KTEV
Kaons at the Tevatron

UNIVERSITY of VIRGINIA

Search for a New Pseudoscalar Particle in the Rare Decay $K_L \to \pi^0 \pi^0 \mu^+ \mu^-$

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Rencontres de Moriond
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What Is The KTeV Experiment?

- KTeV stands for "Kaons at the TeVatron" and consists of two fixed target experiments (E799 and E832) located at Fermilab (on the Neutrino-Muon fixed-target beamline).

- Data was collected in 1996-1997 and 1999-2000; these two runs are referred to as the *'97* and *'99* runs respectively. (Note: the detector and the Tevatron were updated in the intermediary period.)

- the goal of E799 was to detect and measure rare K_L decays, especially CP-violating processes.

- the main purpose of E832 was to measure the *direct CP violation* parameter $Re(\varepsilon'/\varepsilon)$ at the 10^{-4} level.

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)

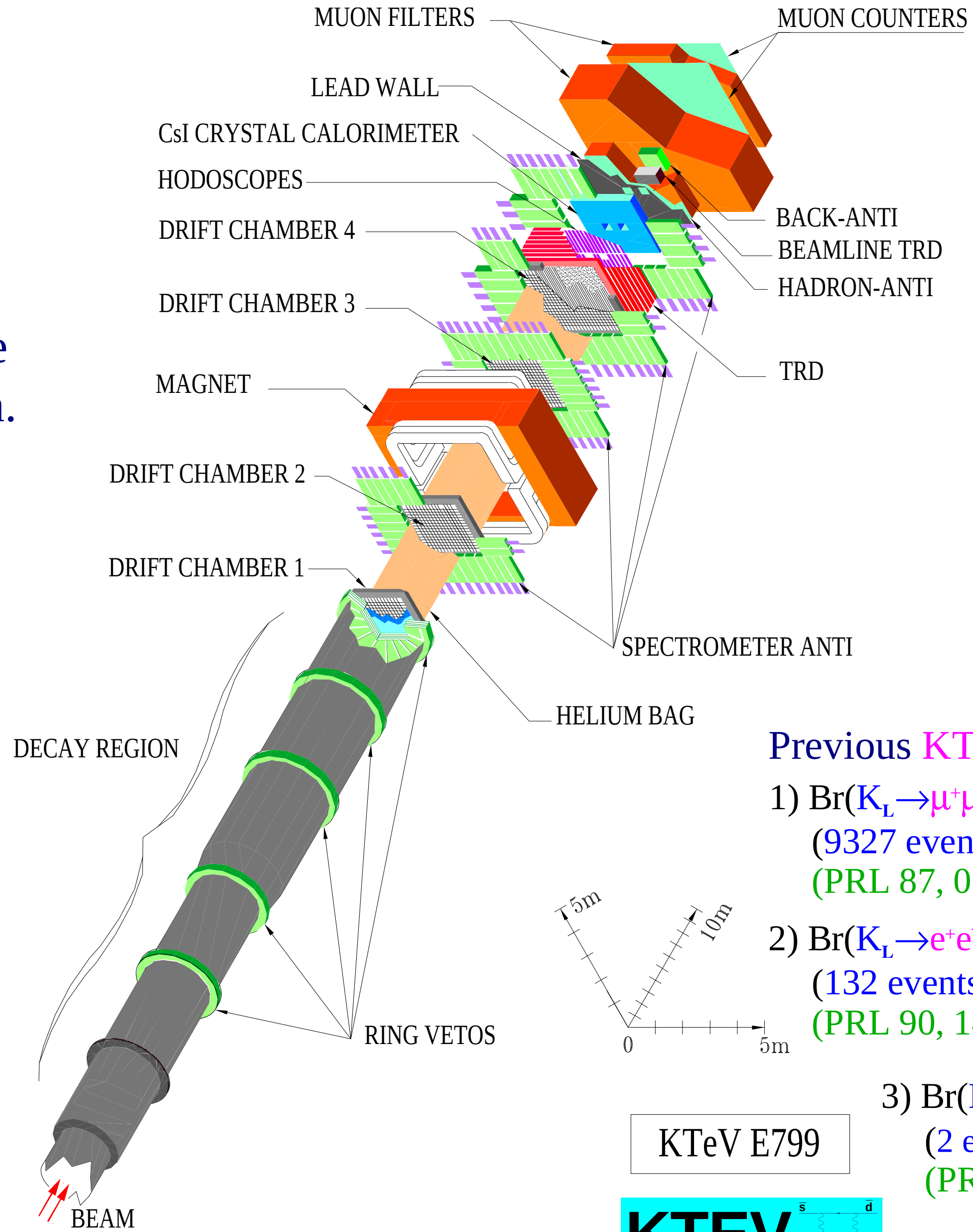
University of Wisconsin (Madison, Wisconsin)

The KTeV Detector

KTeV's coordinate system is:

1) right-handed

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



Previous KTeV Dimuon Results:

1) $Br(K_L \to \mu^+\mu^-) = (3.62 \pm 0.04_{stat} \pm 0.08_{syst}) \times 10^{-7}$
(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))

KTeV E799

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))

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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:

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

(PRL 94, 021801 (2005))

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

3 events observed!

- 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 $Br(\Sigma^+ \to pX^0 \to p\mu^+\mu^-)$:

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

- 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:

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

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

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

News from the World of $K_L \rightarrow \pi^0\pi^0X^0$

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

$$Br(K_L \rightarrow \pi^0\pi^0X^0 \rightarrow \pi^0\pi^0\gamma\gamma) = 1.2 \times 10^{-4}$$ (Phys. Rev. D73, 035002 (2006))

- E391a (KEK) reports an upper limit on the branching ratio for $K_L \rightarrow \pi^0\pi^0X^0$, where $X^0 \rightarrow \gamma\gamma$:

$$Br(K_L \rightarrow \pi^0\pi^0X^0 \rightarrow \pi^0\pi^0\gamma\gamma) < 2.4 \times 10^{-7}$$ (arXiv:0810.4222v2 [hep-ex] 24 Oct 2008)

- in this study, it was assumed that the X^0 has a mass of 214.3 MeV and decays immediately to two photons.

- 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))

→ Many people eagerly await our result!

Status of $K_L \to \pi^0\pi^0\mu^+\mu^-$ 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! An Upper Limit for virtual photon and X^0 channels has been obtained.

  ~ completed identification and estimation of signal mode background.

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

  ~ usage of a constant matrix element in the $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ MC generation. Will eventually explore how a momentum dependent matrix element affects the acceptance.

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

-Crunch Cuts-

$K_L \to \pi^0 \pi^0 \mu^+ \mu^-$ Crunch Cut*	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 μplanes ≥ 1	0.980	0.999	0.989	0.999
# clus (not assoc. w/tracks) = 4	0.444	0.964	0.471	0.970
$\|M_{rec.pi0} - M_{pi0}\| \leq 15$ MeV	0.437	0.967	0.443	0.973
$90.0 \text{ m} \leq Z_{VTX} \leq 160.0$ 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

* = *cuts 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 Cuts-

$K_L \to \pi^0\pi^0\mu^+\mu^-$ Analysis Cut*	γ^* Signal MC (1997)	X^0 Signal MC (1997)	γ^* Signal MC (1999)	X^0 Signal MC (1999)
480 MeV $\leq M_K \leq$ 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) $\leq$ 1.0 GeV	0.974	0.974	0.966	0.965
$P_{track} \leq$ 7.0 GeV	0.999	0.999	0.994	0.995
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq$ 9 MeV	0.997	0.997	0.997	0.997
$M_{\mu\mu} \leq$ 232 MeV	0.999	0.999	0.999	0.999
495 MeV $\leq M_K \leq$ 501 MeV & $p_T^2 \leq 0.00013$ GeV^2/c^2	0.901	0.891	0.906	0.902
213.8 MeV $\leq M_{\mu\mu} \leq$ 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

* = cuts listed in chronological order

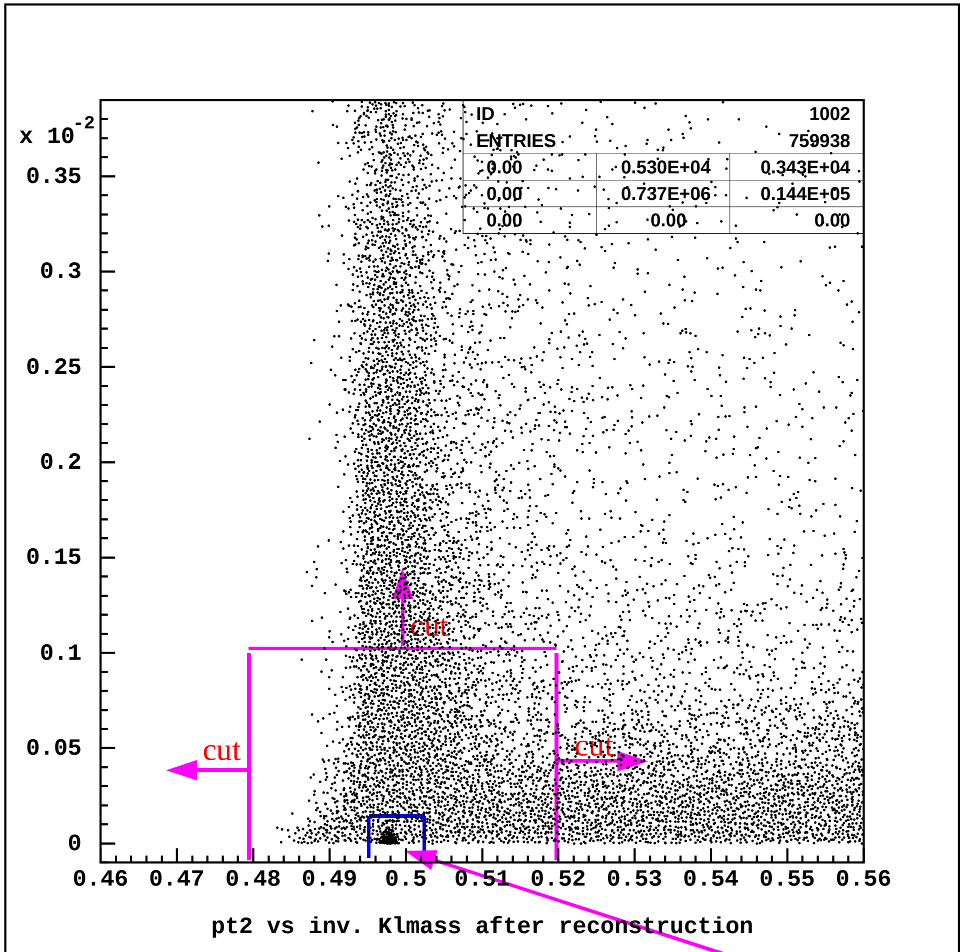
Summary of Backgrounds

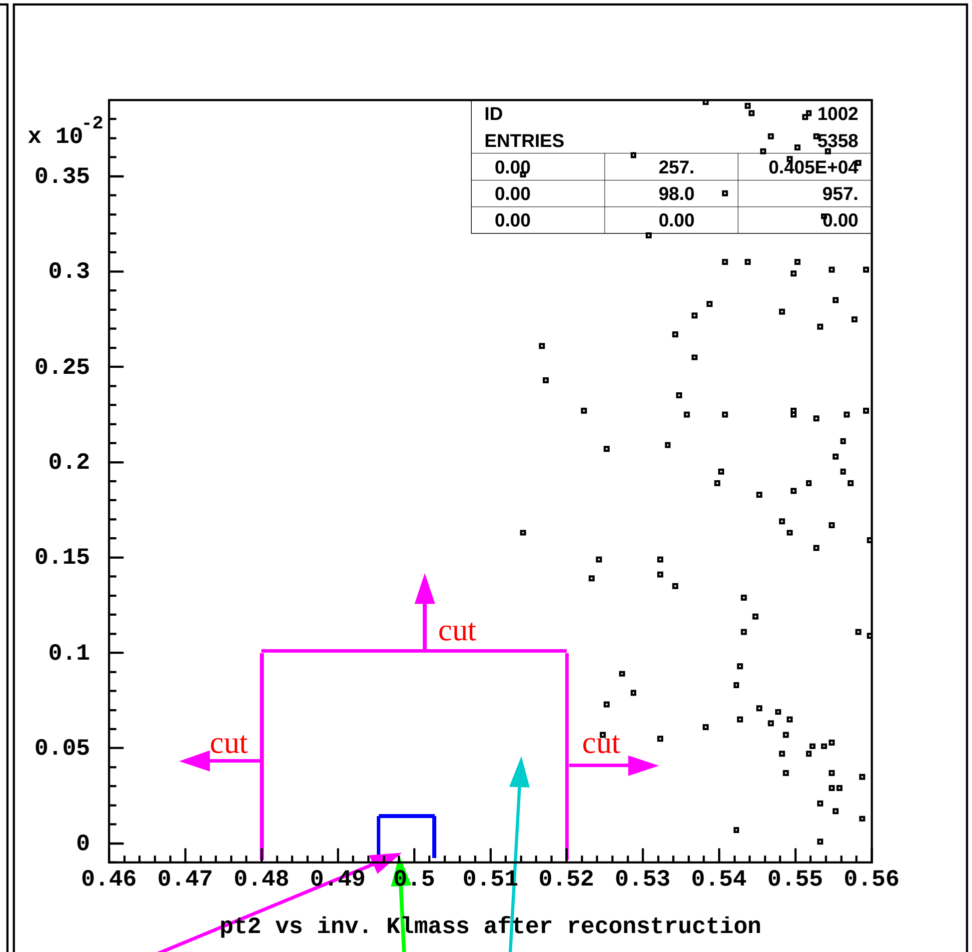
No background survive analysis cuts!!!

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

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

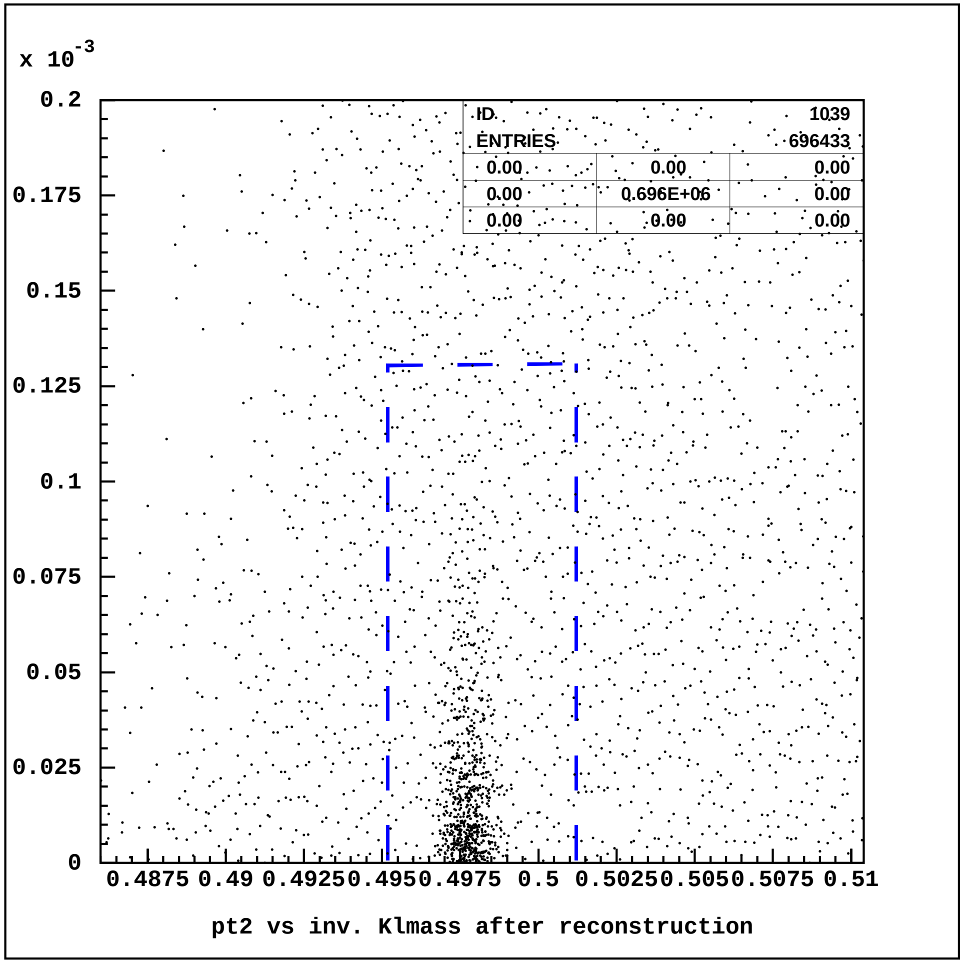
$p_T^2 \leq 130$ MeV^2

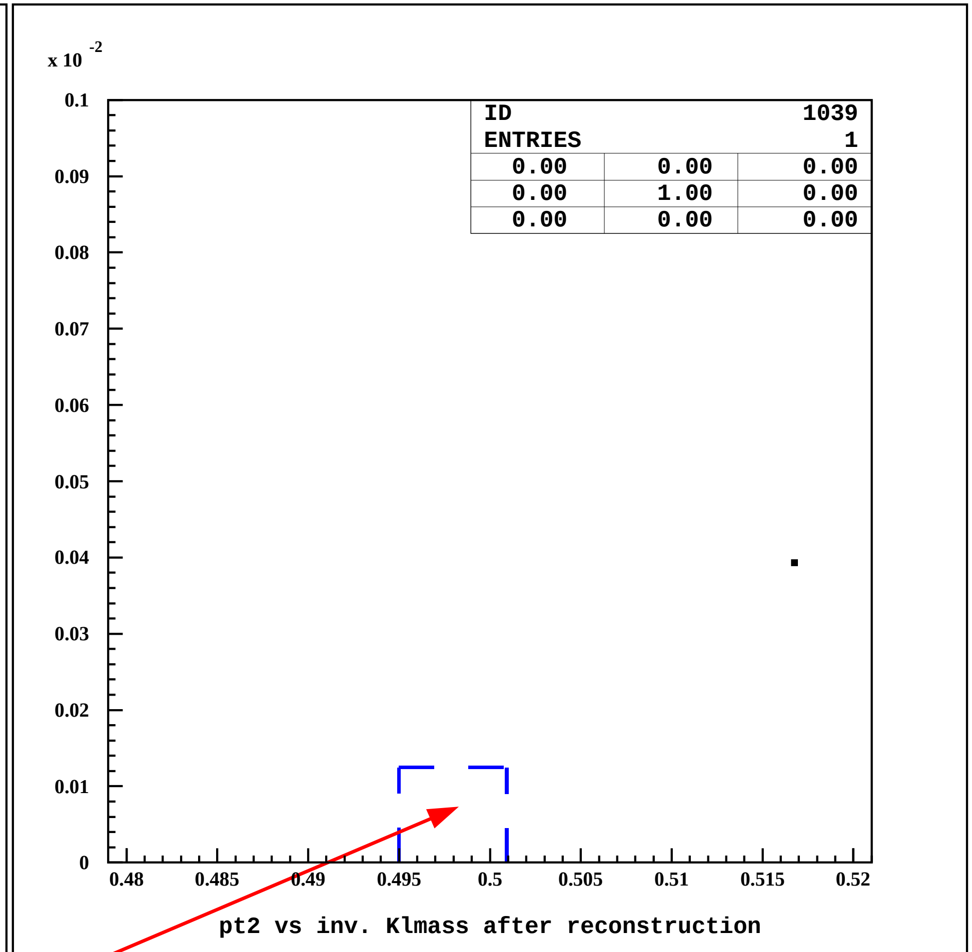
Signal box for MC is open, but for Data remains closed!

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

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

Opening of the 1997 K_L Signal Box!





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

~ Box Dimensions ~

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

$p_T^2 \le 130$ MeV^2

K_L Signal Box Opened and is EMPTY!

EMPTY = No Signal Events AND No Bkgd Events!

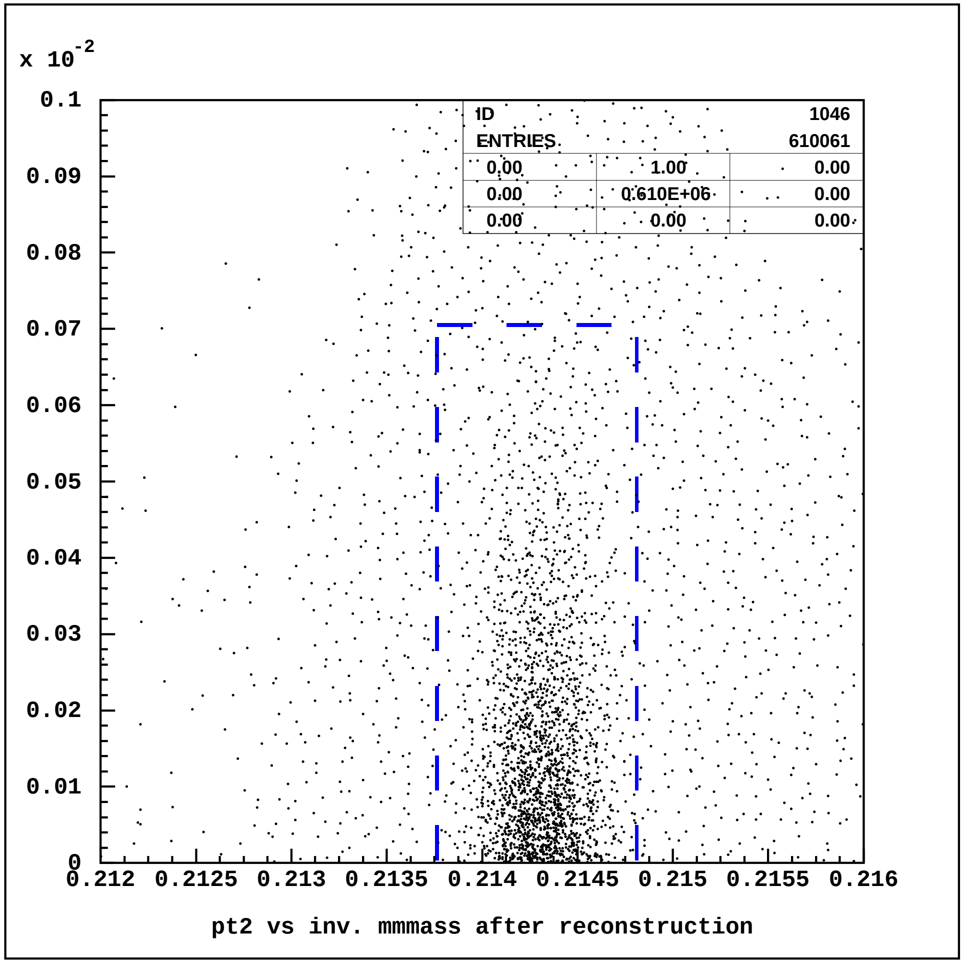
1997 KTeV *Data*

~ Box Dimensions ~

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

$p_T^2 \le 130$ MeV^2

Opening of the 1997 X^0 Box!

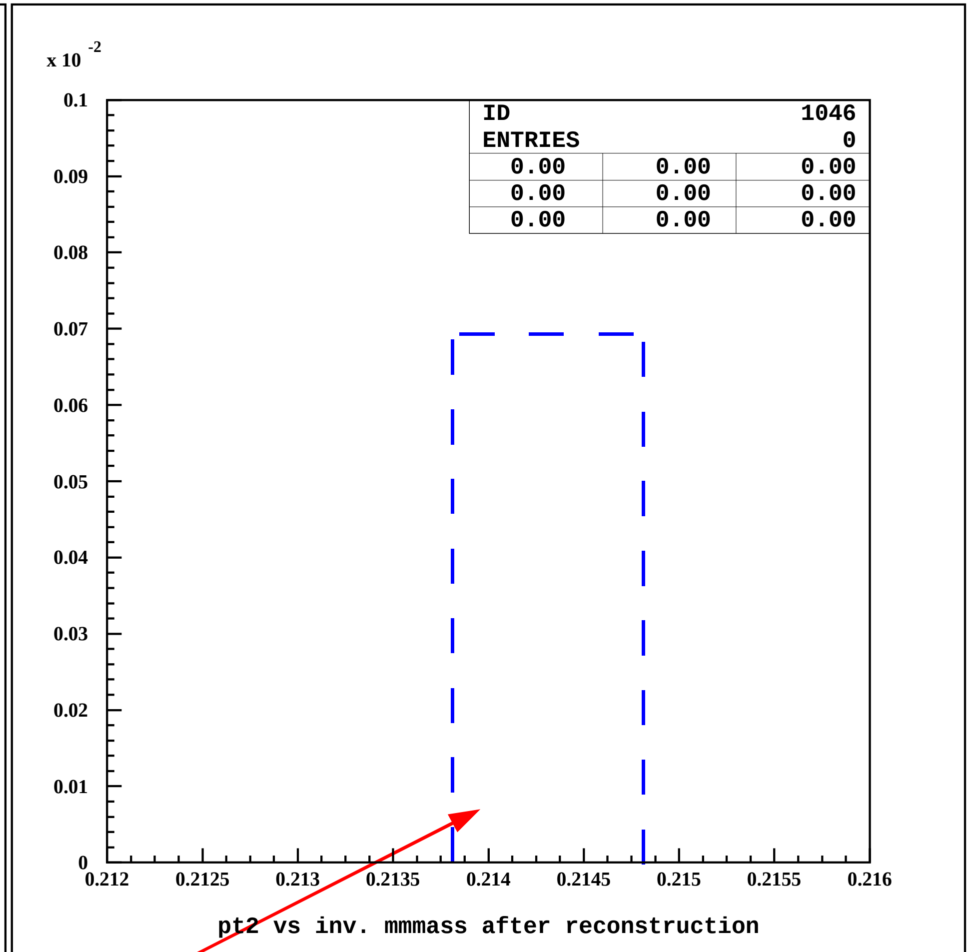


1997 $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ MC

~ Box Dimensions ~

213.8 MeV ≤ $M_{\mu\mu}$ ≤ 214.8 MeV

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



1997 KTeV Data

~ Box Dimensions ~

213.8 MeV ≤ $M_{\mu\mu}$ ≤ 214.8 MeV

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

X^0 Signal Box Opened and is EMPTY!

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

Cut*	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
$0.95 \le E_{cl}(track) / p_{track} \le 1.05$	0.679	0.886	0.848	0.851
NHCLUS ≥ 5	0.916	0.967	1.000	0.972
# clus (not assoc. w/tracks) = 5	0.374	0.447	0.999	0.463
$\lvert M_{rec.pi0} - M_{pi0}\rvert \le 15$ MeV	0.066	0.067	0.071	0.072
$90.0 \text{ m} \le Z_{VTX} \le 160.0$ m	0.977	0.985	0.970	0.982
Bad Spill	0.792	0.789	0.934	0.944
$p_T^2 \le 0.06$ GeV^2/c^2	0.928	0.934	0.928	0.937
$473 \text{ MeV} \le M_K \le 523$ MeV	0.471	0.477	0.494	0.504
$p_T^2 \le 0.001$ GeV^2/c^2	0.259	0.255	0.325	0.323
$\lvert M_{rec.pi0} - M_{pi0}\rvert \le 14$ MeV	0.992	0.992	0.993	0.993
$91.0 \text{ m} \le Z_{VTX} \le 159.0$ m	0.999	0.999	0.999	0.999
Total Acceptance	133215 events	0.006%	368184 events	0.013%

Used a precrunched data set!

Beginning of analysis

110,580 events

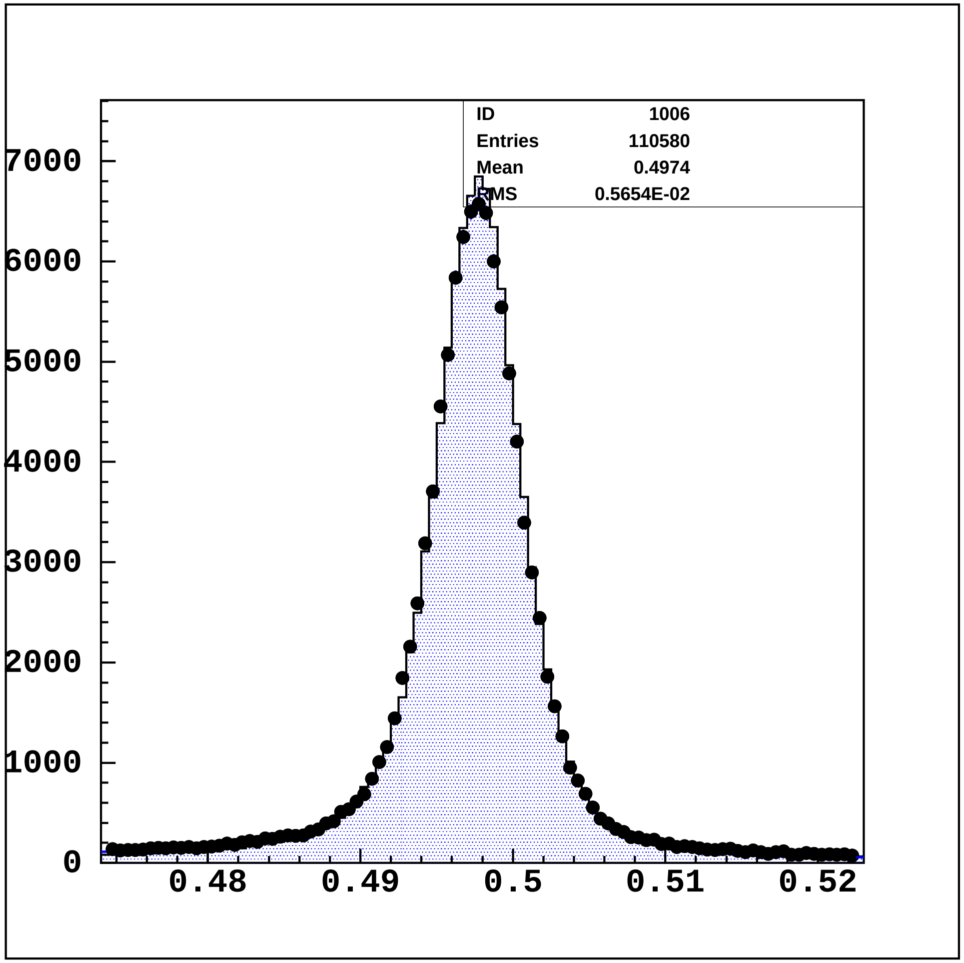
184,766 events

* = *cuts listed in chronological order,*

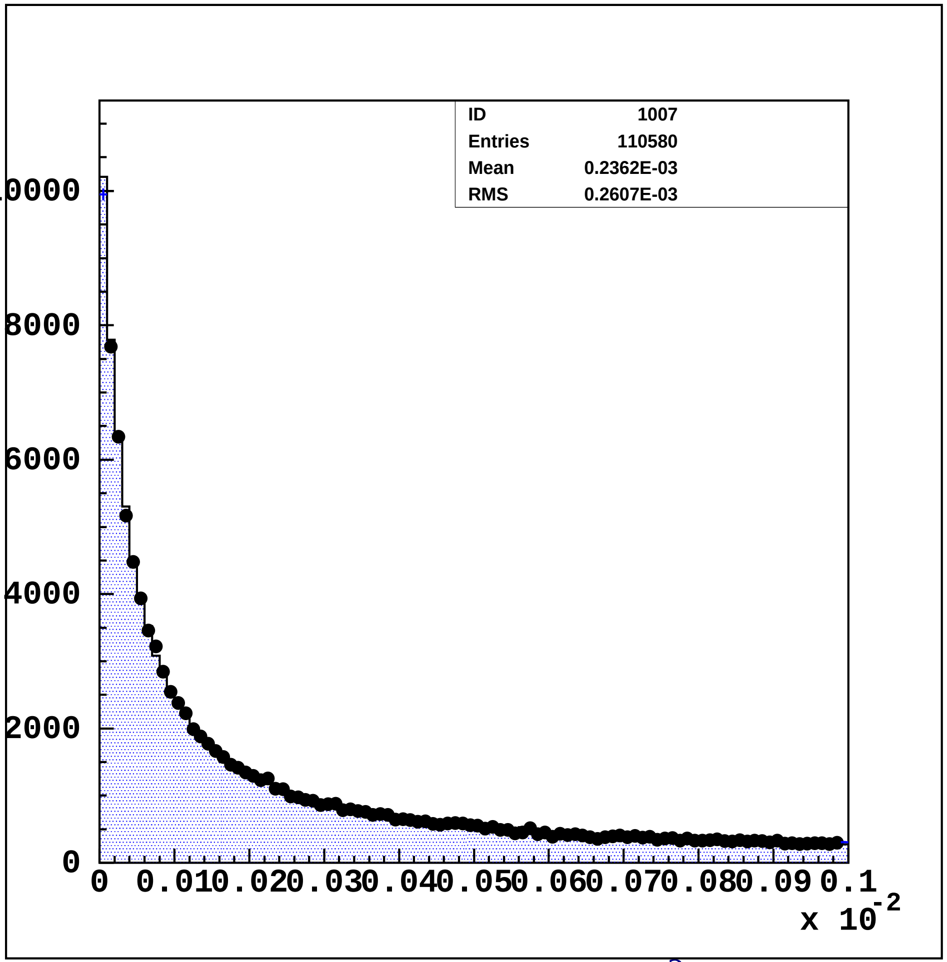
initial # 1997 data events was ~47.2 M (# generated 1999 MC events was ~1.41 G),

initial # 1997 data events was ~50.4 M (# generated 1997 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

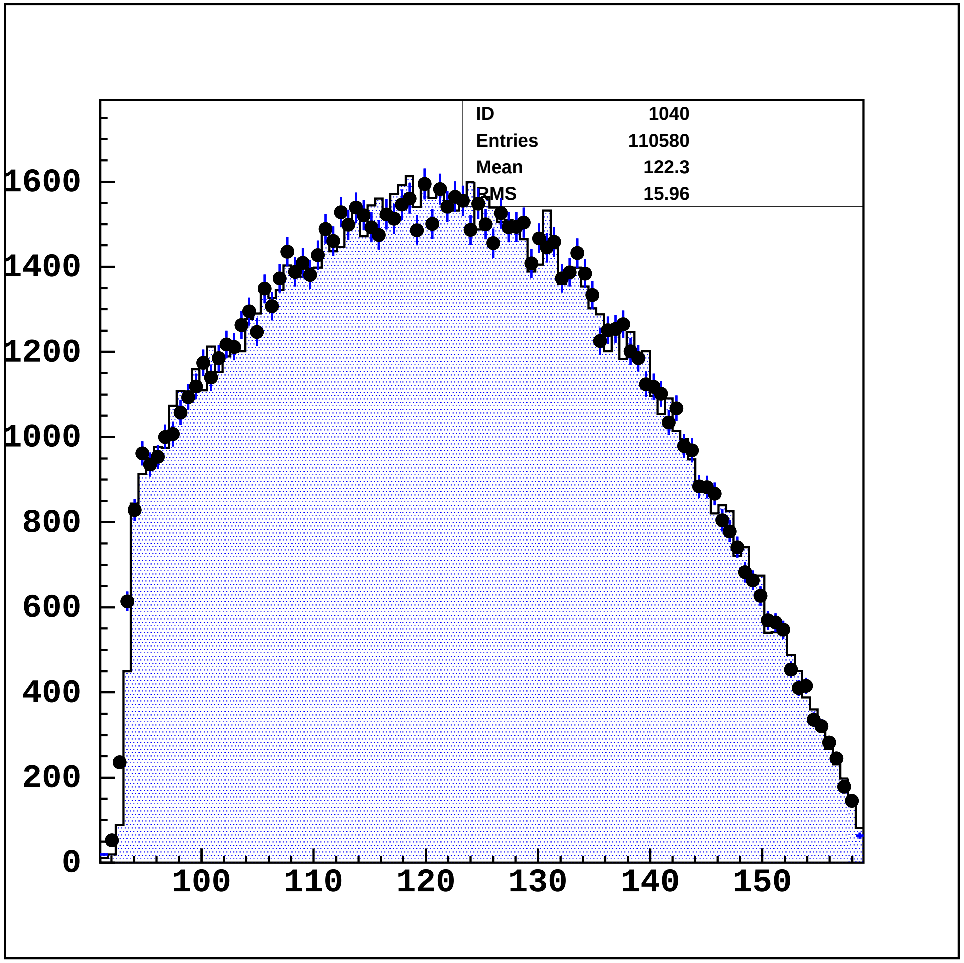


1997 $\pi^0\pi^0\pi^0_D$ P_T^2

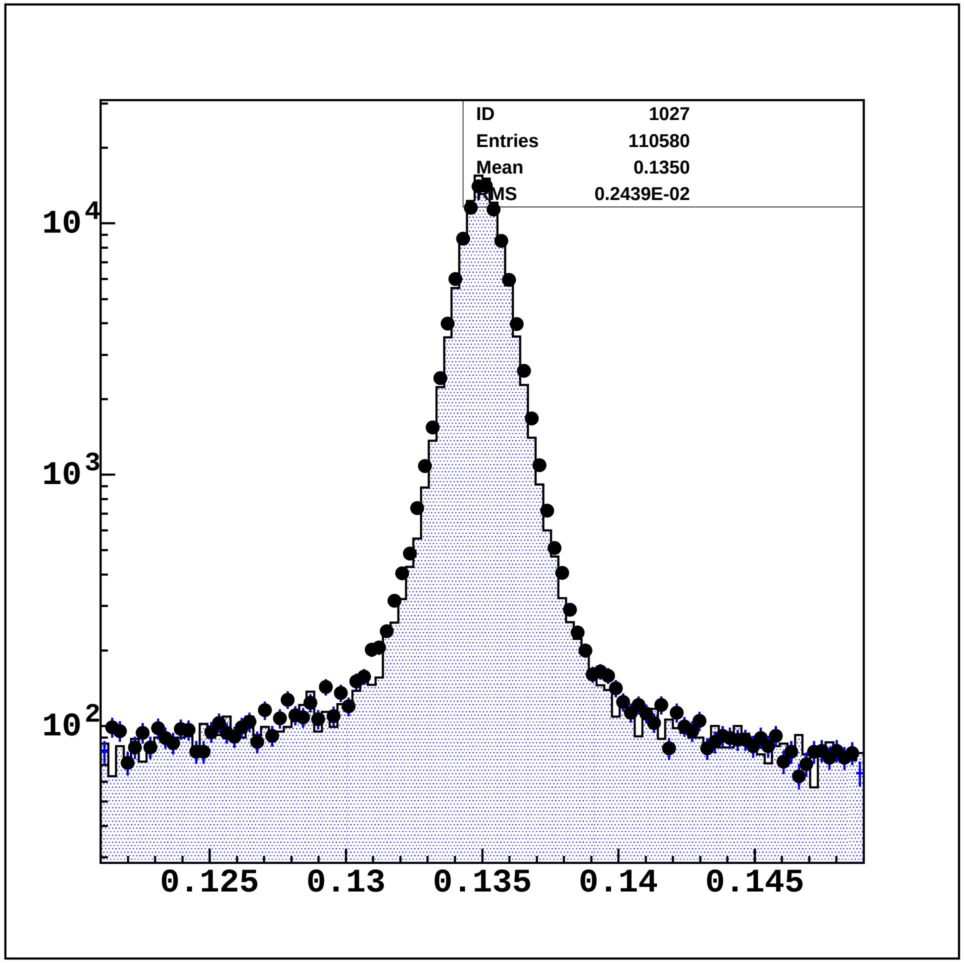
● = Data

□ = MC

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



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



1997 $\pi^0\pi^0\pi^0_D$ 1st π^0 Mass

● = Data

□ = MC

K_L Flux Calculation

$$N_{Norm}^{Data} = F_K \times BR(K_L \to \pi^0 \pi^0 \pi_D^0) \times A_{Norm}, \text{ where } A_{Norm} = \frac{N_{acc}}{N_{aen}}.$$

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

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

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

$$A_{Norm,1997} = \frac{110580}{1842926908} = 6.00 \times 10^{-5} \qquad A_{Norm,1999} = \frac{184766}{1414181218} = 1.31 \times 10^{-4}$$

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

$$N_{Norm,1997}^{Data} = 133215 \text{ events} \qquad N_{Norm,1999}^{Data} = 368184 \text{ events}$$

Putting everything together yields →

$$F_{K,1997} = 3.24 \times 10^{11} \text{ events} \qquad F_{K,1999} = 4.11 \times 10^{11} \text{ events}$$

Acceptance Results

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

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

1997 Acceptance $(K_L \rightarrow \pi^0\pi^0\pi^0_D) = (6.00 \pm 0.02_{stat.}) \times 10^{-5}$

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

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

1999 Acceptance $(K_L \rightarrow \pi^0\pi^0\pi^0_D) = (1.31 \pm 0.003_{stat.}) \times 10^{-4}$

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 ≤ M_K ≤ (523 ± 1) MeV	+0.03% -0.06%	+0.09% -0.11%
$\lvert M_{rec,pi0} - M_{pi0} \rvert \leq (14 \pm 1)$MeV	+0.02% -0.04%	+0.03% +0.02%
(91.0 ∓ 1.0) m ≤ Z_{VTX} ≤ (159.0 ± 1.0) m	+0.02% -0.04%	+0.03% -0.06%
$P_T^2 \leq (1.0 \pm 0.1) \cdot 10^{-3}$ GeV^2	+0.13% +0.02%	+0.13% -0.16%
(0.95 ∓ 0.01) ≤ E/p ≤ (1.05 ± 0.01)	+1.16% - 2.41%	+2.32% - 3.99%
Cracks in µCounting Planes	0.50%	0.50%
Energy Loss in µFilters	0.40%	0.40%
Br($K_L \to \pi^0\pi^0\pi^0$)	0.61%	0.61%
Total Systematic Error from Flux	+1.47% - 2.57%	+2.45% - 4.07%

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

Systematic from P_z still under study!

- 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]

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

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

- 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 $N_{K,1997} = 3.24 \times 10^{11}$, $N_{K,1999} = 4.11 \times 10^{11}$ and σ_r^2, one finds the following upper limits at 90% CL:

Preliminary!!!

(Systematic Error from P_z still under study)

$$Br(K_L \to \pi^0\pi^0\mu^+\mu^-) < 8.60 \times 10^{-11}$$

$$Br(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) < 9.41 \times 10^{-11}$$

Compare with:

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

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

Preliminary Conclusions and Future Plans

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

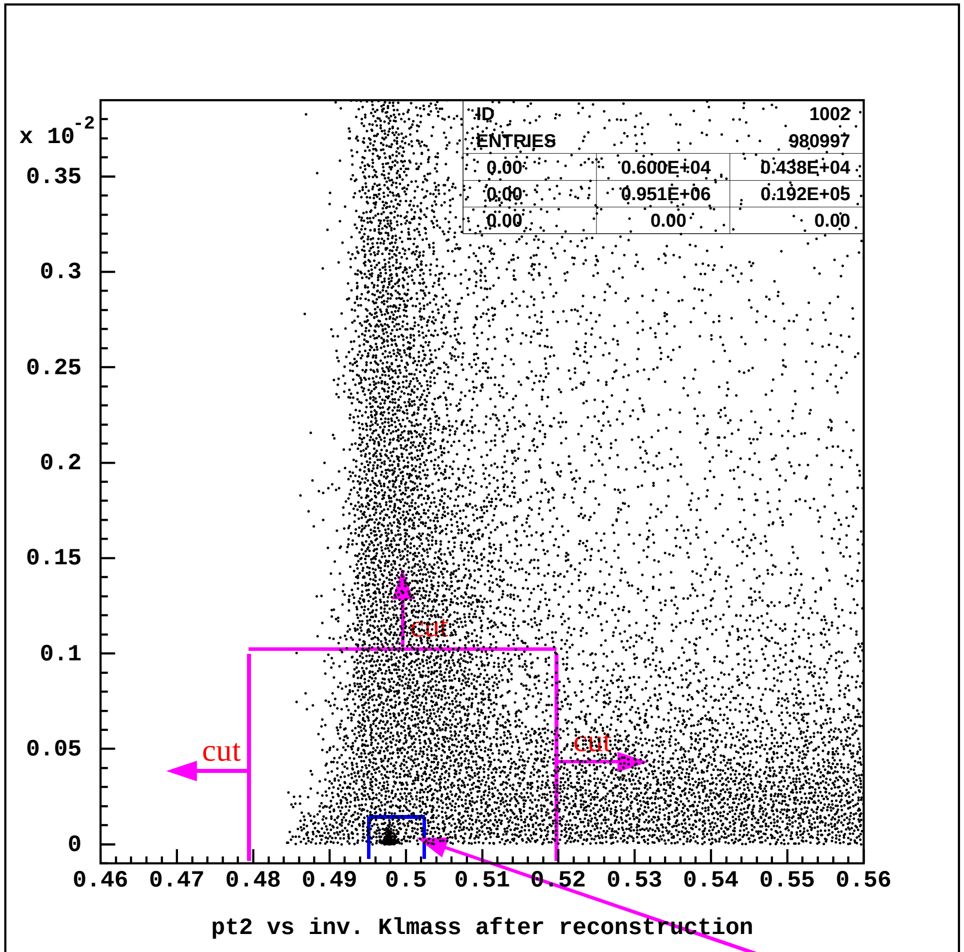
- based on our preliminary results, we have ruled out the pseudoscalar X^0 candidate as an explanation for the neutral boson X^0 observed by HyperCP. We have however not ruled out an axial vector X^0 candidate.

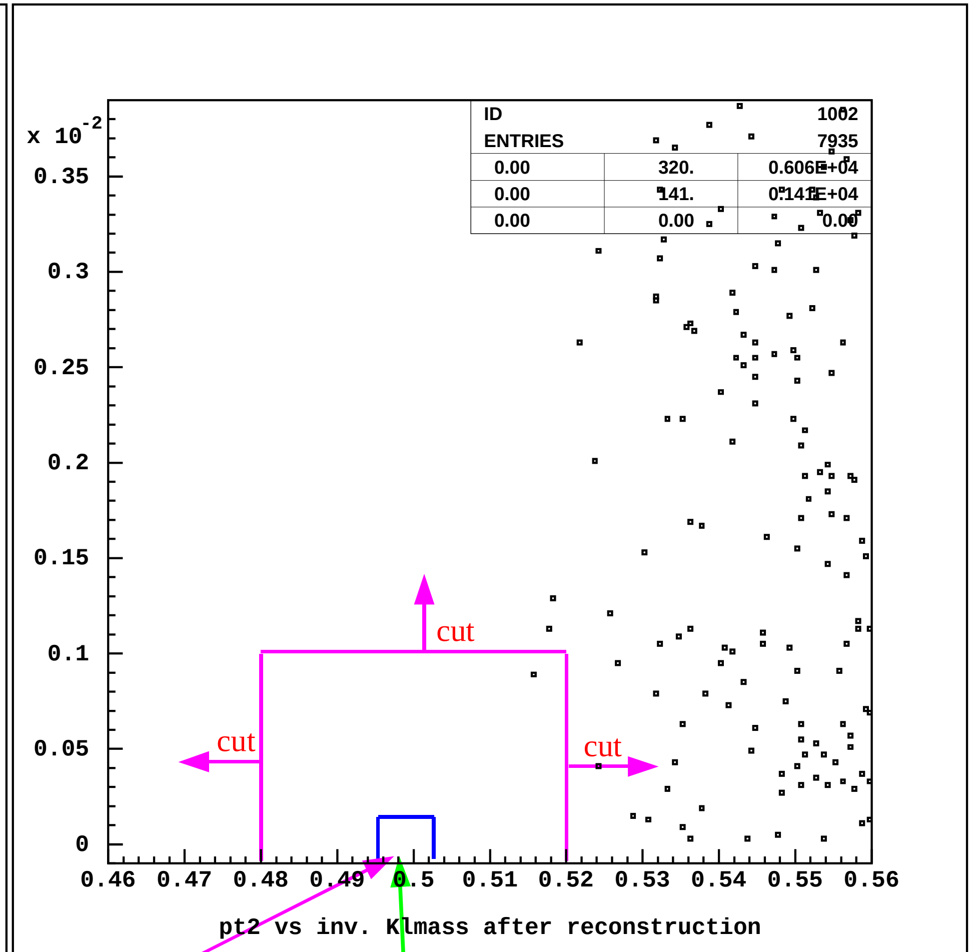
- need to explore how a momentum dependent matrix element (Standard Model and 'Beyond') affects the acceptance.

~ Backup Slides ~

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 ~

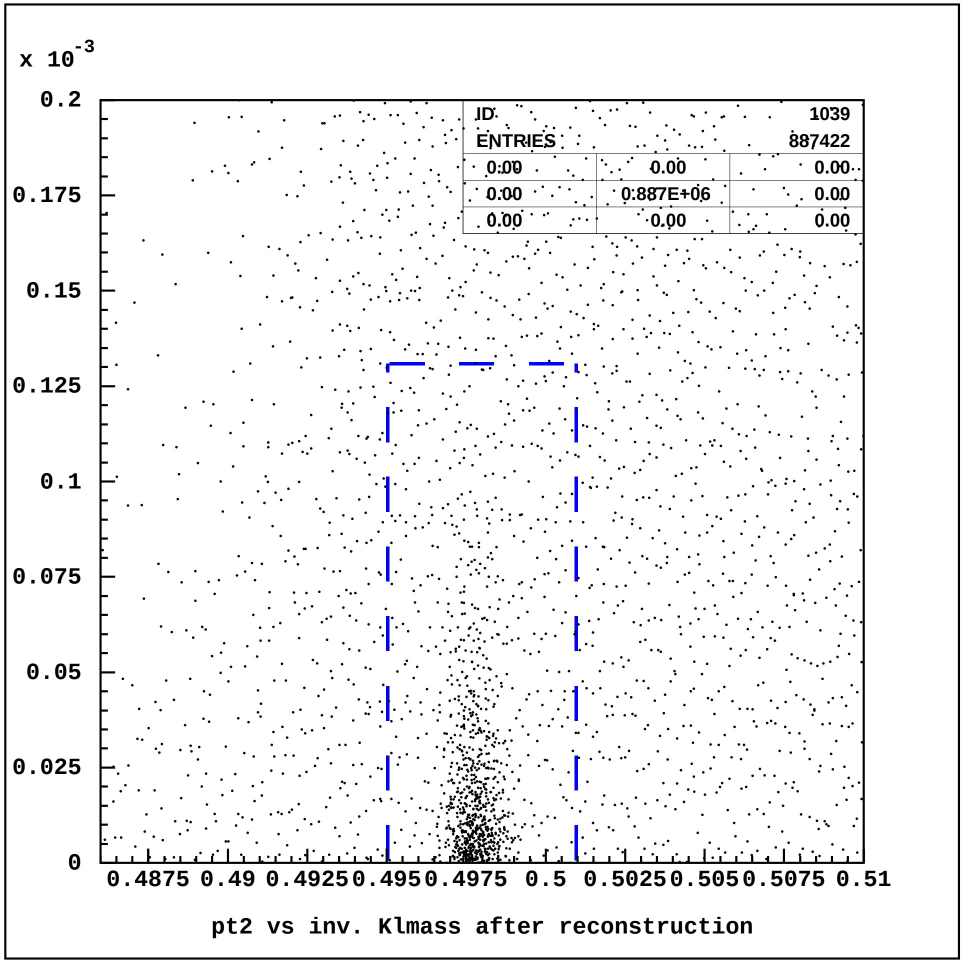
495 MeV $\leq M_{\gamma\gamma\gamma\gamma\mu\mu} \leq$ 501 MeV

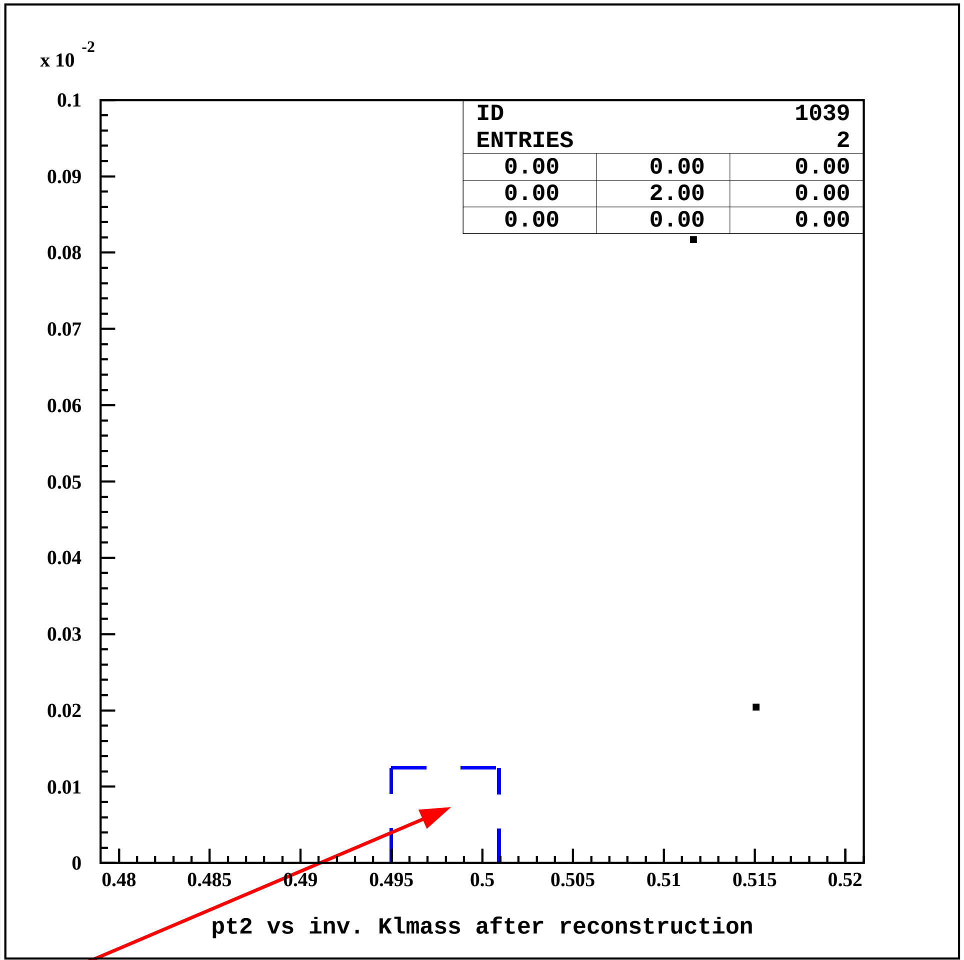
$p_T^2 \leq 130$ MeV^2

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 $K_L \to \pi^0\pi^0\mu^+\mu^-$ 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!

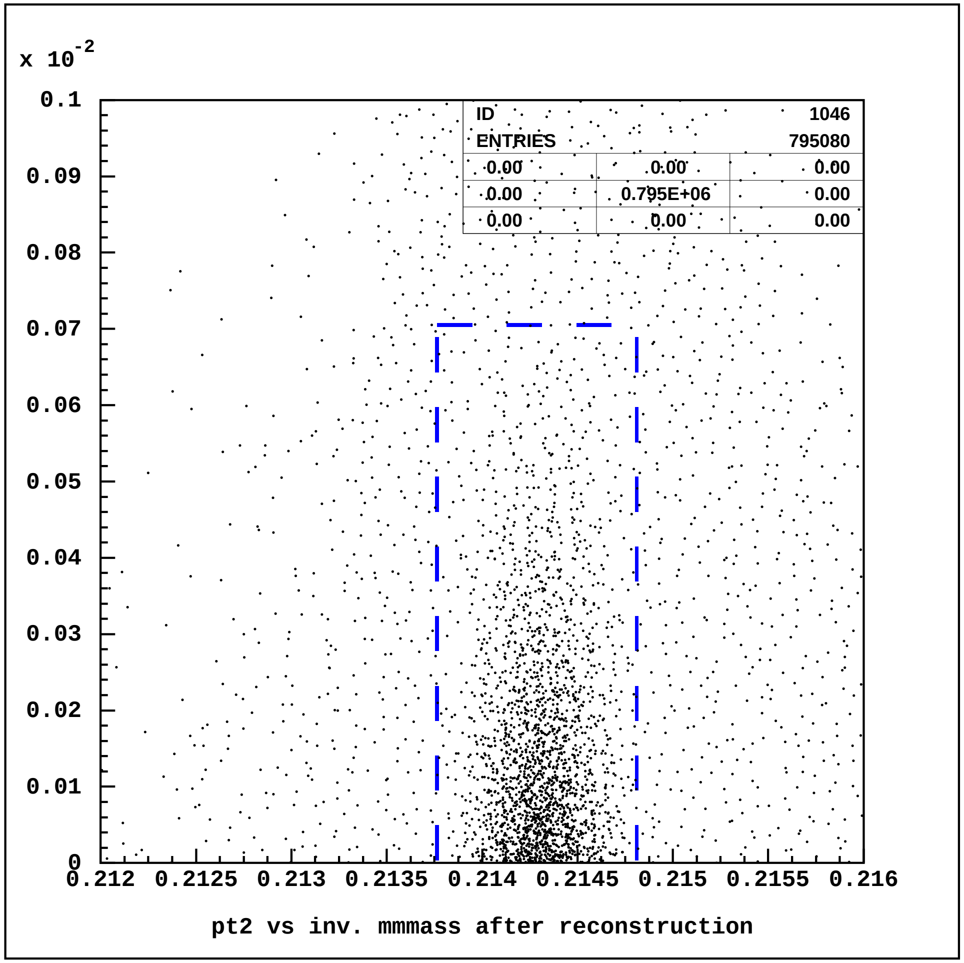
1999 KTeV Data

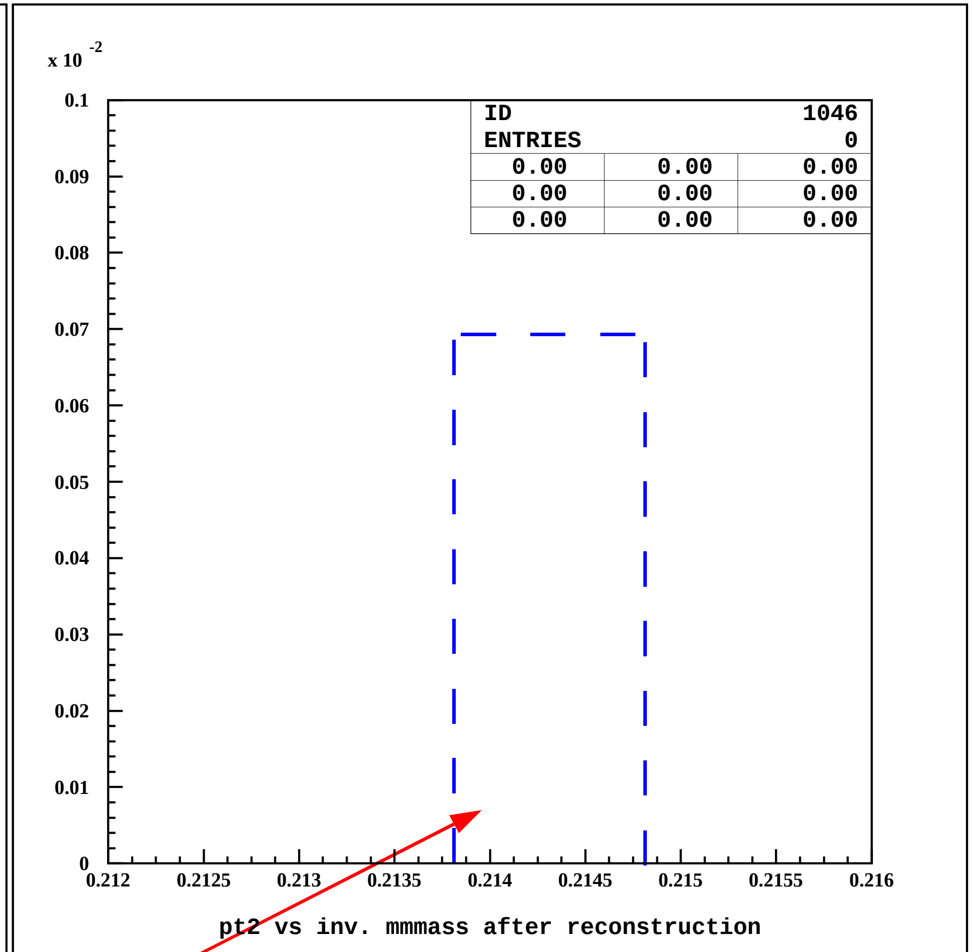
~ Box Dimensions ~

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

~ Box Dimensions ~

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

$p_T^2 \leq 700$ MeV^2

X^0 Signal Box Opened and is EMPTY!

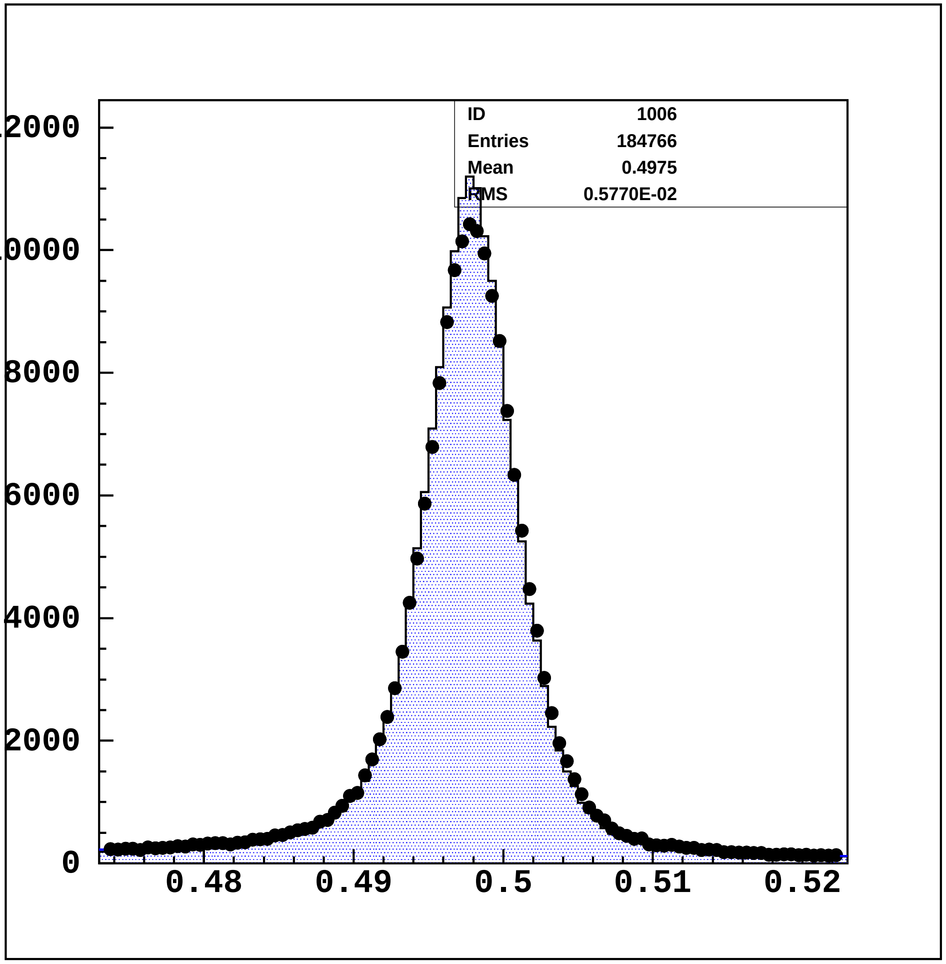
1999 KTeV Data

~ Box Dimensions ~

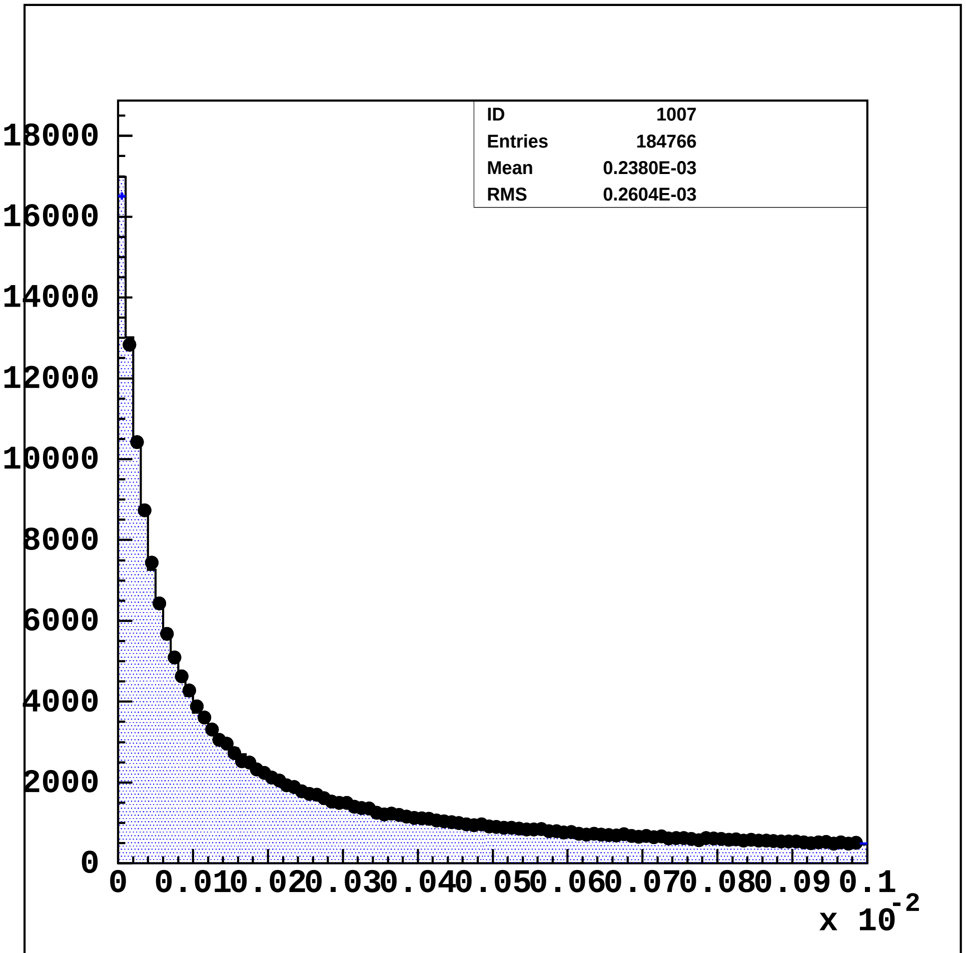
213.8 MeV $\leq M_{\mu\mu} \leq$ 214.8 MeV

$p_T^2 \leq 700$ MeV^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

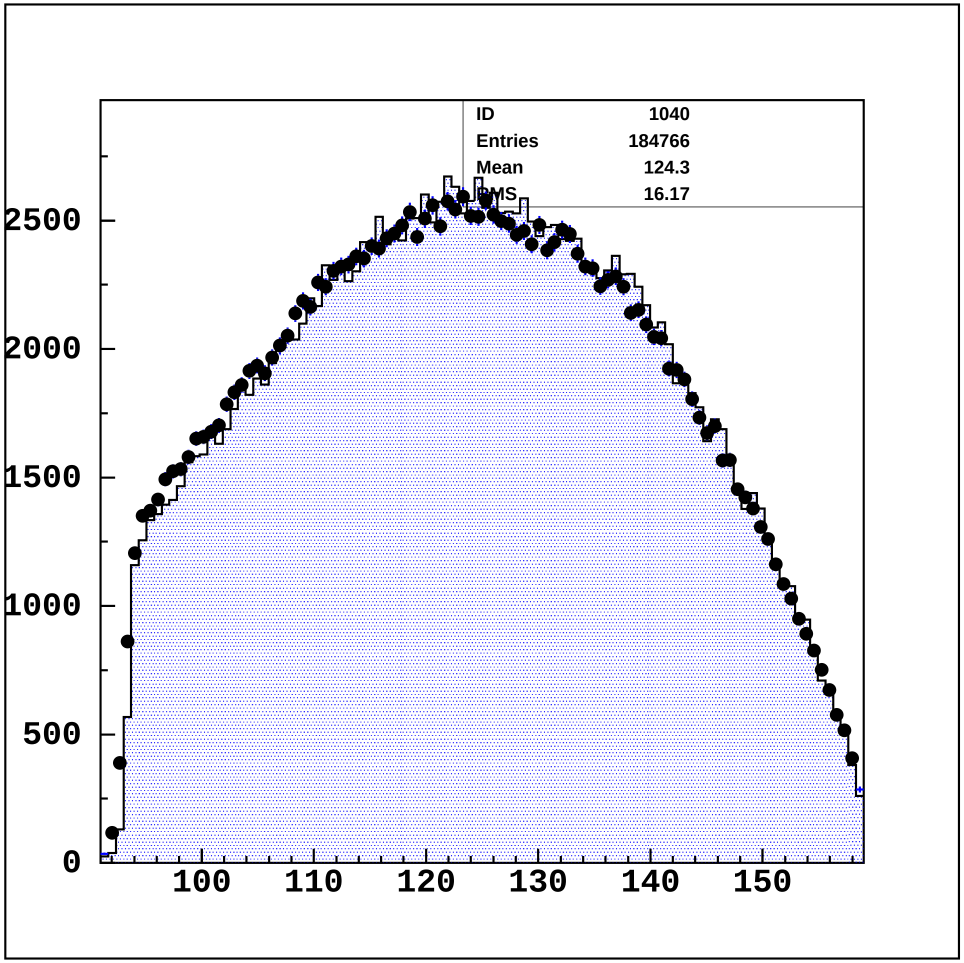


1999 $\pi^0\pi^0\pi^0_D$ P_T^2

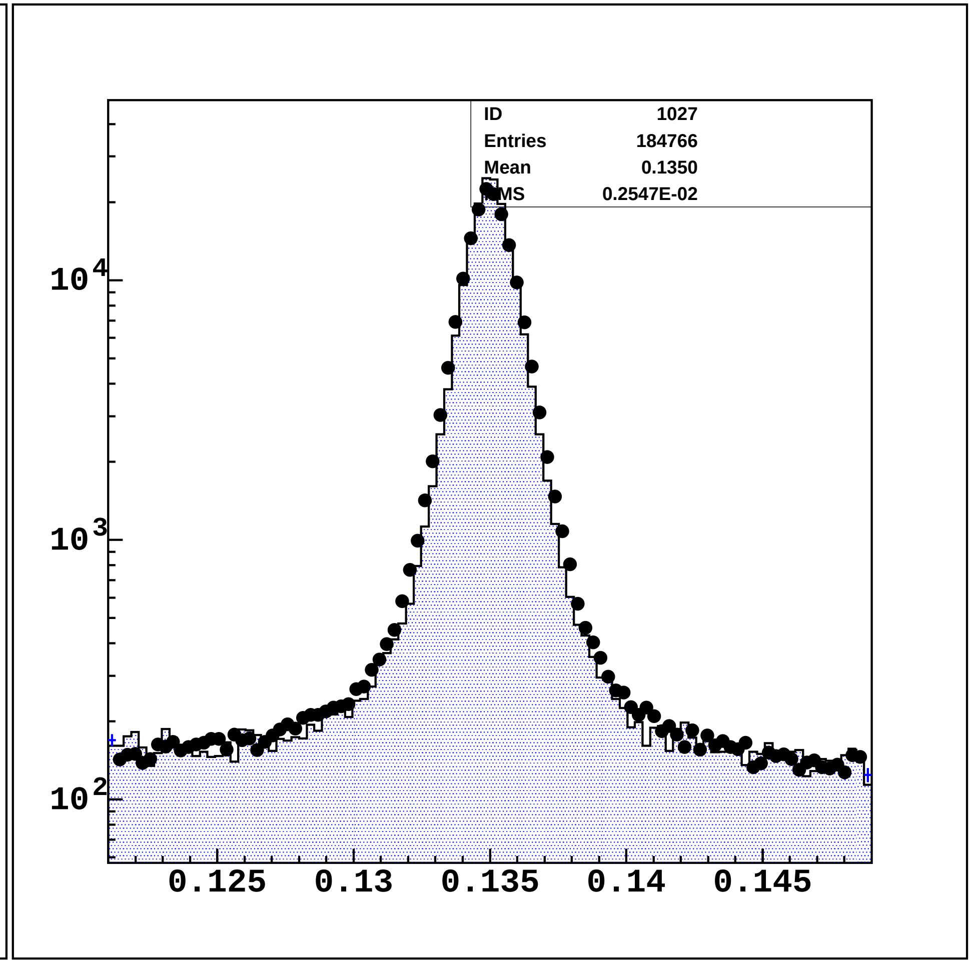
● = Data

□ = MC

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



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



1999 $\pi^0\pi^0\pi^0_D$ 1st π^0 Mass

● = Data

□ = MC

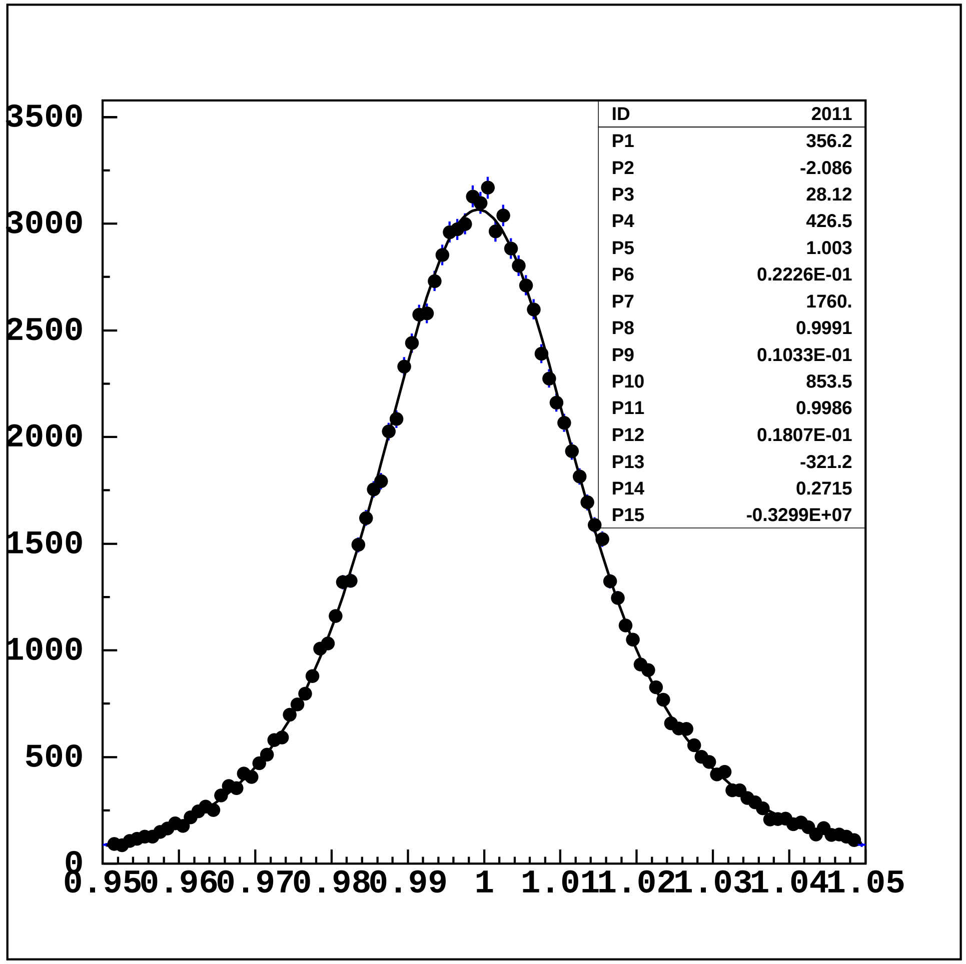
Flux Error from E/p (1997 and 1999) extracted using a 15 parameter Gaussian fit.

Integration is varied from:

$$(0.95 \mp 0.01) \leq E/p \leq (1.05 \pm 0.01)$$

$$\frac{\Delta F_{1997}}{F_{1997}} = {}^{+1.16\%}_{-2.41\%}$$

$$\frac{\Delta F_{1999}}{F_{1999}} = {}^{+2.32\%}_{-3.99\%}$$



E/p Data 1997

Dimuon Uncertainty

i) vary the width of cracks in the muon counting planes to determine range over which there is no measureable improvement in efficiency modeling.

- range was found to be 0.2 mm, which yields $\Delta A_{crack} = 0.5\%$. (Quinn, 2000)

ii) the energy loss simulation in the muon filters also affects dimuon efficiency. This effect can be gauged by varying thickness of muon filters.

- varying thickness by 2.0%, yields $\Delta A_{thick} = 0.4\%$. (Quinn, 2000)

max. possible mismeasurement of filter thickness due to gaps in steel shielding blocks.

Uncertainty from $Br(K_L \rightarrow \pi^0\pi^0\pi^0)$

$Br(K_L \rightarrow \pi^0\pi^0\pi^0) = (19.52 \pm 0.12)\%$ (PDG, 2008)

→ 0.61% uncertainty.