+ \to \pi^+\mu^+\mu^-$ has been measured to be:

$$Br(K^+ \to \pi^+\mu^+\mu^-) = (8.1 \pm 1.4)\,x10^{-8}$$

(PRL 88, 111801 (2002))

2004 PDG Average

- combining the upper result with constraints on scalar and vector couplings, Valencia *et al.* calculates theoretical upper limits on $Br(\Sigma^+ \to pX^0 \to p\mu^+\mu^-)$:

$$Br(\Sigma^+ \to pX^0_S \to p\mu^+\mu^-) < 6x10^{-11}\ ,\ Br(\Sigma^+ \to pX^0_V \to p\mu^+\mu^-) < 3x10^{-11}$$

- the above upper limits effectively eliminate both scalar and vector particles as explanations of the HyperCP result.

- Valencia *et al.* have ruled out the possibility of scalar or vector X^0's. Using existing constraints on pseudoscalar and axial vector X^0's, they predict:

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

(Phys. Lett. B 631 (2005) 100-108)

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

Other Searches and Theories for $K_L \rightarrow \pi^0\pi^0 X^0$

- using an sgoldstino model, the branching ratio for $K_L \rightarrow \pi^0\pi^0 X^0$ (where $X^0 \rightarrow \gamma\gamma$) was predicted to be:

$$Br(K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\gamma\gamma) < 1.2 \times 10^{-4}$$

(Phys. Rev. D73, 035002 (2006))

- E391a (KEK) will report on their search for $K_L \rightarrow \pi^0\pi^0 X^0$ (where $X^0 \rightarrow \gamma\gamma$) in the next talk.

- a recent theoretical study suggests that the hypothetical X^0 neutral boson could be the lightest (pseudoscalar) Higgs boson in the *next-to-minimal supersymmetric standard model* (NMSSM). (PRL 98, 081802 (2007))

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

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

  ~ this is a blind analysis with two signal boxes: one signal box for K_L and one signal box for X^0.

  ~ the boxes for 1997 *AND* 1999 have been opened!

  ~ completed identification and estimation of signal mode background.

  ~ normalization mode ($K_L \rightarrow \pi^0\pi^0\pi^0{}_D$) acceptance has been obtained. Negligible background. Systematic studies have been finished.

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

-Crunch Requirements-

$K_L \to \pi^0\pi^0\mu^+\mu^-$ Crunch Requirement*	1997 Data ♫	1997 MC ♪	1999 Data ♫	1999 MC ♪
Generation Level (MC)	-----	0.092	-----	0.091
Require 2 tracks	0.666	0.970	0.466	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	0.904
$E_{cl}(track) / p_{track} \leq 0.9$	0.999	0.999	0.999	0.999
NHCLUS ≥ 4	0.056	0.636	0.050	0.686
# hits in μ planes ≥ 1	0.980	0.999	0.989	0.999
# γ clus (not assoc. w/tracks) = 4	0.444	0.964	0.471	0.970
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq 15$ MeV	0.437	0.967	0.443	0.973
$90.0\ m \leq Z_{VTX} \leq 160.0\ m$	0.265	0.985	0.310	0.984
Bad Spill	0.813	0.803	0.940	0.966
$p_T^2 \leq 0.06\ GeV^2/c^2$	0.569	0.999	0.700	0.999
Total Acceptance	0.00034	0.0380	0.00043	0.0492

* = *listed in chronological order,* ♫ = *initial # data events was ~291 M (1997) and ~153 M (1999),*
♪ = *initial # MC events for 1997 and 1999 was ~2.0 M (# generated MC events was ~20 M).*

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

-Analysis Requirements-

$K_L \to \pi^0\pi^0\mu^+\mu^-$ Analysis Requirement*	γ^* Signal MC (1997)	X^0 Signal MC (1997)	γ^* Signal MC (1999)	X^0 Signal MC (1999)
480 MeV ≤ $M_{\mu\mu\gamma\gamma\gamma\gamma}$ ≤ 520 MeV	0.962	0.966	0.961	0.965
$p_T^2 \leq 0.001$ GeV^2/c^2	0.982	0.980	0.984	0.983
E_{cl}(track) ≤ 1.0 GeV	0.974	0.974	0.966	0.965
P_{track} ≤ 7.0 GeV	0.999	0.999	0.994	0.995
$\lvert M_{rec.pi0} - M_{pi0}\rvert$ ≤ 9 MeV	0.997	0.997	0.997	0.997
$M_{\mu\mu}$ ≤ 232 MeV	0.999	0.999	0.999	0.999
495 MeV ≤ $M_{\mu\mu\gamma\gamma\gamma\gamma}$ ≤ 501 MeV & $p_T^2 \leq 0.00013$ GeV^2/c^2	0.901	0.891	0.906	0.902
213.8 MeV ≤ $M_{\mu\mu}$ ≤ 214.8 MeV & $p_{T,\mu\mu}^2 \leq 0.0007$ GeV^2/c^2	------	0.954	------	0.954
Total Acceptance (all inclusive)	0.0314	0.0280	0.0403	0.0374

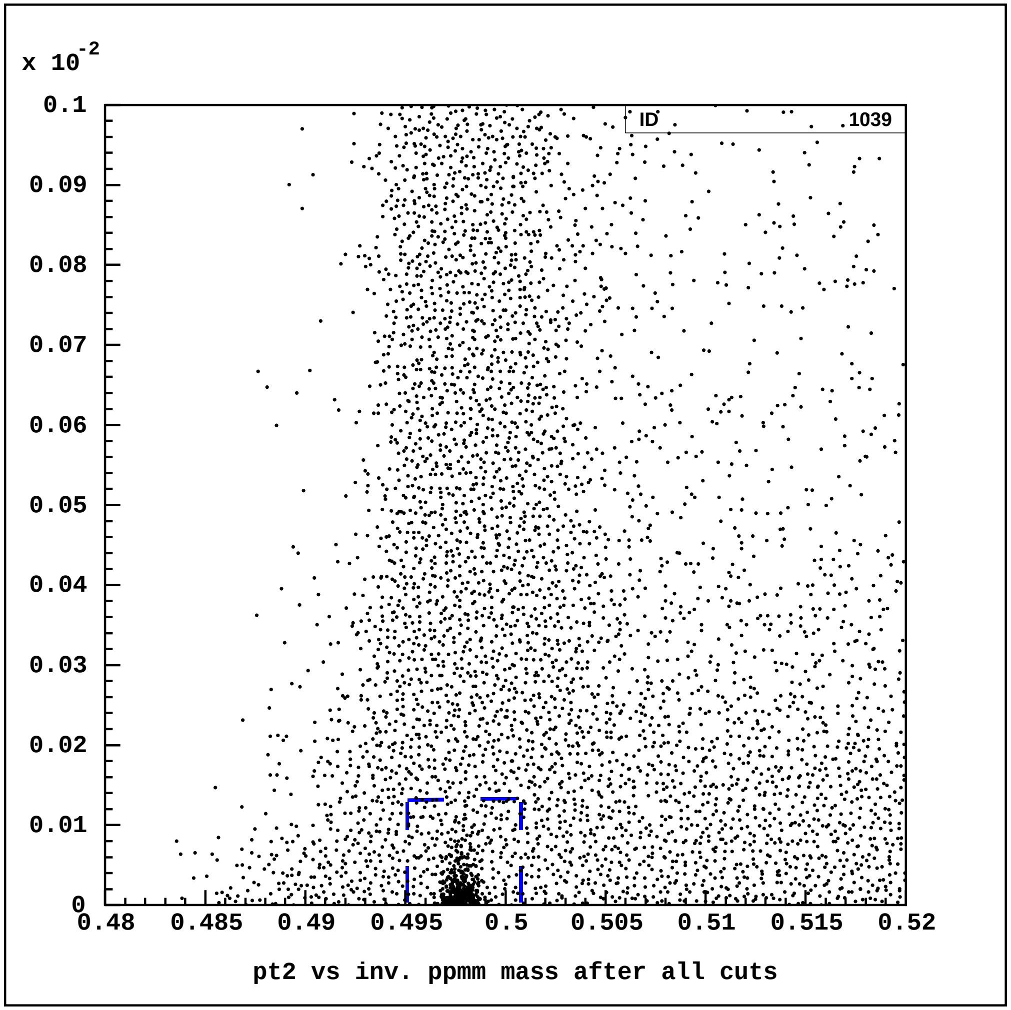
* = requirements listed in chronological order

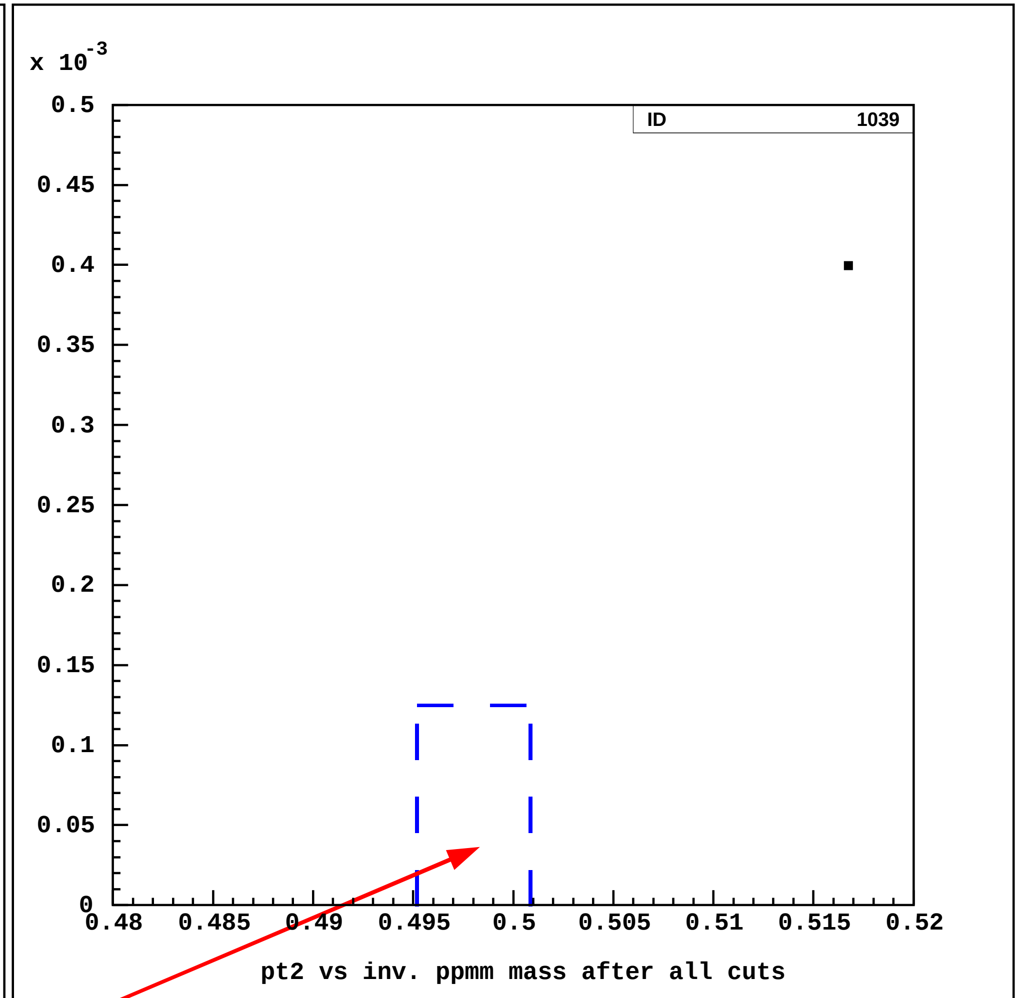
Summary of Backgrounds

No background survive analysis cuts!!!

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 = $\pi^{+,-} \to \mu^{+,-} \nu_\mu$)	244,692,689 (0.0037 f)	421,656,663 (0.0064 f)
$K^0_{\mu 4}$ (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)	455,374,316 (0.015 f)	456,480,690 (0.015 f)
$K_L \to \pi^+\pi^-\gamma$ (2x punch through)	15,034,557 (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)	14,249,908 (1.34 f)	14,495,323 (1.36 f)
$K_L \to \pi^+\pi^-$ (2x punch through)	683,676,428 (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)	50,306,906 (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

Opening of the 1997 $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Signal Box!





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

~ Box Dimensions ~

495 MeV ≤ $M_{\gamma\gamma\gamma\gamma\mu\mu}$ ≤ 501 MeV

$p_T^2 \leq 130$ MeV^2

Signal Box Opened
and is EMPTY!

EMPTY = No Signal Events
AND No Bkgd Events!

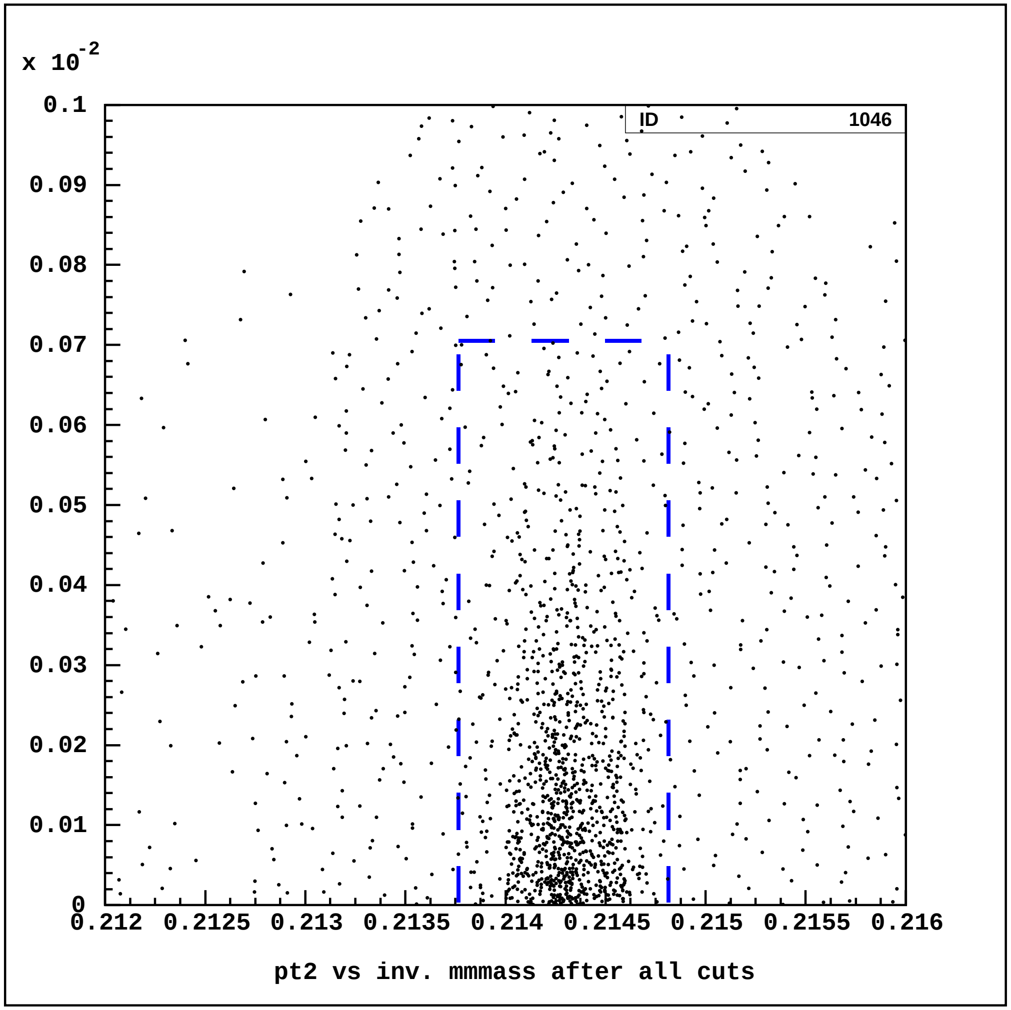
1997 KTeV *Data*

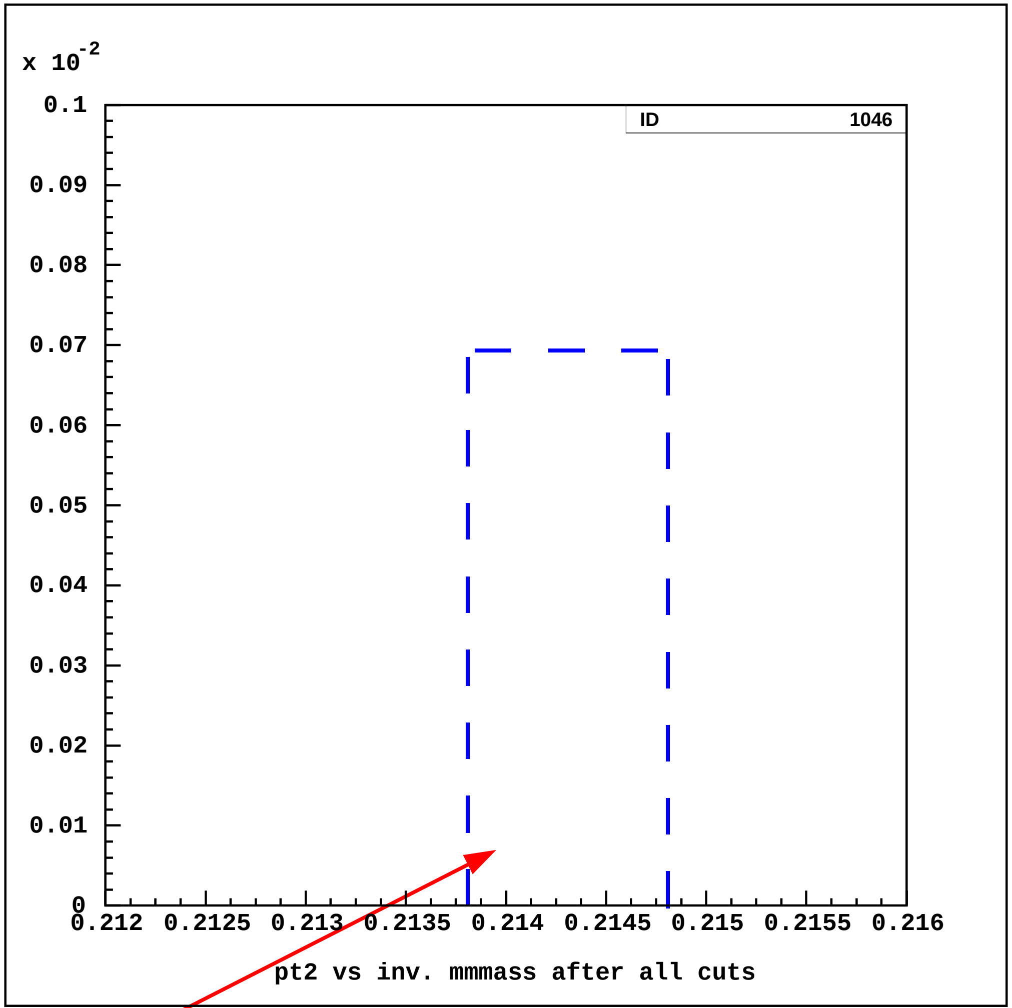
~ Box Dimensions ~

495 MeV ≤ $M_{\gamma\gamma\gamma\gamma\mu\mu}$ ≤ 501 MeV

$p_T^2 \leq 130$ MeV^2

Opening of the 1997 $X^0 \to \mu^+\mu^-$ Signal Box!





1997 $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ MC

~ Box Dimensions ~

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

$p_T^2 \leq 700$ MeV^2

Signal Box Opened and is EMPTY!

1997 KTeV Data

~ Box Dimensions ~

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

$p_T^2 \leq 700$ MeV^2

Normalization Mode ($K_L \rightarrow \pi^0\pi^0\pi^0_D$) *Results*

Requirement*	1997 Data♪	1997 MC♪	1999 Data♫	1999 MC♫
Trigger Level		0.027		0.034
Require 2 tracks	0.889	0.985	0.965	0.985
$C_{track1} = -C_{track2}$	0.999	0.999	0.999	0.999
$0.95 \leq E_{cl}(track) / p_{track} \leq 1.05$	0.679	0.886	0.848	0.851
NHCLUS ≥ 5	0.916	0.967	1.000	0.972
# γ clus (not assoc. w/tracks) = 5	0.374	0.447	0.999	0.463
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq 15$ MeV	0.066	0.067	0.071	0.072
$90.0 \text{ m} \leq Z_{VTX} \leq 160.0 \text{ m}$	0.977	0.985	0.970	0.982
Bad Spill	0.792	0.789	0.934	0.944
$p_T^2 \leq 0.06 \text{ GeV}^2/c^2$	0.928	0.934	0.928	0.937
$473 \text{ MeV} \leq M_{ee\gamma\gamma\gamma\gamma} \leq 523 \text{ MeV}$	0.471	0.477	0.494	0.504
$p_T^2 \leq 0.001 \text{ GeV}^2/c^2$	0.259	0.255	0.325	0.323
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq 14$ MeV	0.992	0.992	0.993	0.993
$94.0 \text{ m} \leq Z_{VTX} \leq 158.0 \text{ m}$	0.987	0.990	0.986	0.990
Total Acceptance	131526 events	0.006%	363531 events	0.013%

Used a precrunched data set!

Beginning of analysis

109,532 events

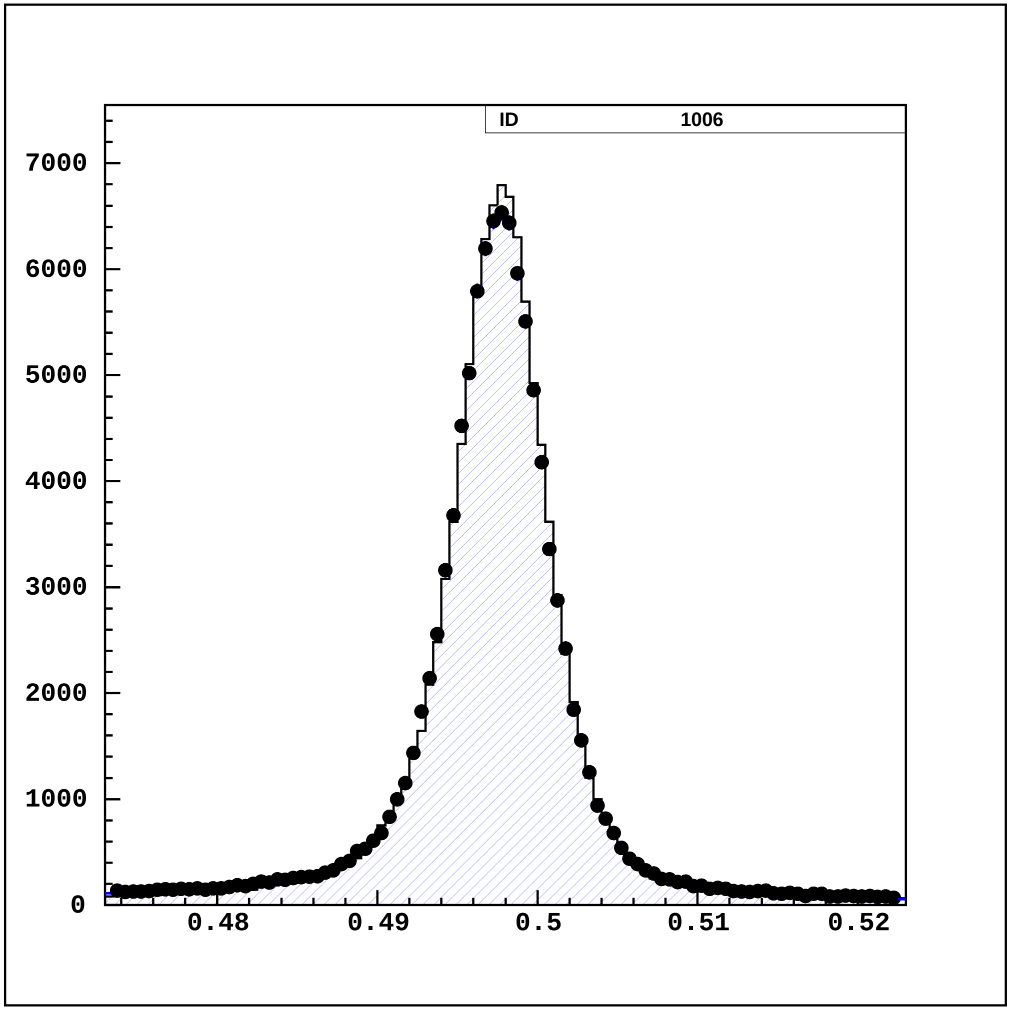
183,131 events

* = *requirements listed in chronological order,*

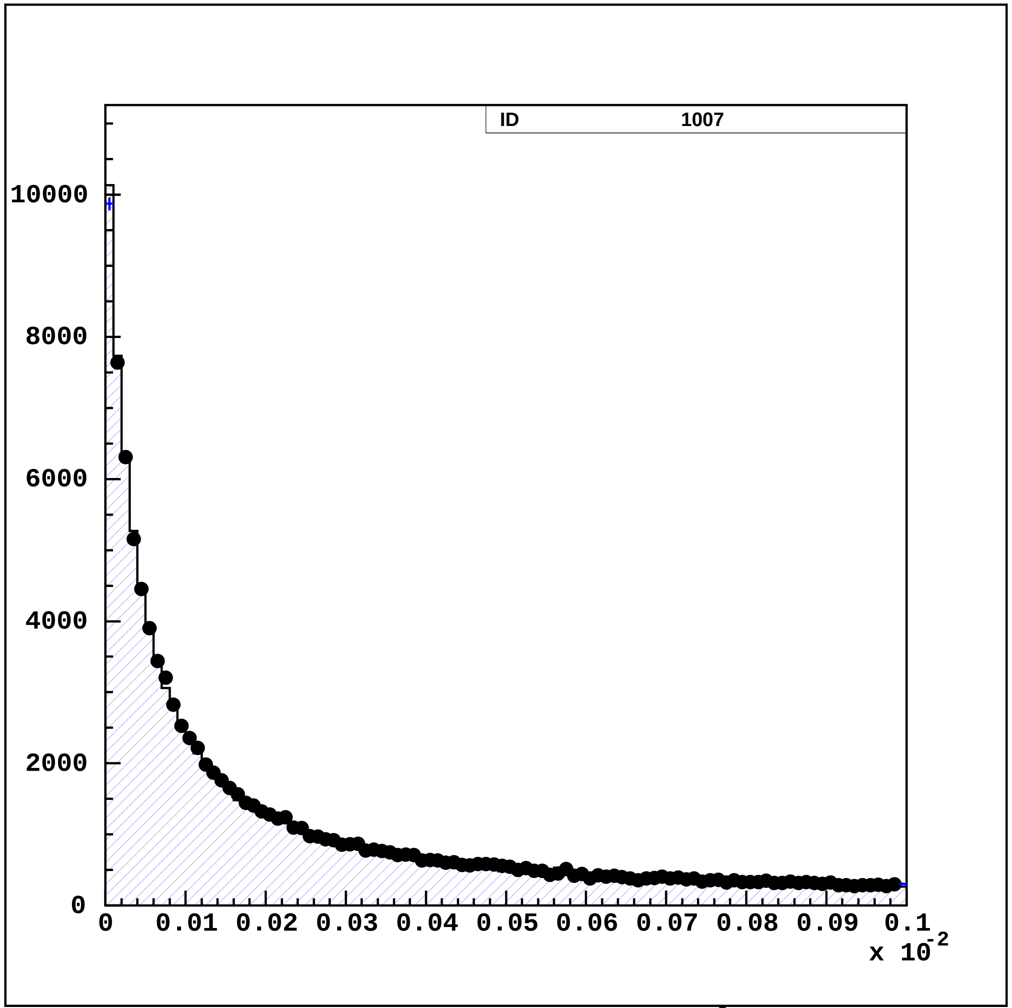
♫ = *initial # data events was ~47.2 M (# generated MC events was ~1.41 G),*

♪ = *initial # data events was ~50.4 M (# generated MC events was ~1.84 G).*

1997 $K_L \to \pi^0\pi^0\pi^0_D$ Inv. Mass and $P_T^{\,2}$ After All Cuts



1997 $\pi^0\pi^0\pi^0_D$ Inv. Mass

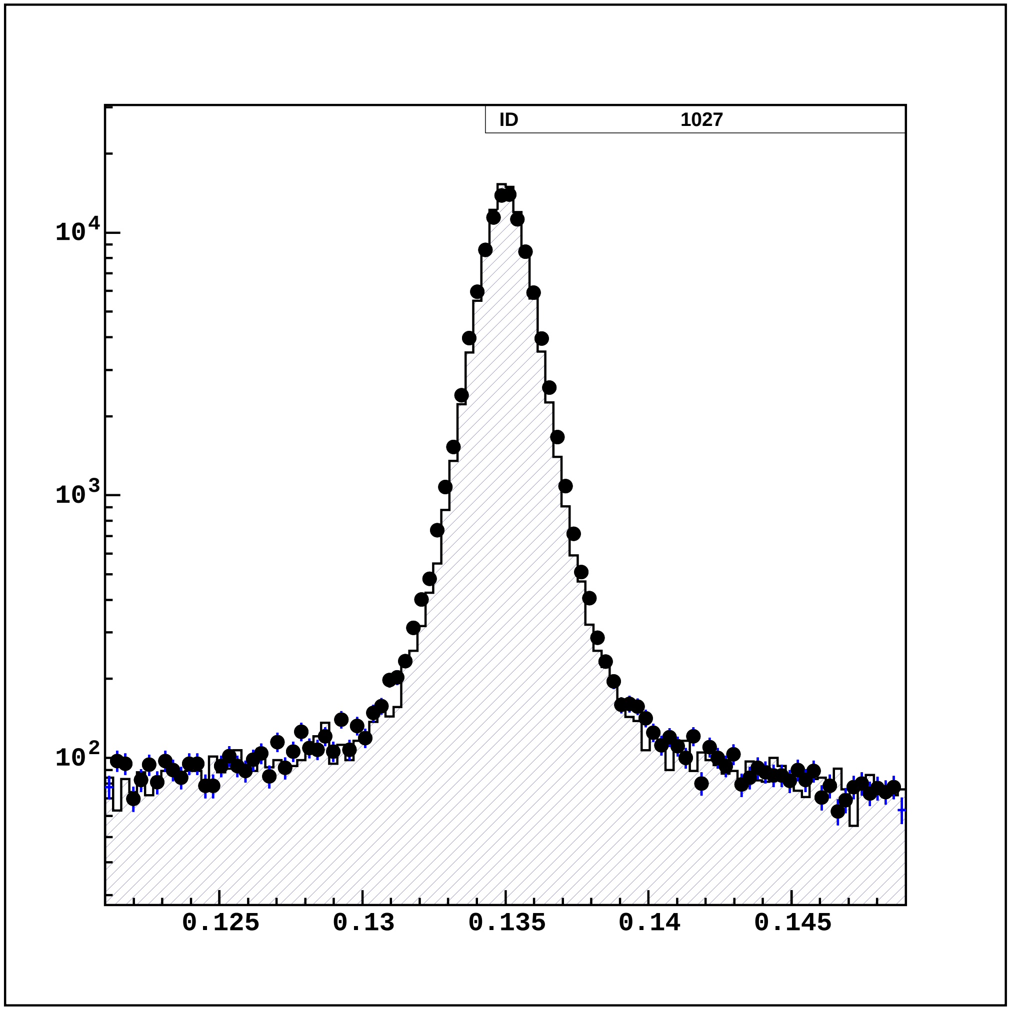


1997 $\pi^0\pi^0\pi^0_D$ $P_T^{\,2}$

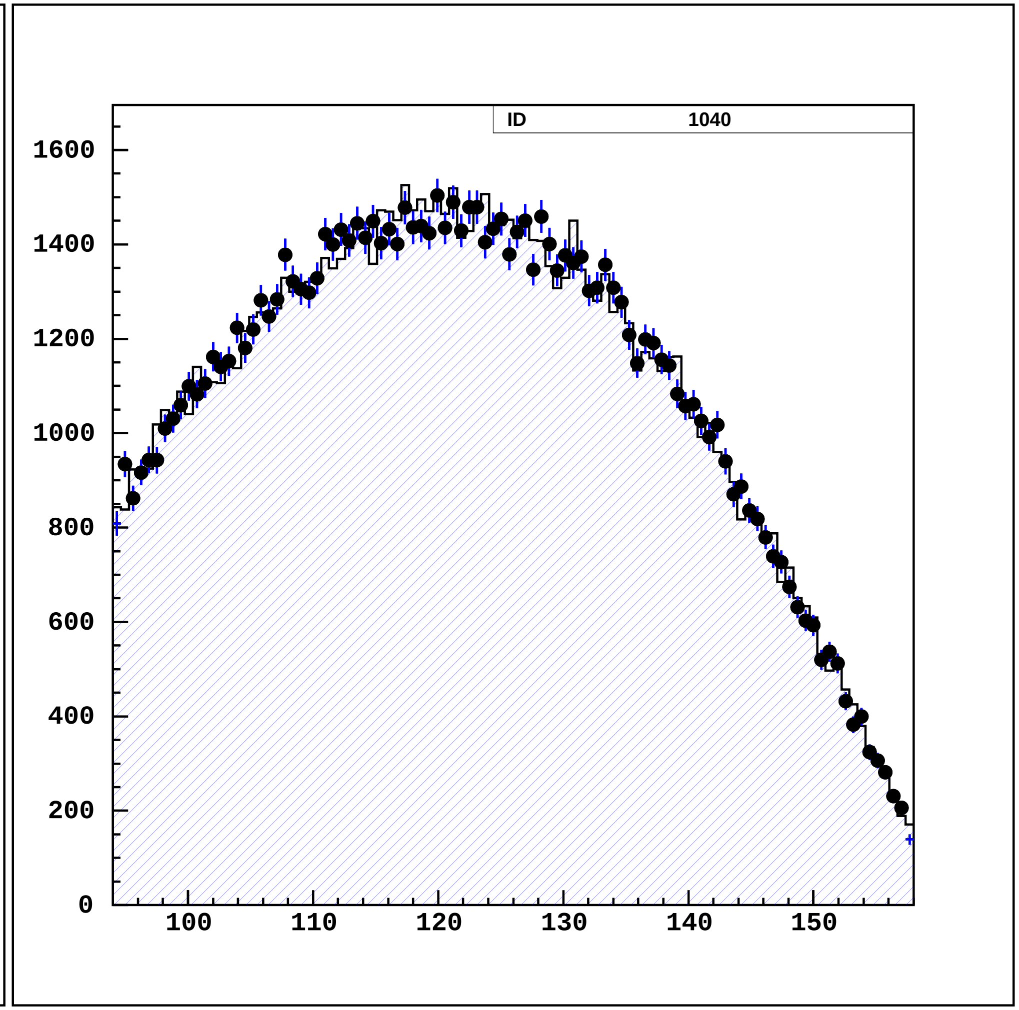
● = Data

□ = MC

1997 $K_L \rightarrow \pi^0\pi^0\pi^0_D$ 1st π^0 Mass and Zvtx After All Cuts



1997 $\pi^0\pi^0\pi^0_D$ 1st π^0 Mass



1997 $\pi^0\pi^0\pi^0_D$ Zvtx

● = Data

□ = MC

Acceptance Results

1997 Acceptance ($K_L \to \pi^0\pi^0\mu^+\mu^-$) = $(3.14 \pm 0.004_{stat.})\%$

1997 Acceptance ($K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$) = $(2.80 \pm 0.004_{stat.})\%$

1997 Acceptance ($K_L \to \pi^0\pi^0\pi^0_D$) = $(5.94 \pm 0.02_{stat.}) \times 10^{-5}$

1999 Acceptance ($K_L \to \pi^0\pi^0\mu^+\mu^-$) = $(4.03 \pm 0.005_{stat.})\%$

1999 Acceptance ($K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$) = $(3.74 \pm 0.004_{stat.})\%$

1999 Acceptance ($K_L \to \pi^0\pi^0\pi^0_D$) = $(1.29 \pm 0.003_{stat.}) \times 10^{-4}$

K_L Flux Calculation

$$N^{Data}_{Norm} = F_K \times BR(K_L \to \pi^0 \pi^0 \pi^0_D) \times A_{Norm}\,,\, where\ A_{Norm} = \frac{N_{acc}}{N_{gen}}.$$

$$N^{Data}_{Norm} = number\ of\ data\ events\ after\ all\ normalization\ mode\ cuts.$$

$$N_{acc} = number\ of\ MC\ events\ after\ all\ normalization\ mode\ cuts.$$

$$N_{gen} = number\ of\ MC\ events\ generated.$$

$$A_{Norm,1997} = \frac{109532}{1842926908} = 5.94 \times 10^{-5} \qquad A_{Norm,1999} = \frac{183131}{1414181218} = 1.29 \times 10^{-4}$$

$$BR(K_L \to \pi^0 \pi^0 \pi^0_D) = 3\mathrm{BR}(K_L \to \pi^0 \pi^0 \pi^0) \times BR(\pi^0_D) \times BR(\pi^0 \to \gamma\gamma)^2 = (6.85 \pm 0.23) \times 10^{-3}$$

$$N^{Data}_{Norm,1997} = 131526\, events \qquad N^{Data}_{Norm,1999} = 363531\, events$$

Putting everything together yields →

$$F_{K,1997} = 3.23 \times 10^{11}\, events \qquad F_{K,1999} = 4.10 \times 10^{11}\, events$$

Systematic Errors in Flux from $K_L \to \pi^0\pi^0\pi^0_D$

Source of Systematic Error	$\frac{\Delta F_{Norm,1997}}{F_{Norm,1997}}$	$\frac{\Delta F_{Norm,1999}}{F_{Norm,1999}}$
(473 ∓ 1) MeV $\leq M_{ee\gamma\gamma\gamma\gamma} \leq (523\pm1)$ MeV	+0.04% -0.05%	+0.05% -0.06%
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq (14\pm1)$ MeV	+0.02% -0.03%	+0.02% +0.01%
(94.0 ∓ 1.0) m $\leq Z_{VTX} \leq (158.0\pm1.0)$ m	+0.16% +0.02%	+0.20% -0.10%
$P_T^2 \leq (1.0\pm0.1)*10^{-3}$ GeV^2	+0.11% +0.02%	+0.06% -0.08%
$(0.95\mp0.1) \leq E_{cl}(\text{track}) / p_{track} \leq (1.05\pm0.1)$	+1.24% -2.41%	+2.23% -4.05%
P_z Weighting	-------	1.87%
Cracks in μ Counting Planes	0.50%	0.50%
Energy Loss in μ Filters	0.40%	0.40%
$Br(K_L \to \pi^0\pi^0\pi^0)$	0.61%	0.61%
Total Systematic Error from Flux	+1.54% - 2.57%	+3.05% - 4.55%

$$F_{Norm} = \frac{N^{Data}_{Norm}}{A_{Norm}} = F_K \times BR(K_L \to \pi^0\pi^0\pi^0_D), \qquad \Delta F_{Norm} = \frac{N^{Data}_{Norm} \pm \Delta N}{A_{Norm} \pm \Delta A} - F_{Norm}$$

- after all analysis cuts, there were ZERO signal events found in the Data and 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:

[1]

$$Br = 2.30*(1 + 2.30\sigma_r^2/2)*SES_{total},$$

where $SES_{total} = (F_{K,1997}*A_{1997} + F_{K,1999}*A_{1999})^{-1}$

- this result holds for either a Bayesian or a Classical viewpoint [2] and can also be found in the 2008 PDG [3].

[1] R.D. Cousins and V.L. Highland, ***Incorporating Systematic Uncertainties into an Upper Limit,***NIM A320 (1992), 331-335.

[2] 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.

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

- Using $F_{K,1997} = 3.23 \times 10^{11}$, $F_{K,1999} = 4.10 \times 10^{11}$ and σ_r^2, one finds the following upper limits at 90% CL:

Preliminary!!!

$$Br(K_L \to \pi^0\pi^0\mu^+\mu^-) < 8.63 \times 10^{-11}$$

$$Br(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) < 9.44 \times 10^{-11}$$

Compare with:

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

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

Preliminary Conclusions and Future Plans

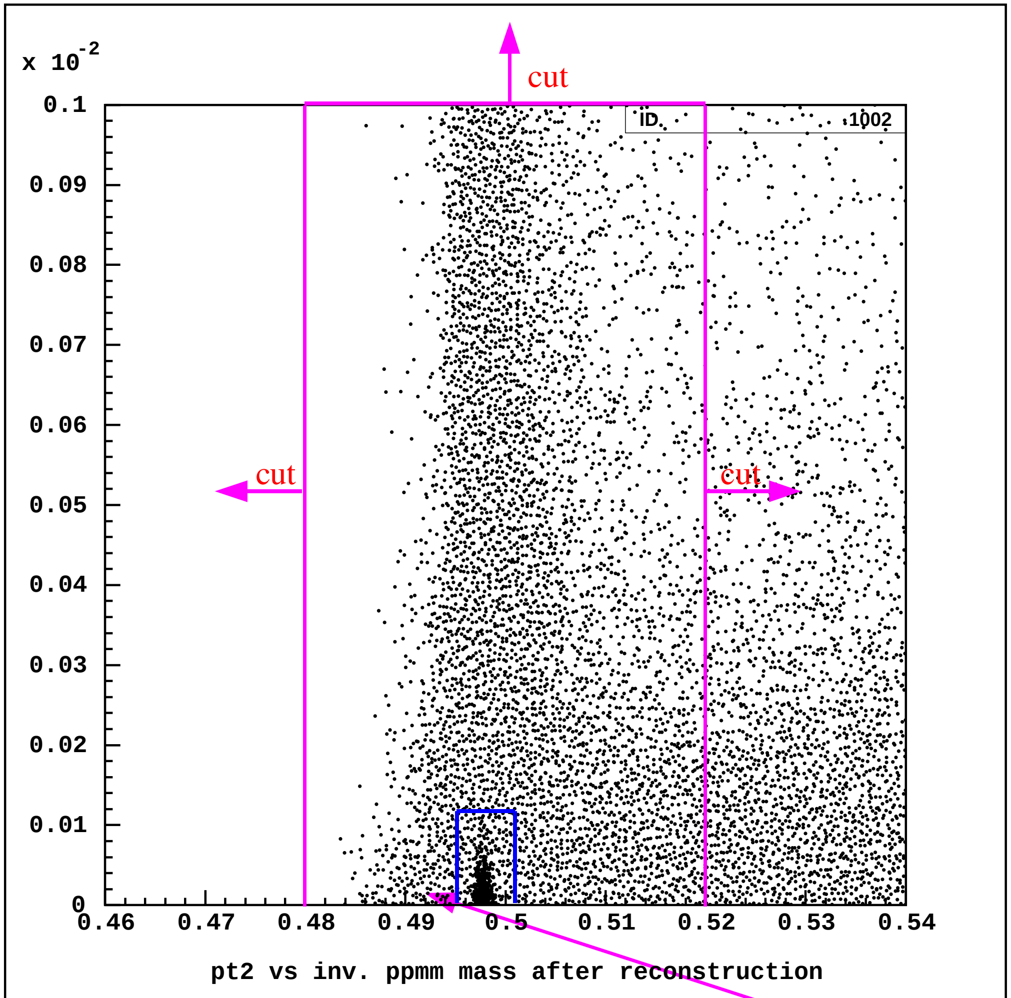
- the preliminary upper limit for $Br(K_L \rightarrow \pi^0\pi^0X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-)$ is roughly two orders of magnitude less than the theoretical prediction of the same decay with a pseudoscalar X^0.

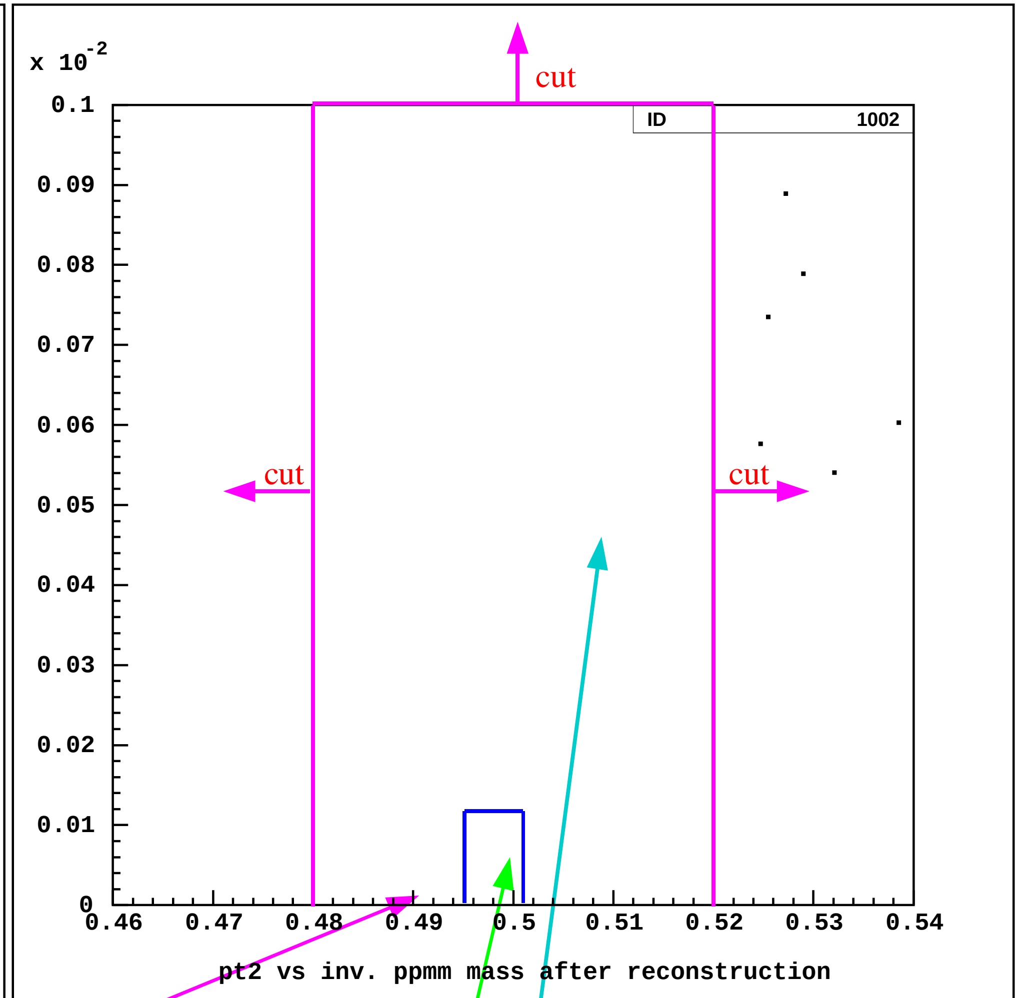
- based on these preliminary results, the pseudoscalar X^0 candidate has been ruled out as an explanation for the neutral boson X^0 observed by HyperCP. However, an axial vector X^0 candidate has not been ruled out.

~ Backup Slides ~

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

$p_T^2 \leq$ 130 MeV^2

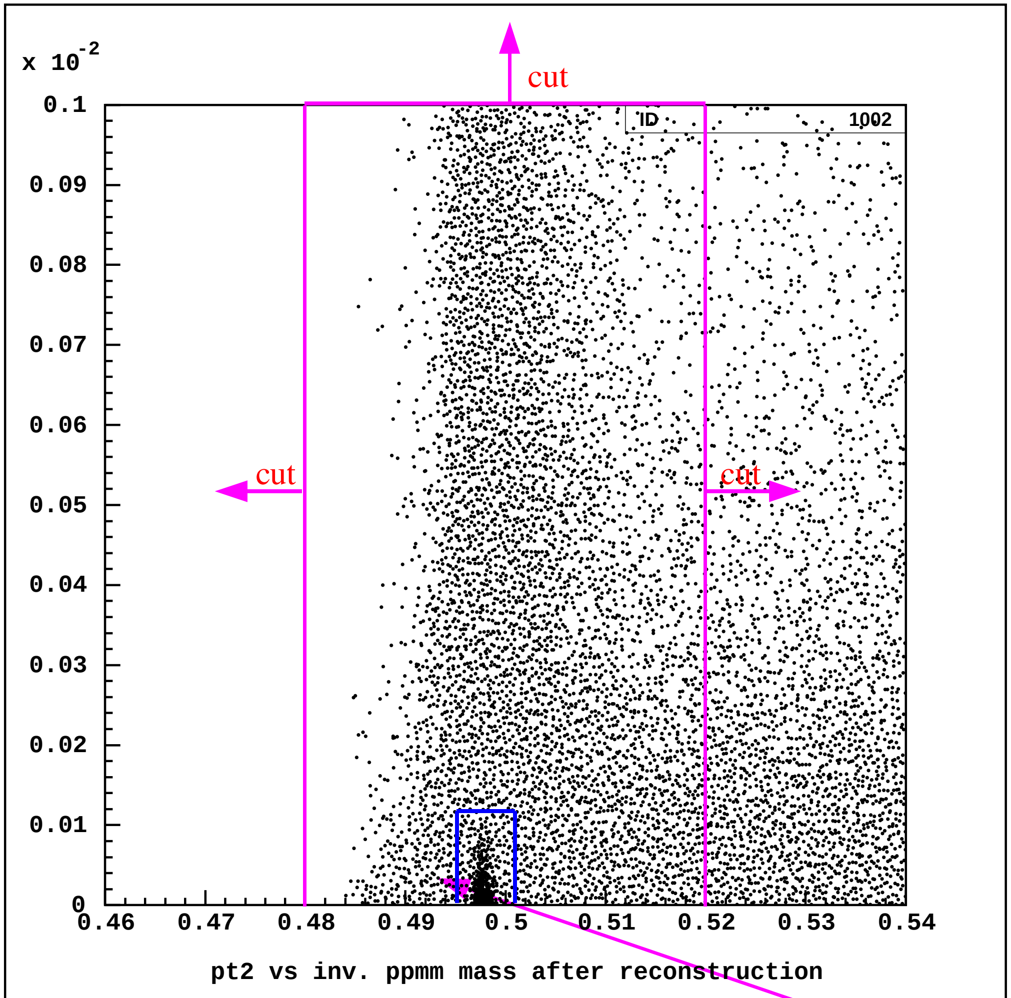
Signal box for MC is open, but for Data remains closed!

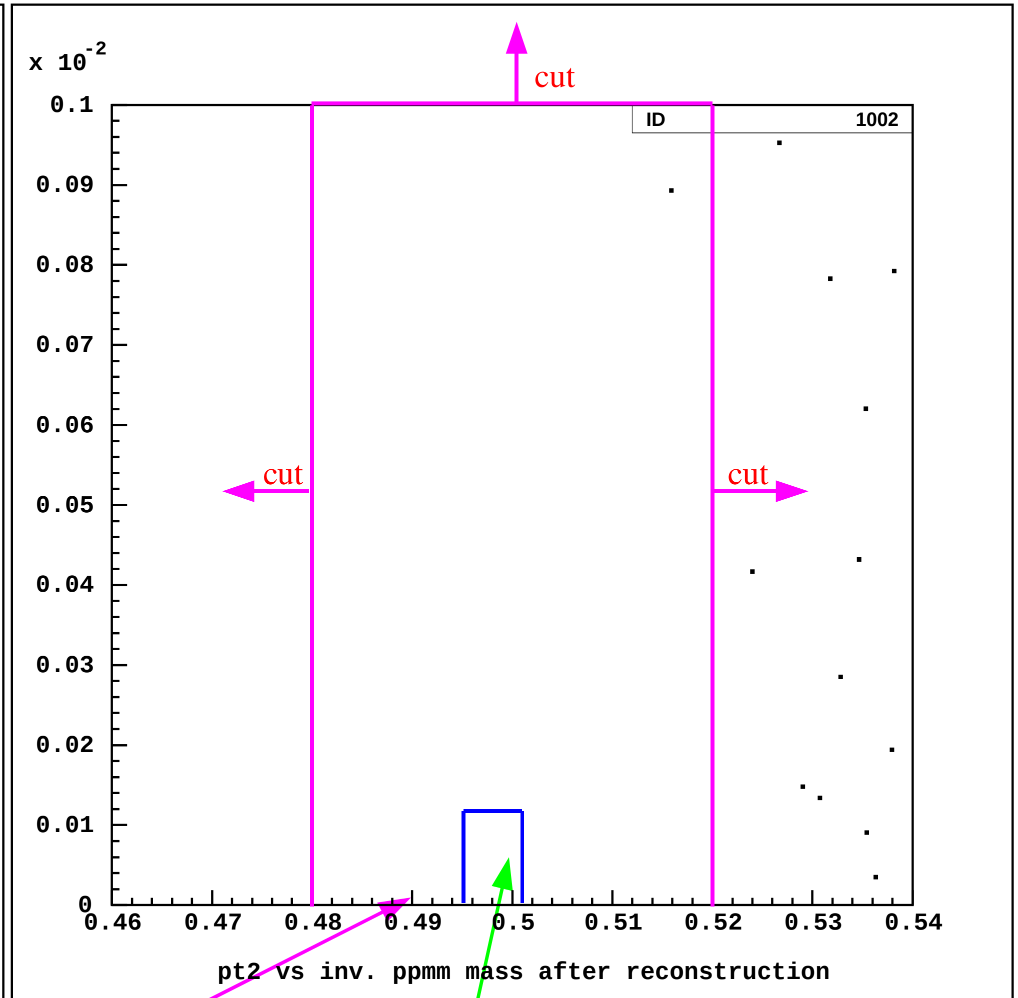
*$K^0_{\mu 4}$ is the most dangerous bkgd, but is not really so dangerous.

According to MC, no $K^0_{\mu 4}$ events in the signal box.

Cut on P_T^2 vs. Inv. K_L Mass

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





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

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

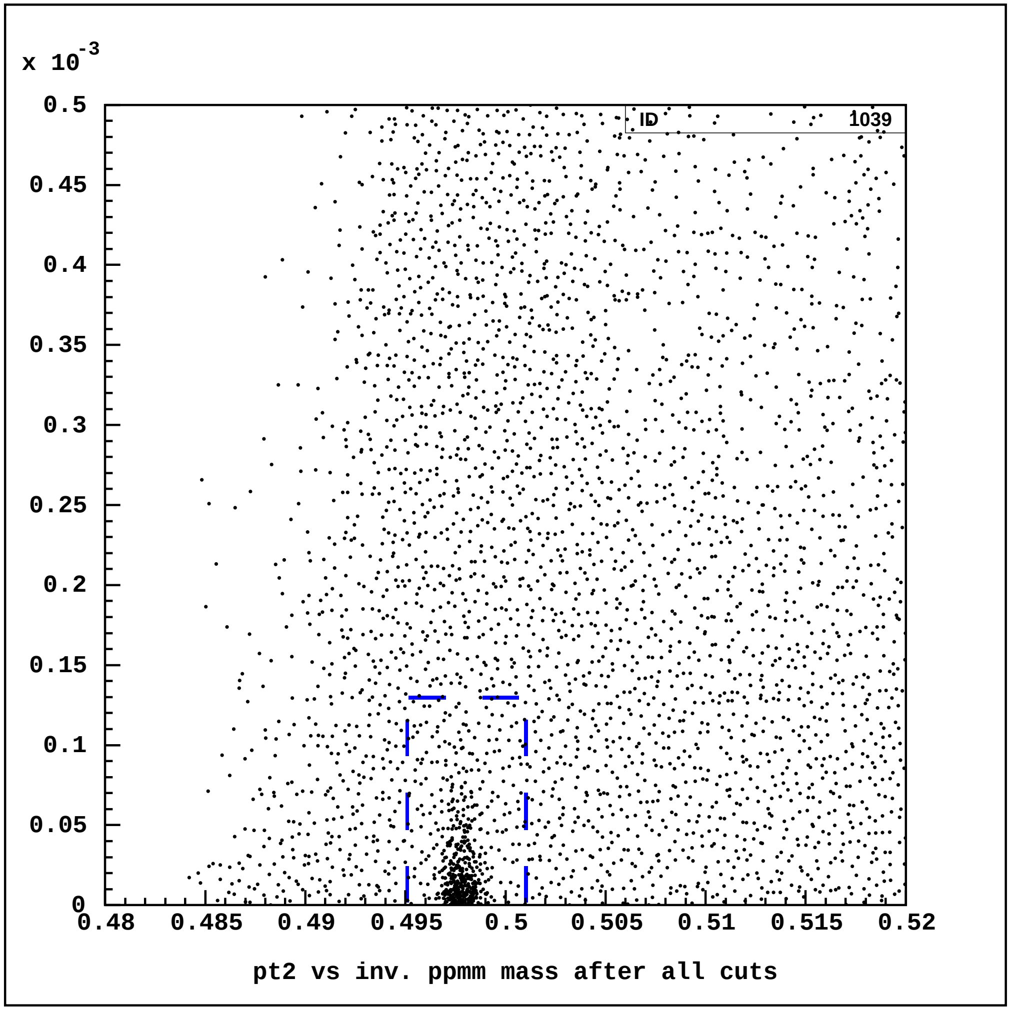
~ Box Dimensions ~

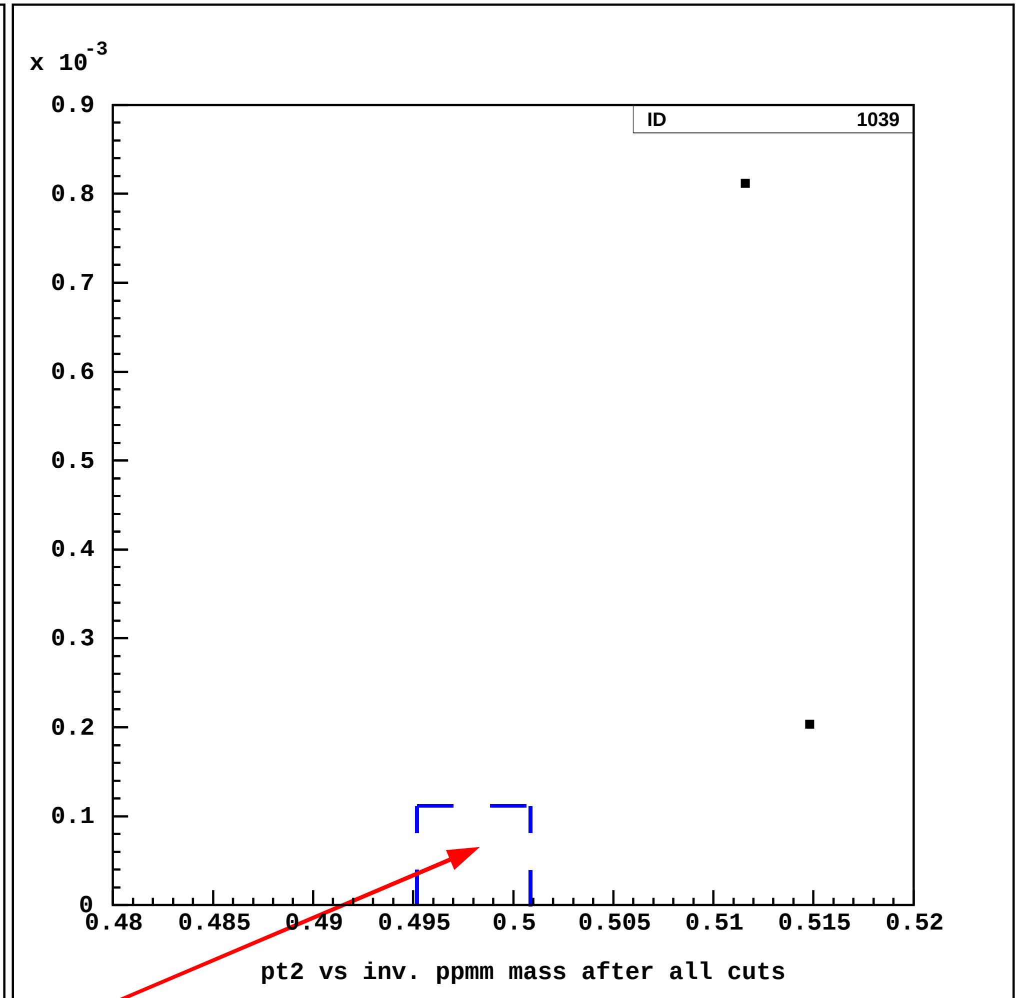
495 MeV $\leq M_{\gamma\gamma\gamma\gamma\mu\mu} \leq$ 501 MeV
$p_T^2 \leq$ 130 MeV^2

Signal box for MC is open, but for Data remains closed!

According to MC, no $K^0_{\mu 4}$ events in the signal box.

Opening of the 1999 K_L Signal Box!





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

~ Box Dimensions ~

495 MeV ≤ $M_{\gamma\gamma\gamma\gamma\mu\mu}$ ≤ 501 MeV

$p_T^2 \leq 130$ MeV^2

K_L Signal Box Opened and is EMPTY!

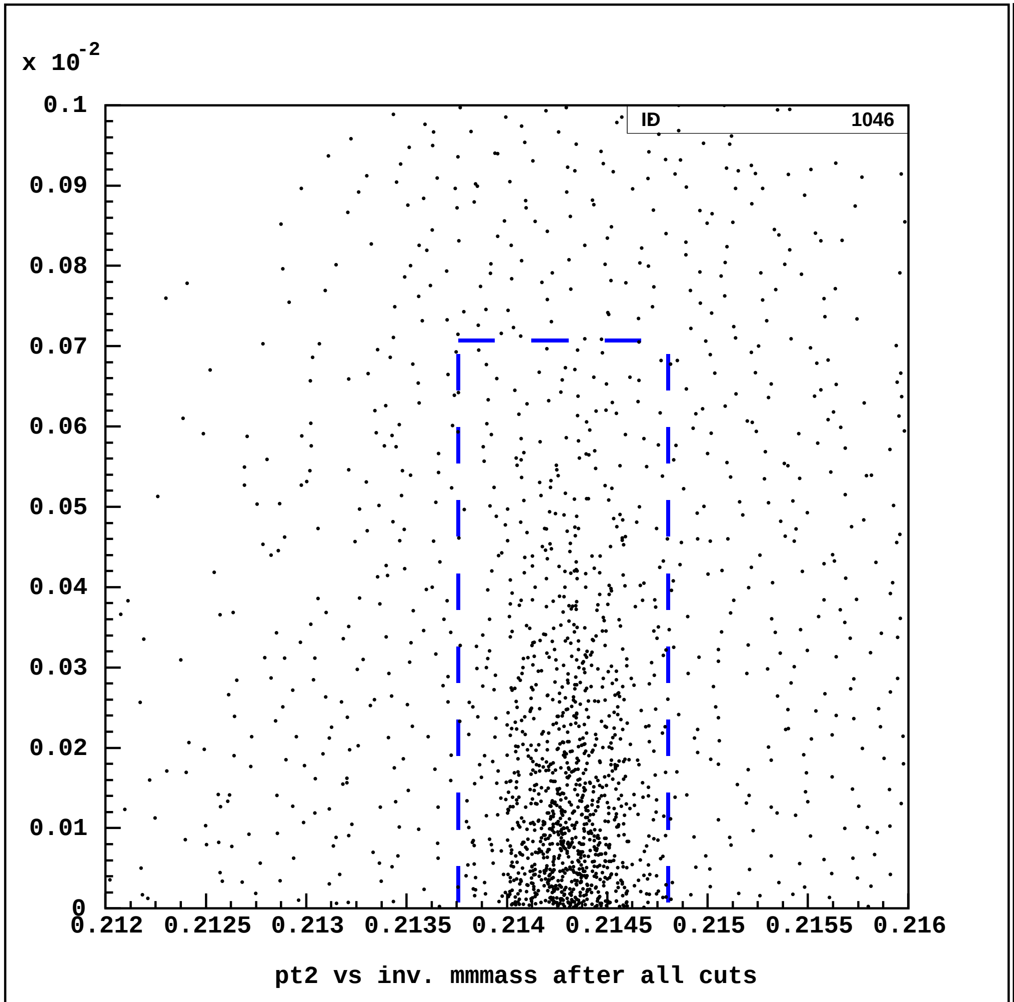
1999 KTeV Data

~ Box Dimensions ~

495 MeV ≤ $M_{\gamma\gamma\gamma\gamma\mu\mu}$ ≤ 501 MeV

$p_T^2 \leq 130$ MeV^2

Opening of the 1999 X^0 Box!

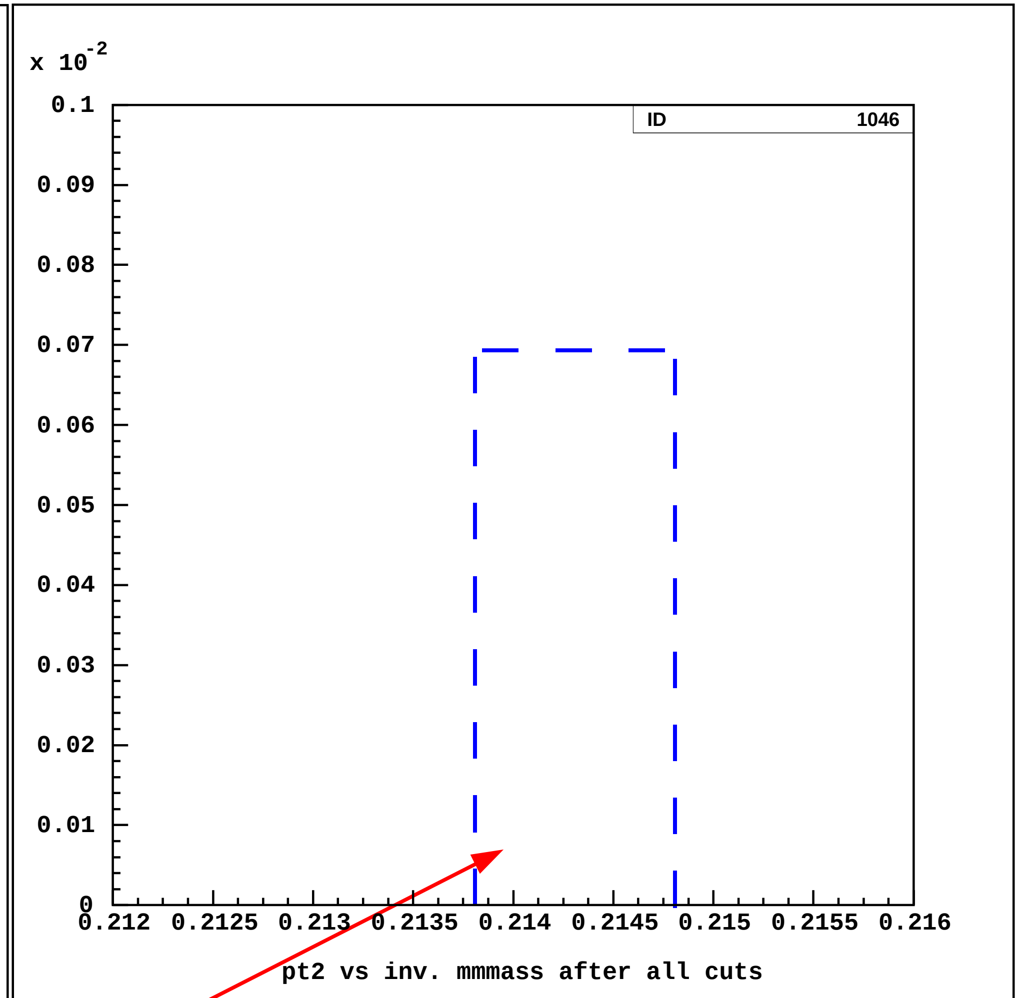


1999 $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ MC

~ Box Dimensions ~

213.8 MeV ≤ $M_{\mu\mu}$ ≤ 214.8 MeV

$p_T^2 \leq 700$ MeV^2



1999 KTeV Data

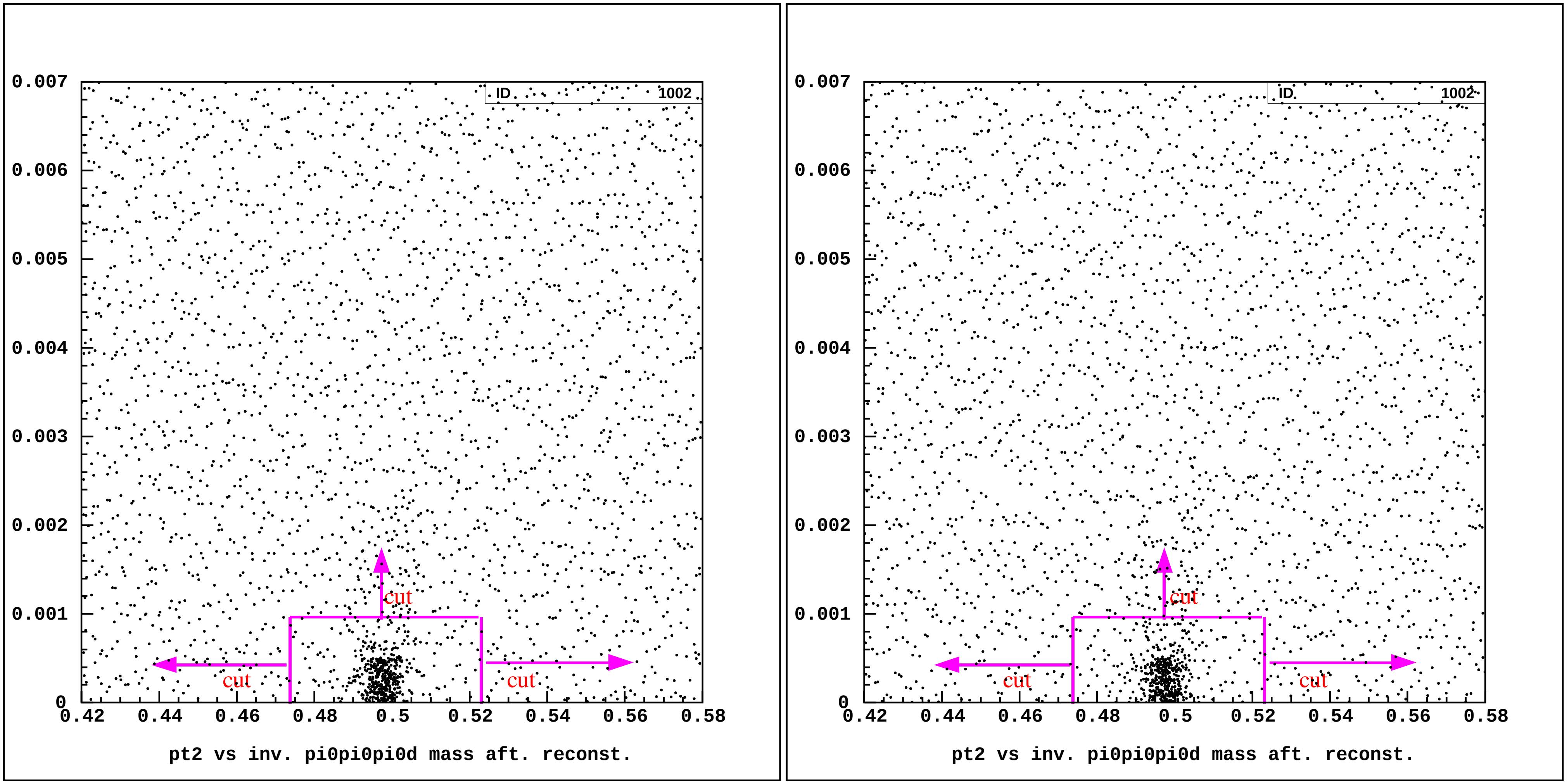
~ Box Dimensions ~

213.8 MeV ≤ $M_{\mu\mu}$ ≤ 214.8 MeV

$p_T^2 \leq 700$ MeV^2

X^0 Signal Box Opened and is EMPTY!

1997 Normalization Mode ($K_L \to \pi^0\pi^0\pi^0_D$)



1997 $K_L \to \pi^0\pi^0\pi^0_D$ MC

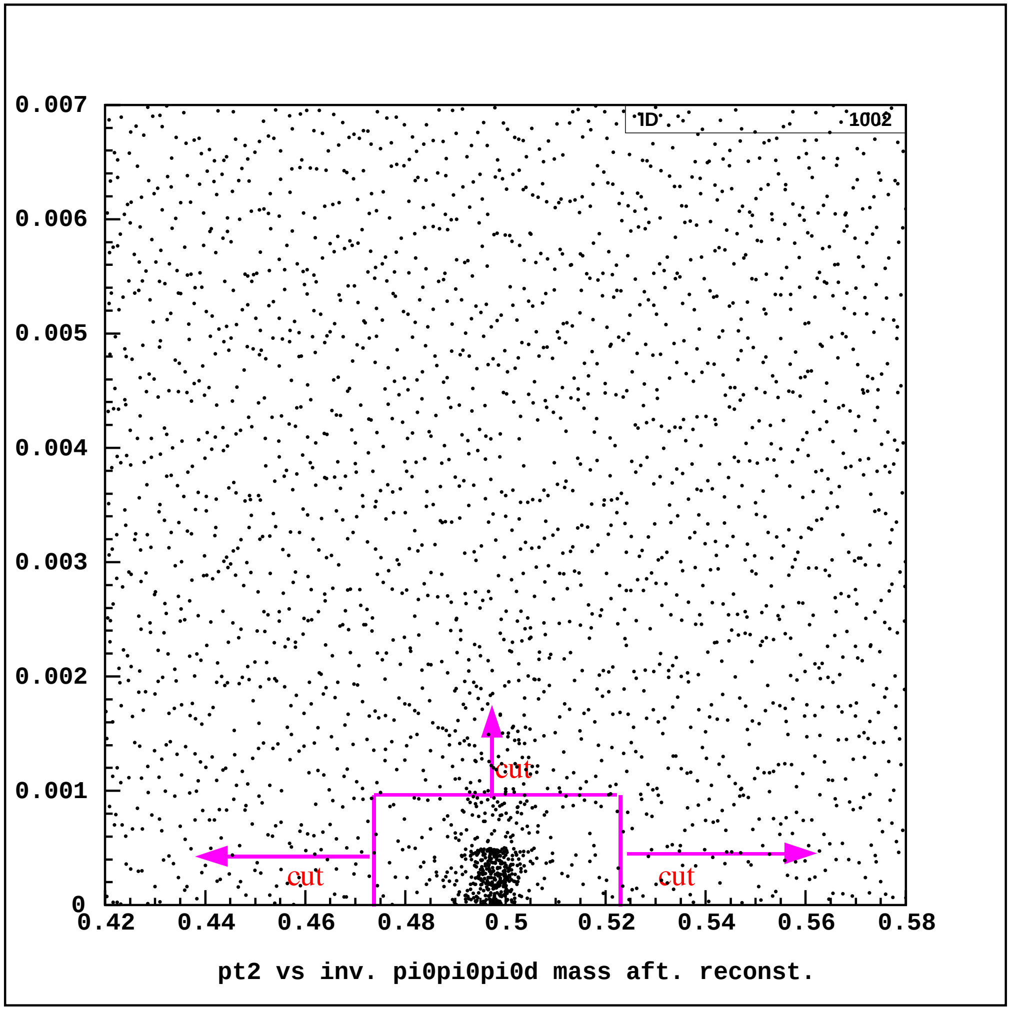
1997 KTeV Data

~ Initial $K_L \to \pi^0\pi^0\pi^0_D$ Analysis Cuts ~

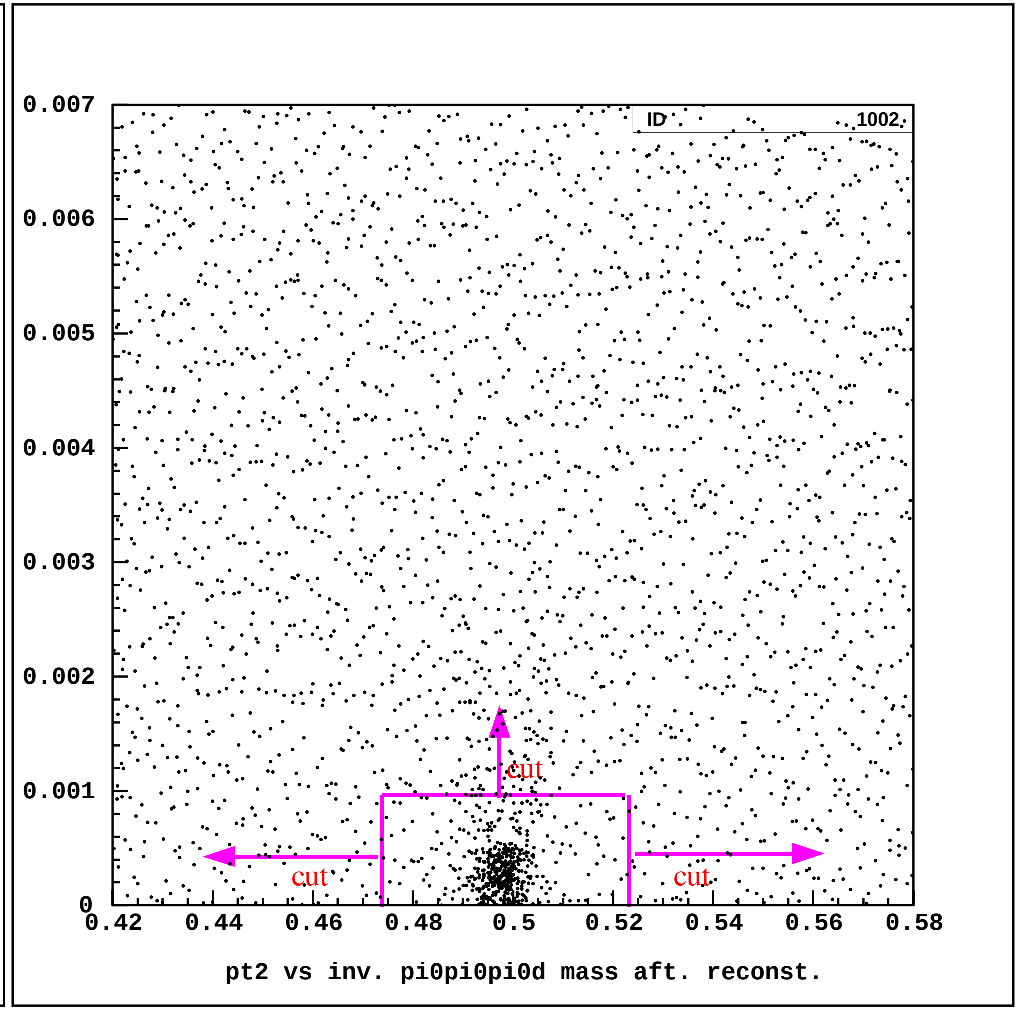
473 MeV $\leq M_{\gamma\gamma\gamma\gamma ee} \leq$ 523 MeV

$p_T^2 \leq 0.001$ GeV^2

1999 Normalization Mode ($K_L \to \pi^0\pi^0\pi^0_D$)



1999 $K_L \to \pi^0\pi^0\pi^0_D$ MC



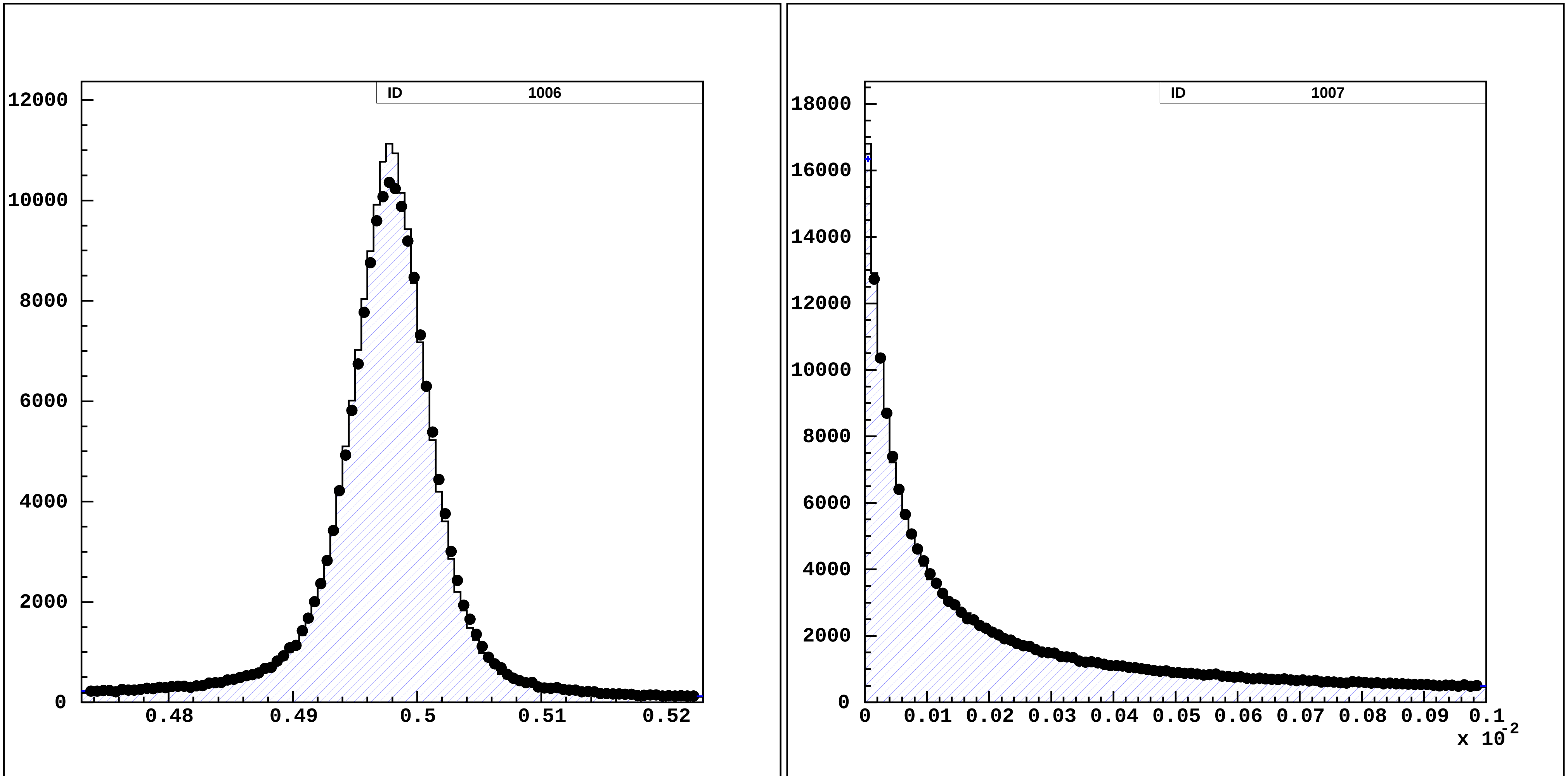
1999 KTeV Data

~ Initial $K_L \to \pi^0\pi^0\pi^0_D$ Analysis Cuts ~

473 MeV $\leq M_{\gamma\gamma\gamma\gamma ee} \leq$ 523 MeV

$p_T^{\,2} \leq 0.001$ GeV^2

1999 $K_L \to \pi^0\pi^0\pi^0_D$ Inv. Mass and P_T^2 After All Cuts



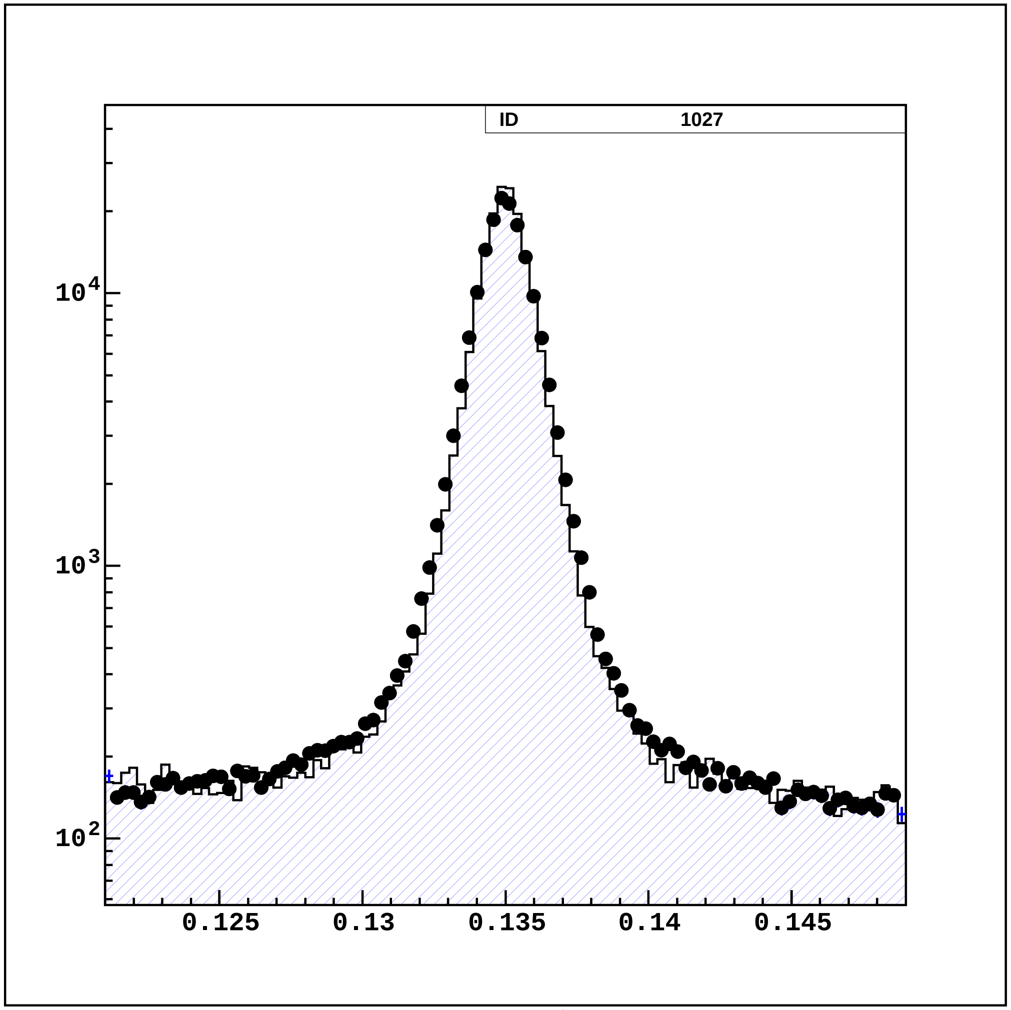
1999 $\pi^0\pi^0\pi^0_D$ Inv. Mass

1999 $\pi^0\pi^0\pi^0_D$ P_T^2

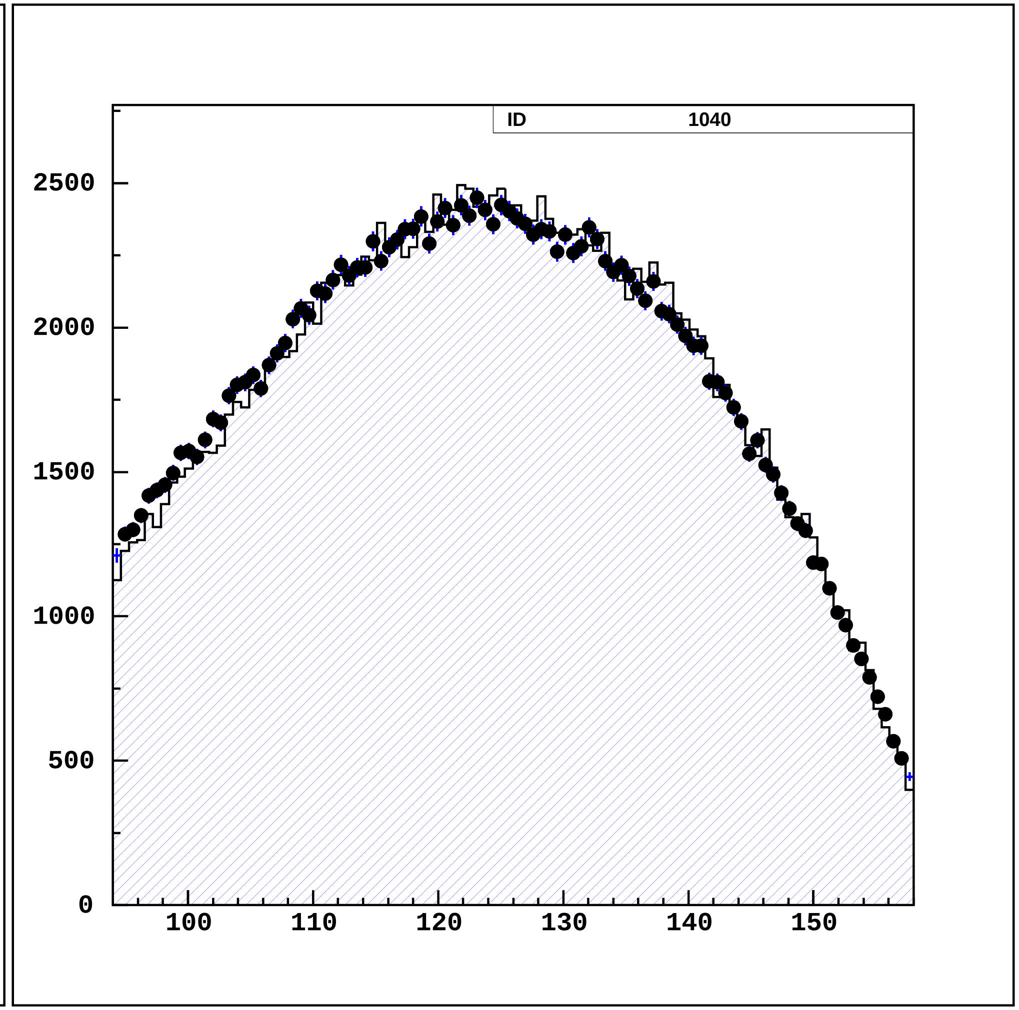
● = Data

□ = MC

1999 $K_L \to \pi^0\pi^0\pi^0_D$ 1st π^0 Mass and Zvtx After All Cuts



1999 $\pi^0\pi^0\pi^0_D$ 1^{st} π^0 Mass



1999 $\pi^0\pi^0\pi^0_D$ Zvtx

● = Data

□ = MC