KTEV

Kaons at the Tevatron

UNIVERSITY of VIRGINIA

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

David G. Phillips II

Fermilab Seminar

April 7, 2009

Fermilab

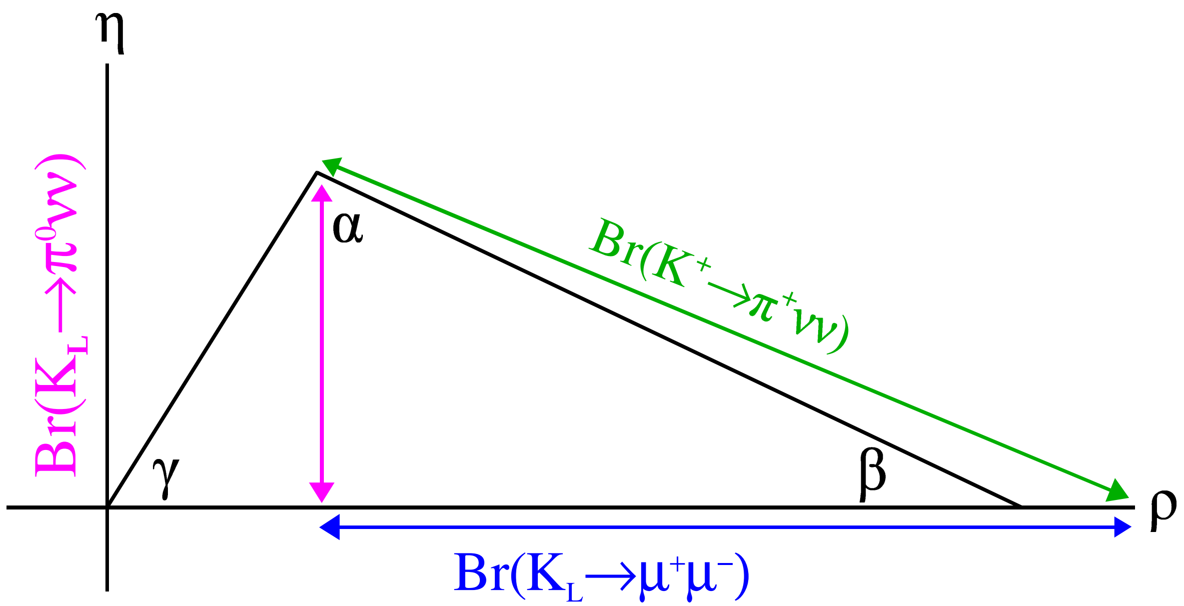
Table of Contents

Introduction

UVa team members on shift for the 1999 KTeV data run!

Why Study Kaons?

Unitarity Triangle and CP Violation



- Br($K_L \to \pi^0 \nu\nu$) measures height, η, of the unitarity triangle directly.

Br($K_L \to \pi^0 \nu\nu$) $< 6.7 \times 10^{-8}$ (E391a)

SM Prediction:

Br($K_L \to \pi^0 \nu\nu$) $< (2.76 \pm 0.40)\, x10^{-11}$ (Mescia and Smith 2007)

(See http://www.lnf.infn.it/wg/vus)

- still a lot of work to do. E391a will be upgraded by addition of CsI from KTeV and moved to J-Parc as E-14.

Additional Interesting Applications of Kaon Physics

- lepton flavor violation in K decays: KTeV leads the way with the following analyses:

  ~ $K_L \to \pi^0 \mu^+ e^-$

  ~ $K_L \to \pi^0 \pi^0 \mu^+ e^-$

  ~ $\pi^0 \to \mu^+ e^-$

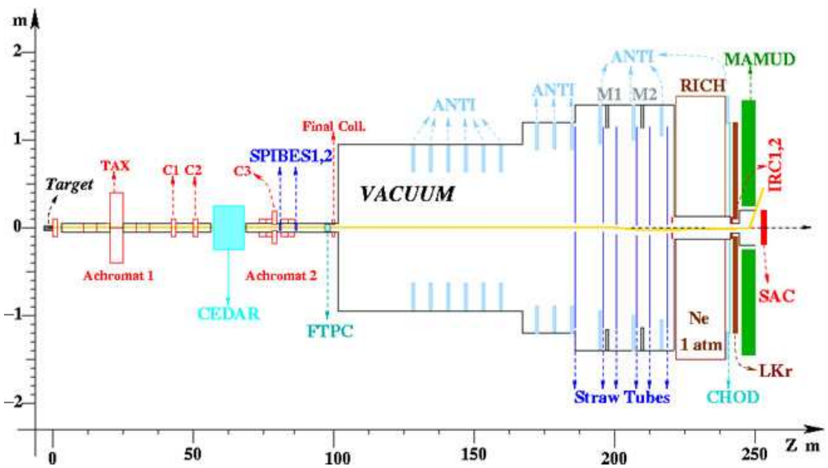
- test of lepton universality in K decays. In SM, μ^- & e^- differ only by mass and coupling to the Higgs.

  ~ $\Gamma(K_{e3})/\Gamma(K_{\mu 3}) \to G_F^e/G_F^\mu$ (measure ratio of coupling constants and seek deviations from theory in well-determined SM processes)

- redo first row unitarity of the CKM matrix (specifically V_{us}) through remeasurement of various K branching ratios.

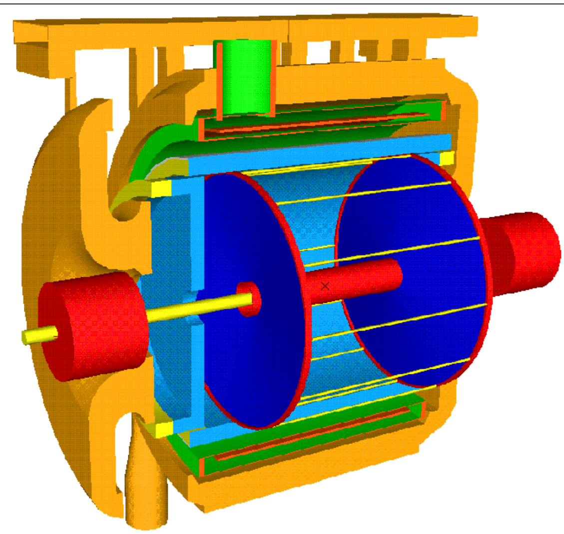
- many probes of ChPT in K_L sector, such as: $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 e^+ e^- \gamma$ & $K_L \to \pi^0 \gamma\gamma$.

Active Kaon Collaborations



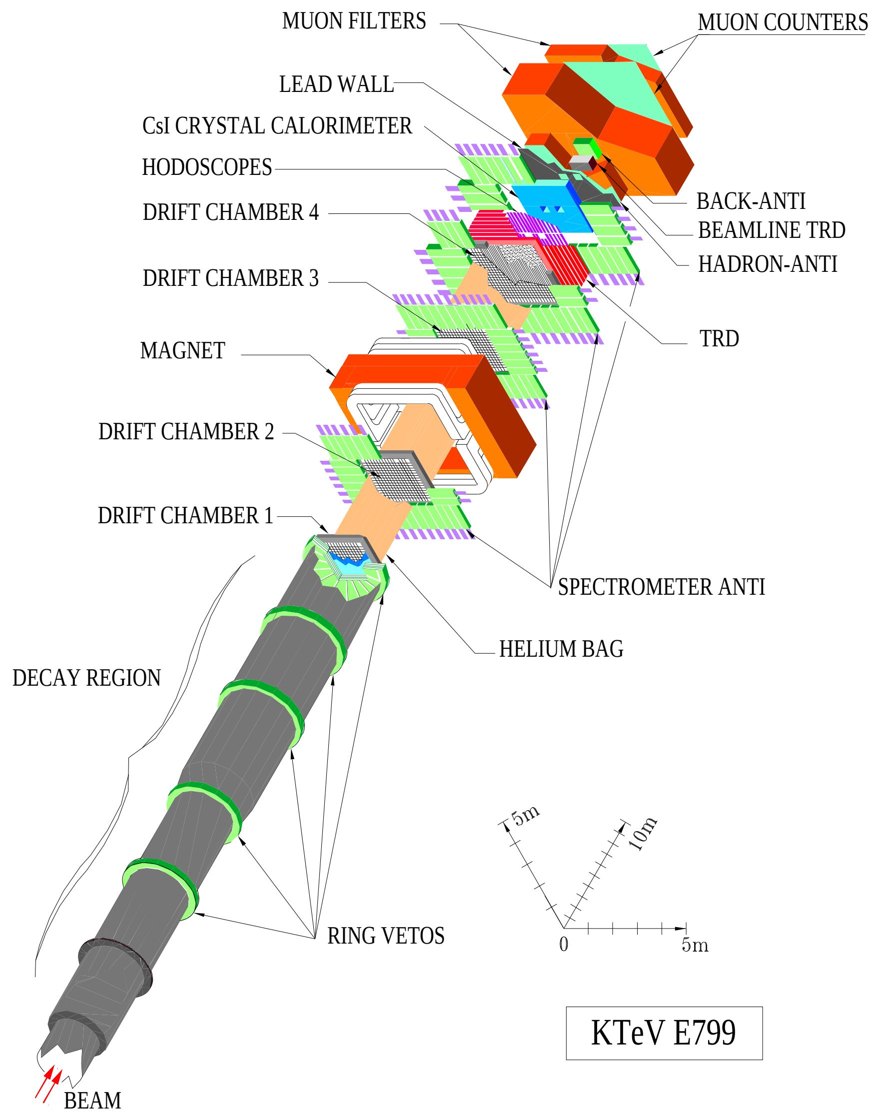
©CERN

NA62 (specific search for $K^+ \rightarrow \pi^+ \nu\nu$)



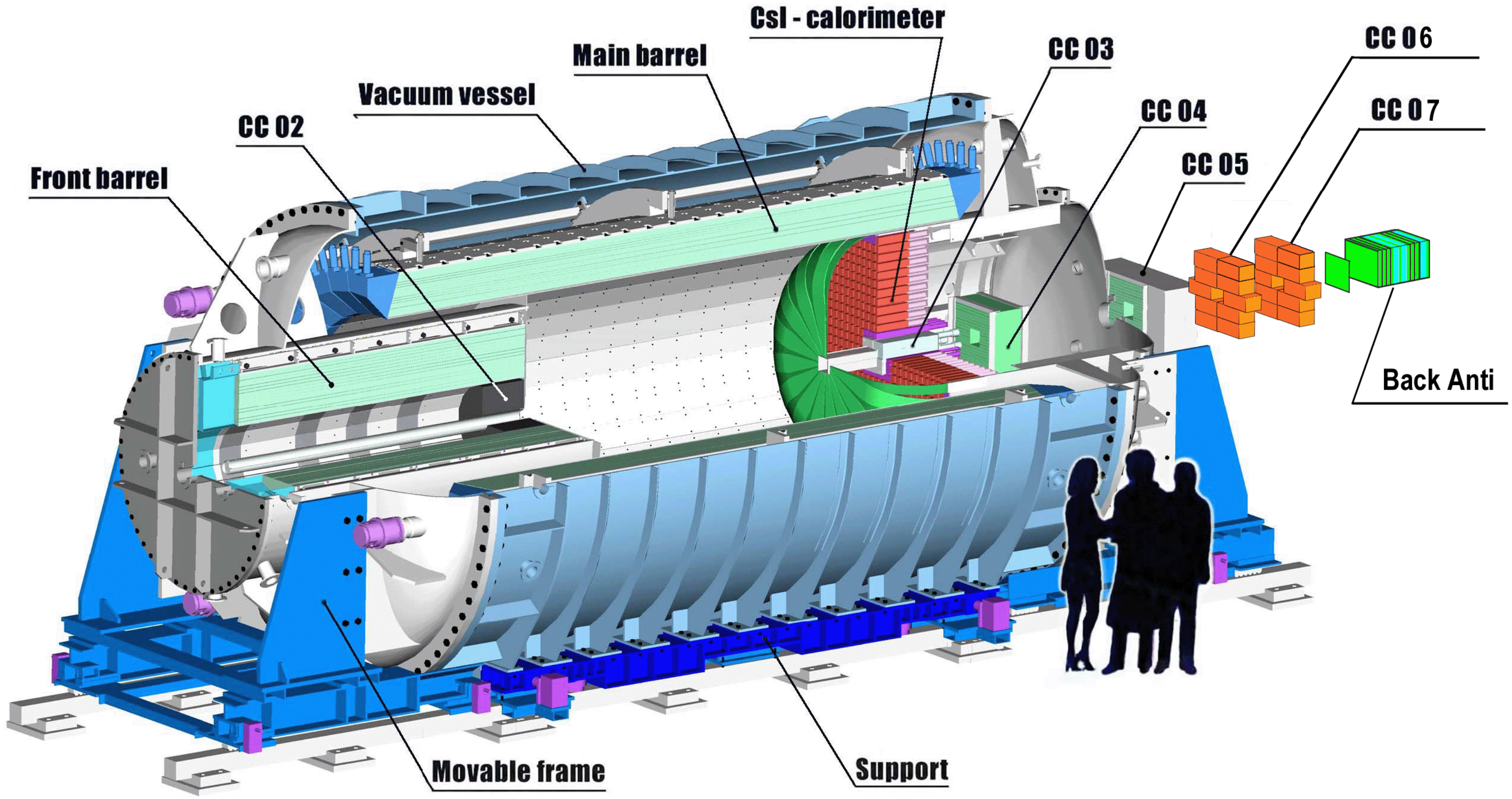
KLOE

(Future KLOE II)



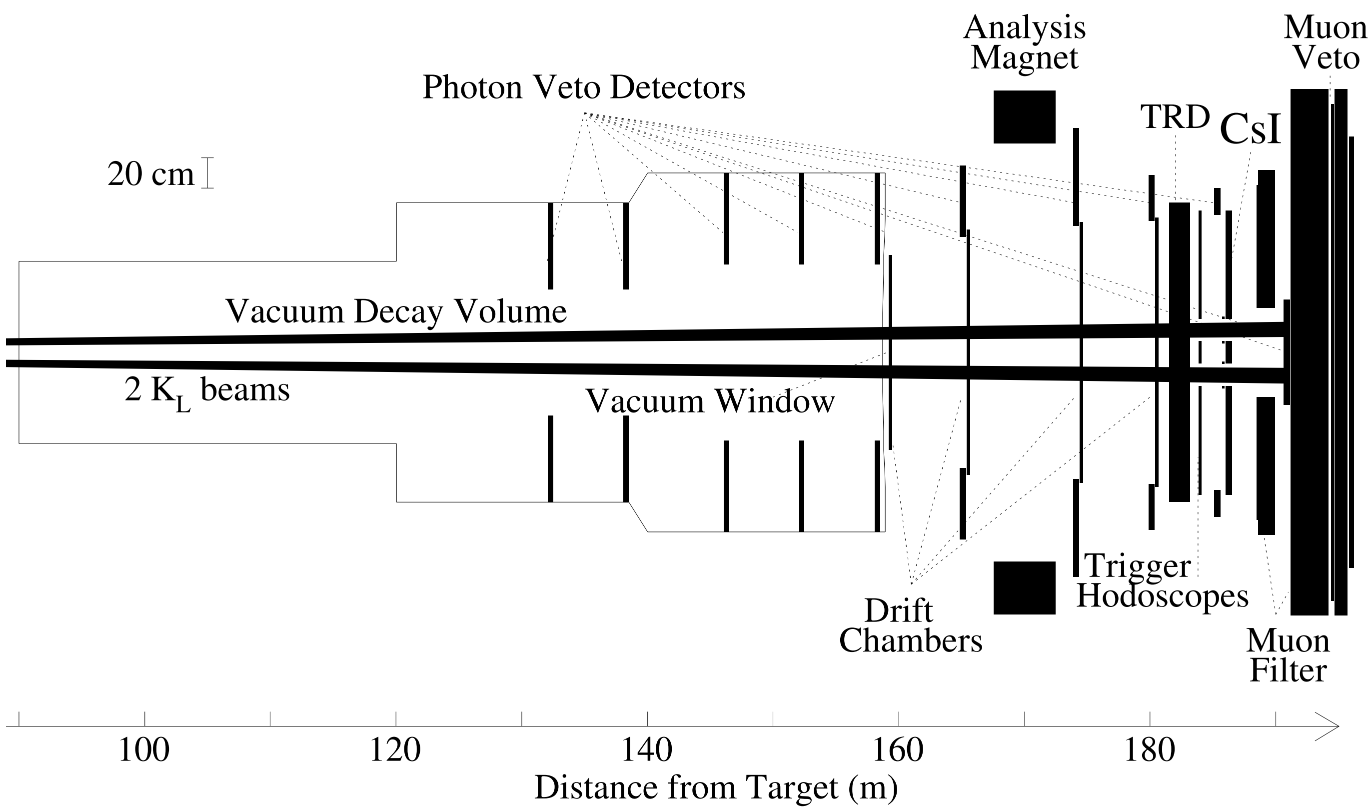
KTeV E799

KTEV
Kaons at the Tevatron



KEK E391a (First committed $K_L \to \pi^0 \nu\nu$ experiment)

The KTeV Experiment



KTEV

Kaons at the Tevatron

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)

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.

Creation of the Neutral Kaon Beam

- neutral kaons were created by a proton beam hitting a fixed BeO target with transverse dimensions of 3x3 mm and a length of 30 cm (~1.1 interaction lengths).

- the Tevatron provided 2.5 to 5 trillion 800 GeV/c protons in a 20 s 'spill' once per minute.

- the proton beam has a 53 MHz nanostructure such that the protons arrive in ~1 ns 'buckets' once every 19 ns.

- the center of the BeO target defined the origin of the KTeV right-handed co-ordinate system, where the +z-axis is defined from the target to the center of the detector.

- the incident proton beam was directed at an angle of - 4.8 mrad with respect to the +z-axis in order to maximize the kaon flux and optimize the K-n ratio.

- the beam exiting the BeO target contained very few kaons compared to the number of hadrons and photons produced.

- a series of collimators and sweeping magnets were designed to create two side-by-side beams of neutral particles and rid them of any hadrons and photons.

KTeV Decay Region (looking upstream)

- at $z = 90$ m, the two beams enter the KTeV decay region, which is an evacuated volume held at ~1 μTorr and is 69 meters in length.

- at the end of the decay region was a Mylar laminated Kevlar vacuum window. The window was made extremely thin (0.0015 radiation lengths) in order to minimize photon conversion and bremsstrahlung.

The KTeV '*Double Beam*' Technique

- KTeV used two parallel neutral kaon beams to produce K_L and K_S decays.

  ~ E799 used two identical K_L beams.
  (Note: nearly all of the K_S's and hyperons were produced at the target decay before they reached the decay region, which is ~90 m from the target.)

  ~ E832 also has two K_L beams, but one of them passed through a plastic regenerator to produce K_S's.

- This novel technique was beneficial, because it enabled collection of K_L and K_S decays at the same time and under the same conditions.

- This reduces biases due to temporal fluctuations during data taking, such as changes in beam intensity and variations in detector response.

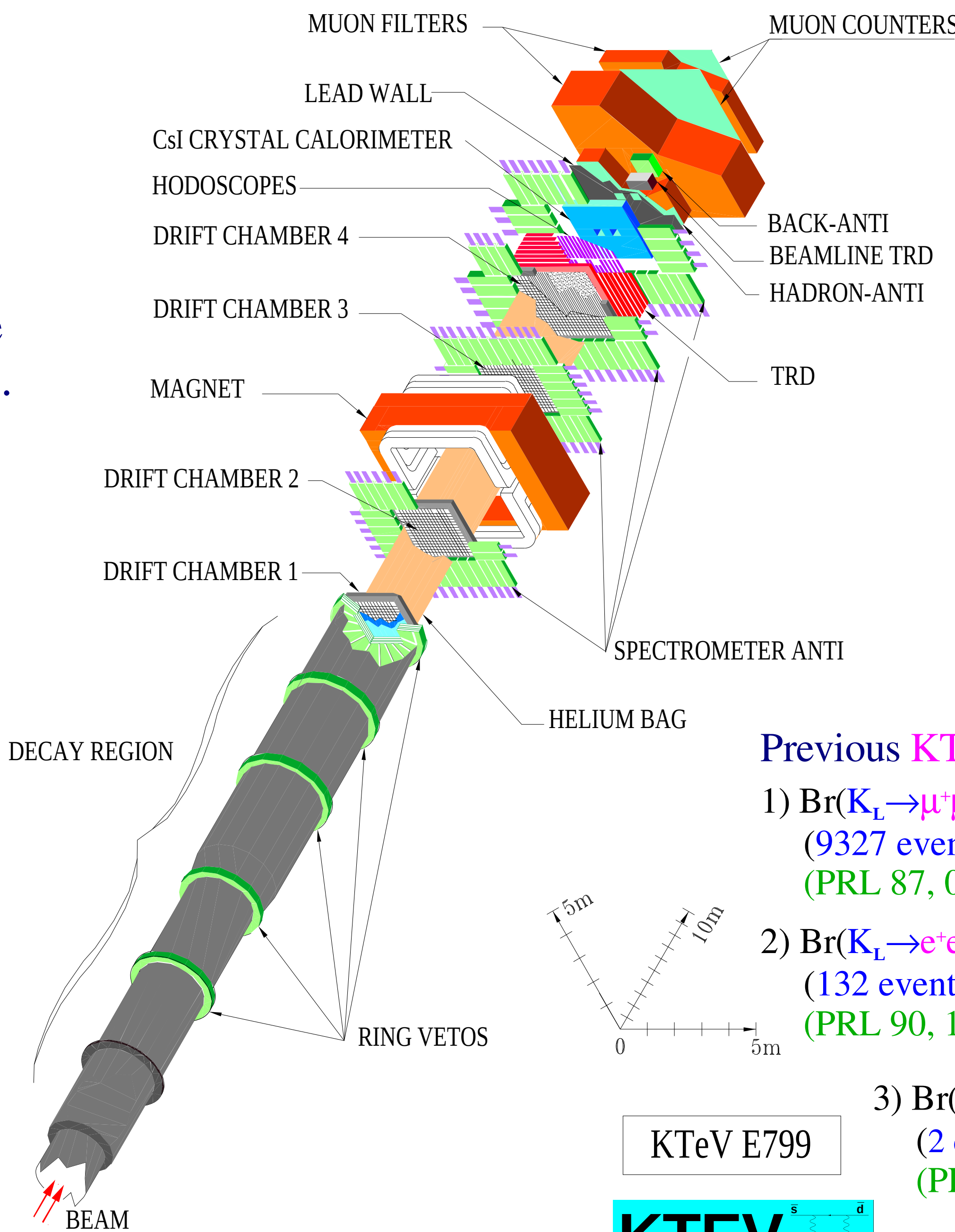
- Biases due to different levels of activity in the kaon beams from neutral hadrons are also suppressed.

The KTeV Detector

KTeV's coordinate system is:

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))

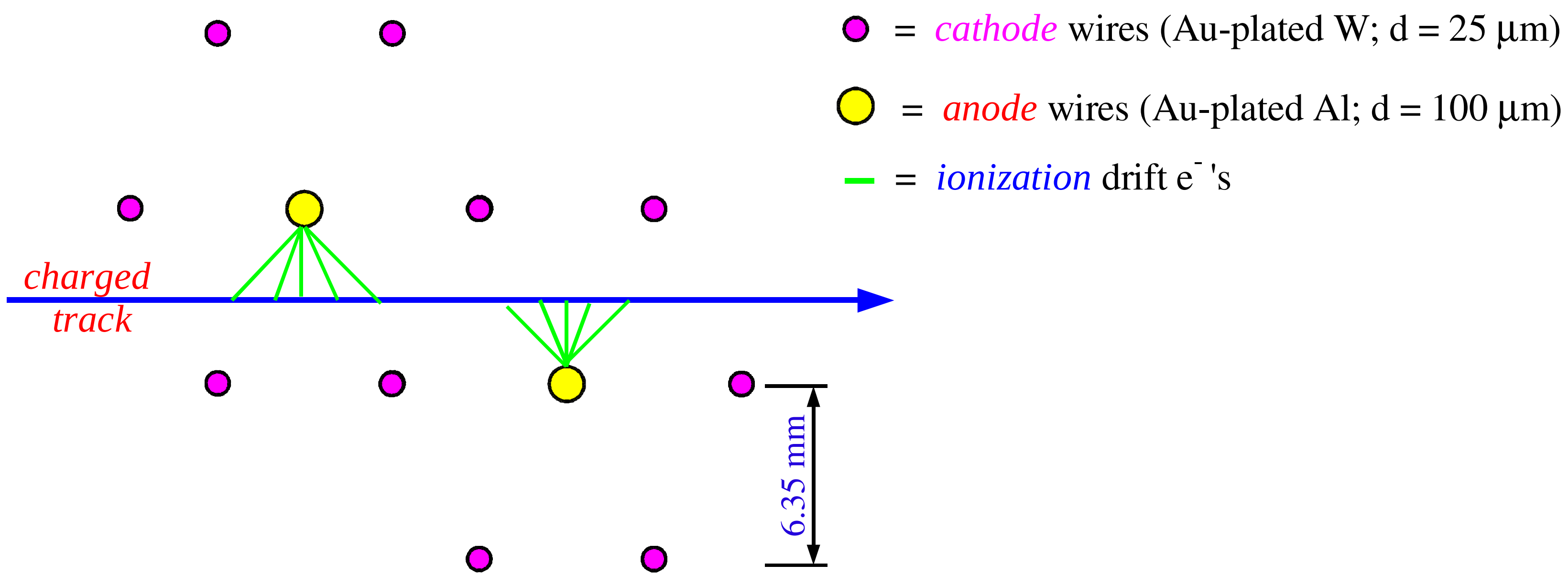
2) $Br(K_L \to e^+e^-\mu^+\mu^-) = (2.69 \pm 0.24_{stat} \pm 0.12_{syst}) \times 10^{-9}$
(132 events)
(PRL 90, 141801 (2003))

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

The KTeV Spectrometer

- the KTeV Spectrometer used an analysis magnet sandwiched between four drift chambers to measure charged track momenta and trajectories.



- Drift Chamber Wire Geometry -

- each drift chamber was filled with a 50/50 mix of argon/ethane along with a bit (~1%) of isopropyl alcohol; the alcohol slowed chamber aging by absorbing harmful ultraviolet light.

- helium bags were placed before, behind and between each drift chamber to reduce photon conversions, multiple scattering and beam interactions.

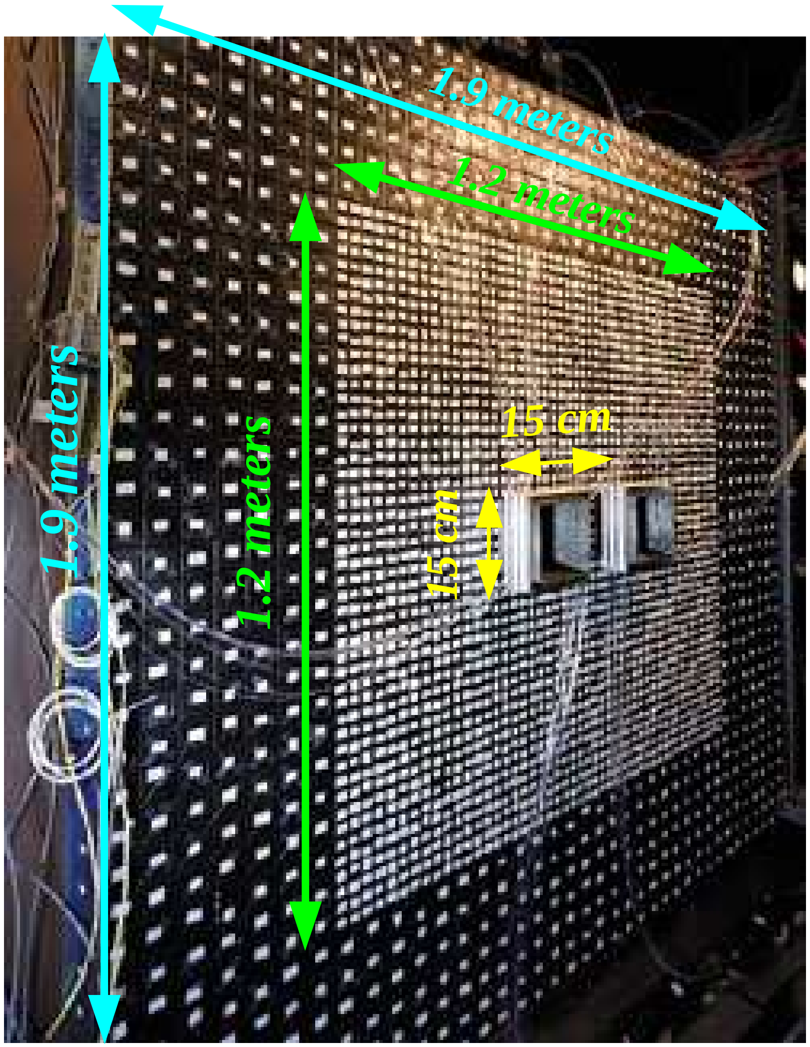
- the magnet had a strength of up to 0.5 T, produced a field that's uniform to better than 1% and imparted a 0.205 GeV/c kick in the horizontal plane.

In 1997. In 1999, this was 0.15 GeV/c.

- the momentum resolution of the spectrometer was:

$$\sigma_P / P = (0.038 \oplus 0.016\,P)\%, \text{ where P is in GeV/c.}$$

The KTeV Electromagnetic Calorimeter

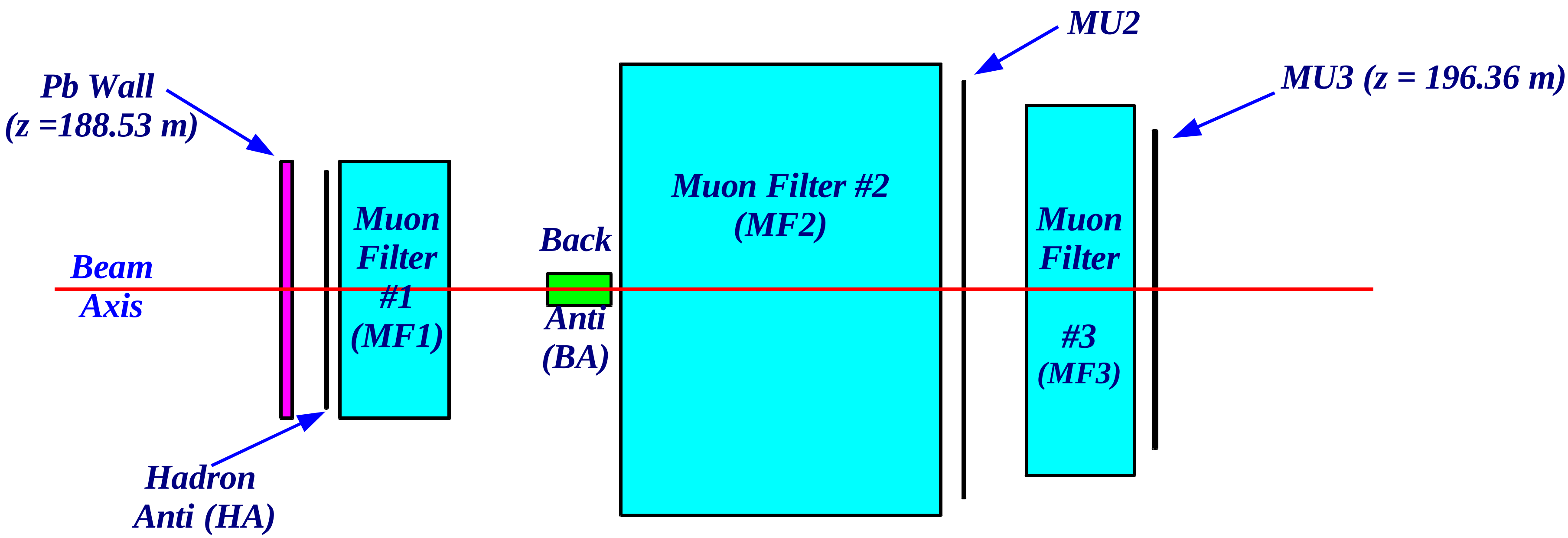


- the KTeV ECAL was composed of 3100 pure CsI crystals.
- the 868 larger outer crystals have a 5 x 5 cm^2 cross-section, while the inner crystals have an area of 2.5 x 2.5 cm^2.
- all crystals are 50 cm long (27 radiation lengths, 1.4 interaction lengths)
- the energy resolution for photons was:

σ_E/E = (0.4 ⊕ $2/\sqrt{E}$) %, where E is in GeV.

- the position resolution was ~1.0 mm for small crystals and ~1.8mm for large crystals.

The KTeV Muon ID System



- Muon ID System Schematic -

- the ***Muon ID System*** was a series of particle filters and scintillator planes that were designed to identify muons by filtering out other charged particles.

Pb Wall – the purpose of the *10 cm thick* lead wall was twofold:
1) absorption of EM showers that leaked out of the CsI ECAL.
2) induction of hadronic showers for the hadrons that didn't shower in the CsI ECAL.

HA – a plane of 28 non-overlapping scintillator paddles used to veto events with hadronic activity.

MF1 – a 1 meter thick steel barrier, which provided protection for the HA against backsplash off the neutral beamdump, *MF2* (*Pb Wall*, *HA* and *MF1* all had holes in the center to allow for passage of the neutral beams).

MF2 & MU2 – at 3 meters thick and composed of 44 m^2 of battleship steel, *MF2* stopped a large majority of hadronic activity. *MU2* is a plane of 56 150cm x15cm x1.5cm scintillator counters that was user as an acceptance detector for muon calibration triggers.

MF3 – an additional 1 meter steel barrier located behind *MU2*. A muon would need a min. momentum of *7 GeV/c* to pass through the Pb wall and the 3 muon filters. All in all, the Pb wall and muon filters add up to a total of 31 nuclear interaction lengths.

MU3 – two planes of 40 non-overlapping scintillator counters each. *MU3* is used to trigger on rare decays with muons in the final state. The hit resolution in X & Y is 15 cm.

Why is $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Interesting?

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))

3 events observed!

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

- 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:

$$Br(K_L \to \pi^0\pi^0X^0_P \to \pi^0\pi^0\mu^+\mu^-) = 8.0\times10^{-9}$$ (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:

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

(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 $K_L \rightarrow \pi^0\pi^0 X^0$

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

$$Br(K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\gamma\gamma) < 2.4 \times 10^{-7}$$

(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!

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

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! An Upper Limit for virtual photon and X^0 channels has been obtained.

  ~ completed identification and estimation of signal mode background.

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

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

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

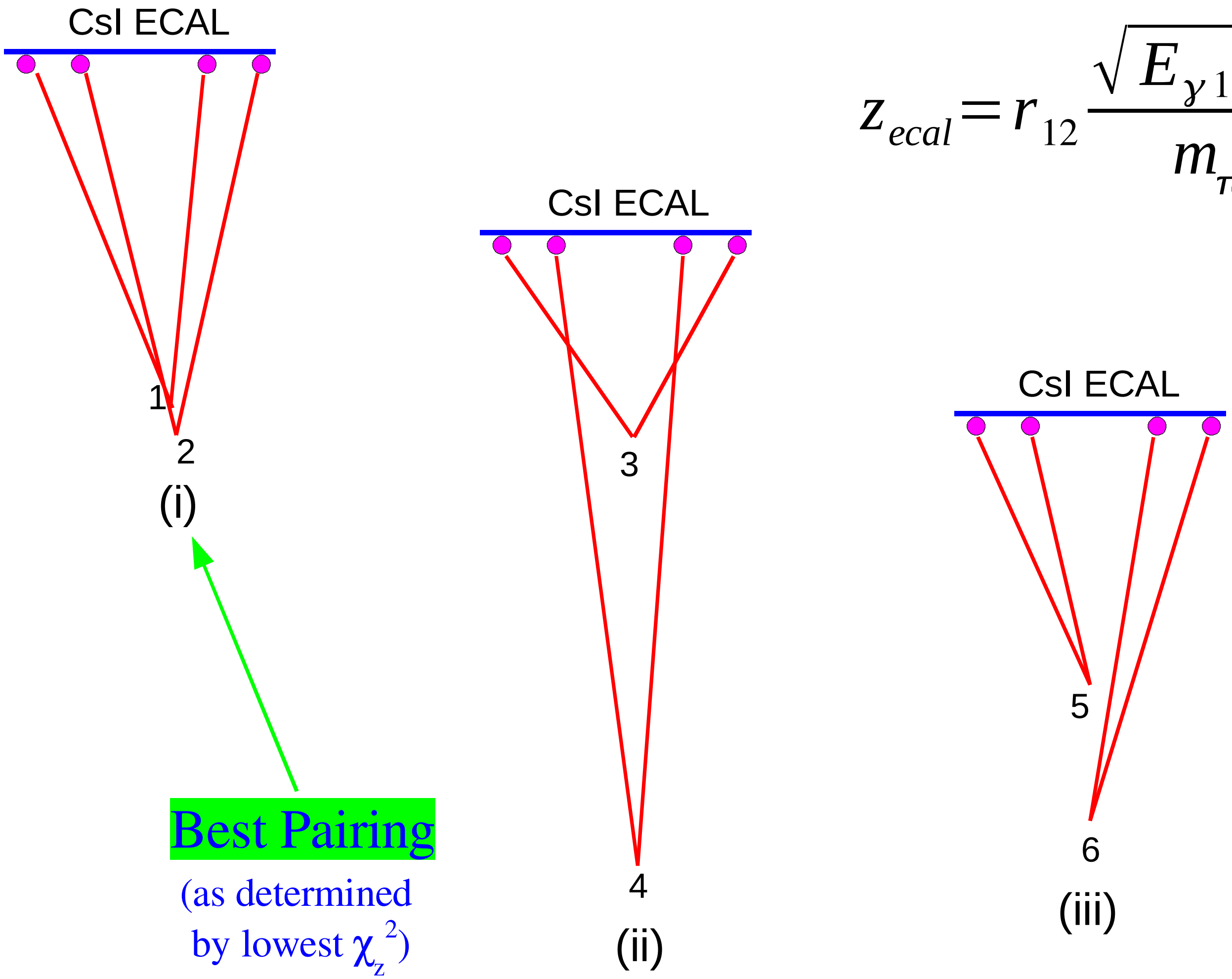
-Crunch Cuts-

$K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ Crunch Cut*	1997 Data ♫	1997 MC ♪	1999 Data ♫	1999 MC ♪
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) ≤ 2.0 GeV	0.391	0.913	0.436	0.904
E_{cl}(track) / p_{track} ≤ 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 ≤ Z_{VTX} ≤ 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).*

Neutral Vertex Reconstruction

$$z_{ecal} = r_{12} \frac{\sqrt{E_{\gamma 1} E_{\gamma 2}}}{m_{\pi^0}}$$



$K_L \to \pi^0 \pi^0 \mu^+ \mu^-$ 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 ≤ $M_{\mu\mu\gamma\gamma\gamma\gamma}$ ≤ 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
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq 9$ 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

* = cuts listed in chronological order

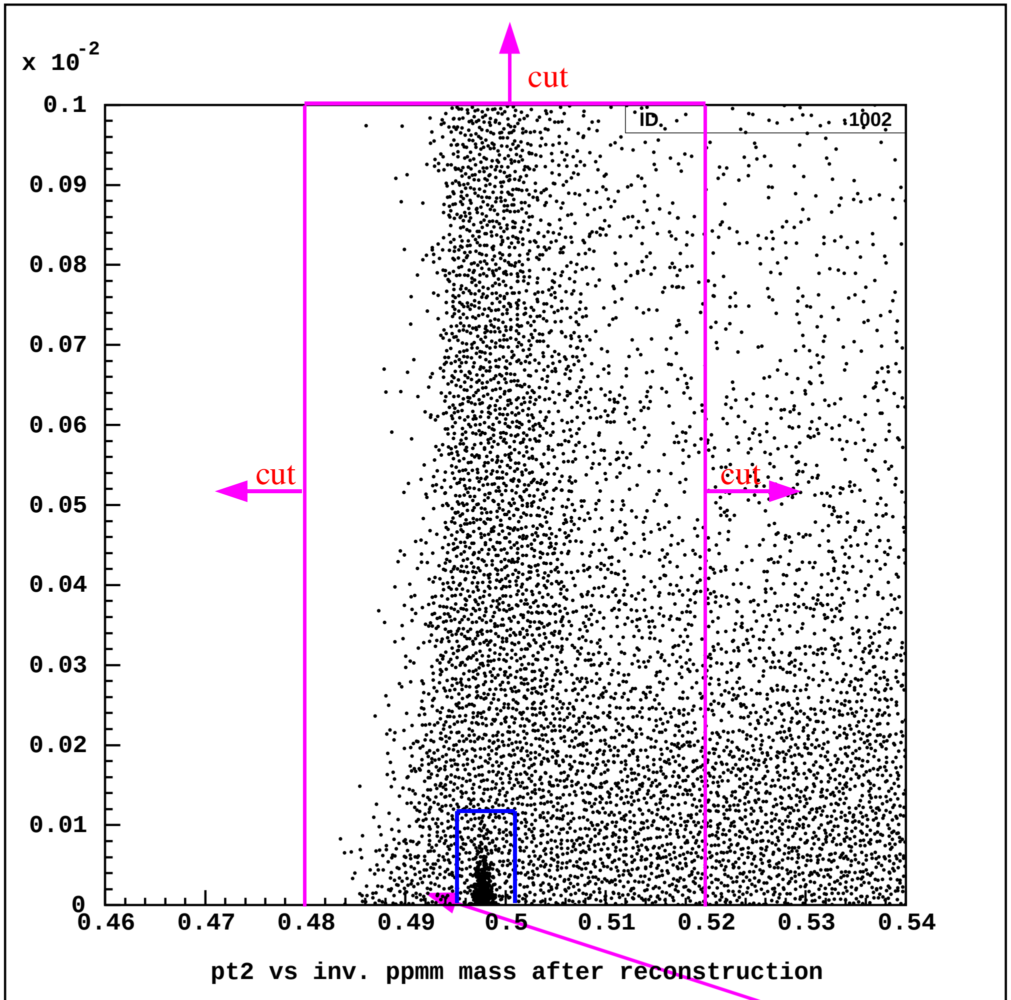
Summary of Backgrounds

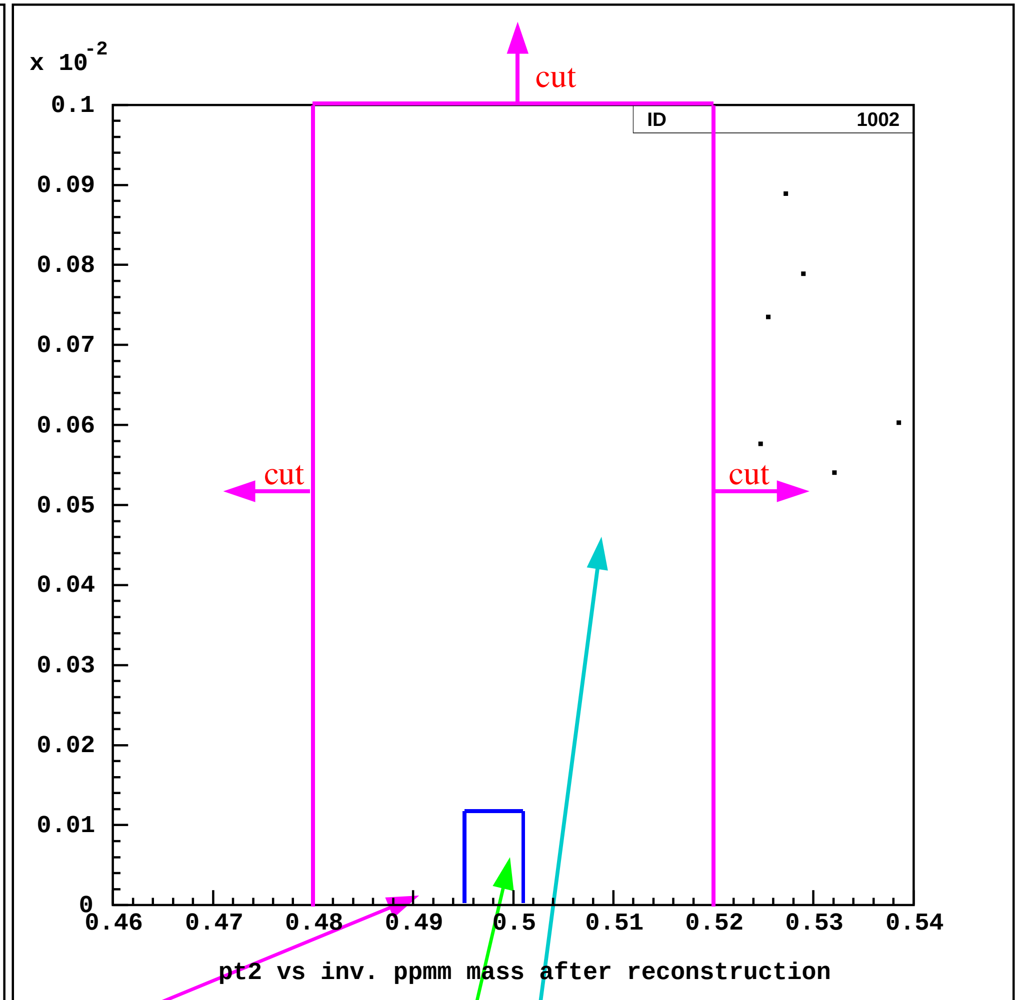
No background survive analysis cuts!!!

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 = $\pi^{+,-} \rightarrow \mu^{+,-} \nu_\mu$)	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)
$K_L \rightarrow \pi^+\pi^-\pi^0$ (2x punch through)	1,848,796,492 (0.060 f)	1,062,004,339 (0.035 f)
$K_L \rightarrow \pi^+\pi^-\pi^0$ (2x pion decay)	85,552,978 (0.0028 f)	106,912,811 (0.0035 f)
$K_L \rightarrow \pi^+\pi^-\pi^0$ (punch & decay)	455,374,316 (0.015 f)	456,480,690 (0.015 f)
$K_L \rightarrow \pi^+\pi^-\gamma$ (2x punch through)	15,034,557 (1.41 f)	21,646,250 (2.03 f)
$K_L \rightarrow \pi^+\pi^-\gamma$ (2x pion decay)	20,304,857 (1.90 f)	16,311,114 (1.53 f)
$K_L \rightarrow \pi^+\pi^-\gamma$ (punch & decay)	14,249,908 (1.34 f)	14,495,323 (1.36 f)
$K_L \rightarrow \pi^+\pi^-$ (2x punch through)	683,676,428 (1.35 f)	671,923,195 (1.32 f)
$K_L \rightarrow \pi^+\pi^-$ (2x pion decay)	8,529,573 (0.017 f)	21,840,183 (0.044 f)
$K_L \rightarrow \pi^+\pi^-$ (punch & decay)	50,306,906 (0.100 f)	26,557,616 (0.053 f)
$K_L \rightarrow \mu^+\mu^-$	1,183,635 (670.0 f)	5,240,705 (2967 f)
$K_L \rightarrow \mu^+\mu^-\gamma$	9,582,978 (109.8 f)	119,650,358 (1372 f)
$K_L \rightarrow \mu^+\mu^-\gamma\gamma$	10,869,003 (4473 f)	48,801,465 (20084 f)
$K_L \rightarrow \pi^0\mu^+\mu^-$	11,042,193	13,008,645

Cut on P_T^2 vs. Inv. K_L Mass

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





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

~ Box Dimensions ~

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

$p_T^2 \leq 130$ MeV^2

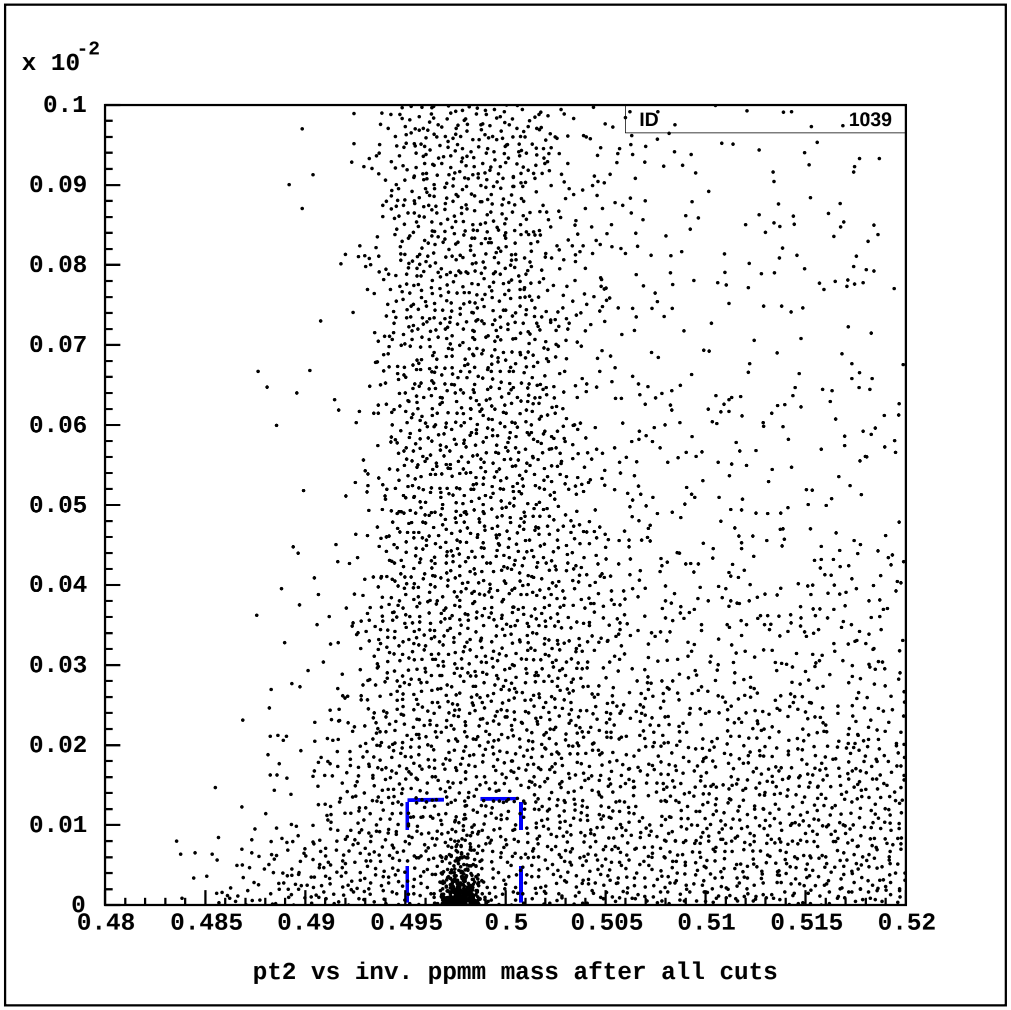
Signal box for MC is open, but for Data remains closed!

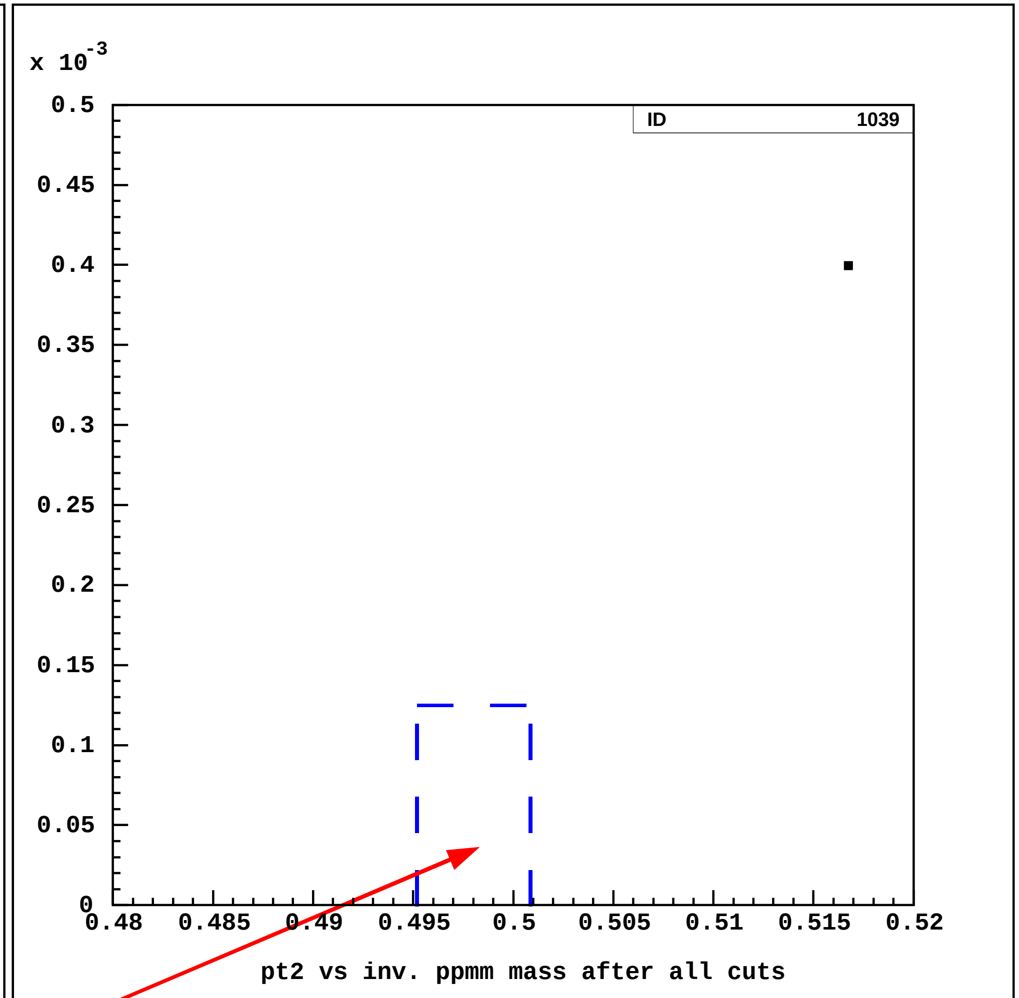
1997 $K^0_{\mu4}$ MC Background

According to MC, no $K^0_{\mu4}$ events in the signal box.

*$K^0_{\mu4}$ is the most dangerous bkgd, but is not really so dangerous.

Opening of the 1997 K_L 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

K_L Signal Box Opened and is EMPTY!

EMPTY = No Signal Events AND No Bkgd Events!

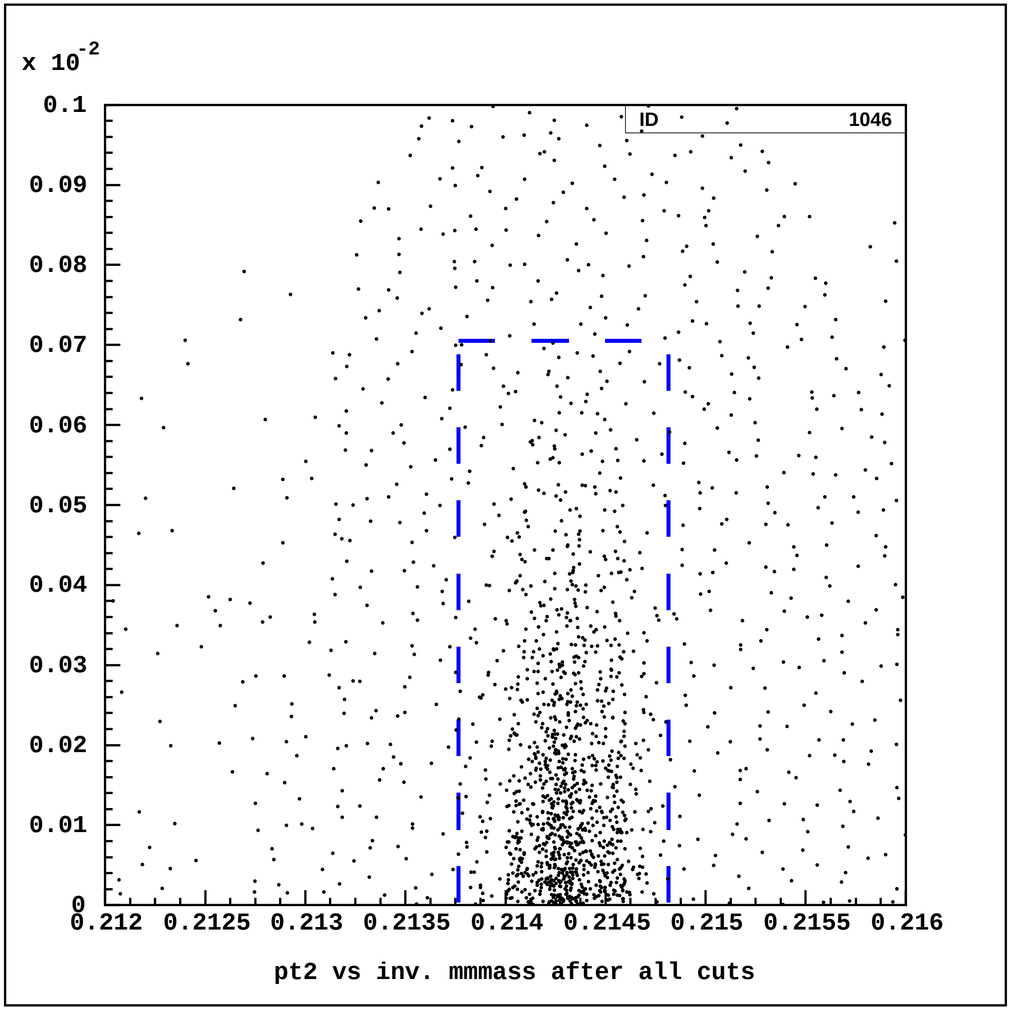
1997 KTeV *Data*

~ Box Dimensions ~

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

$p_T^2 \leq 130$ MeV^2

Opening of the 1997 X^0 Box!

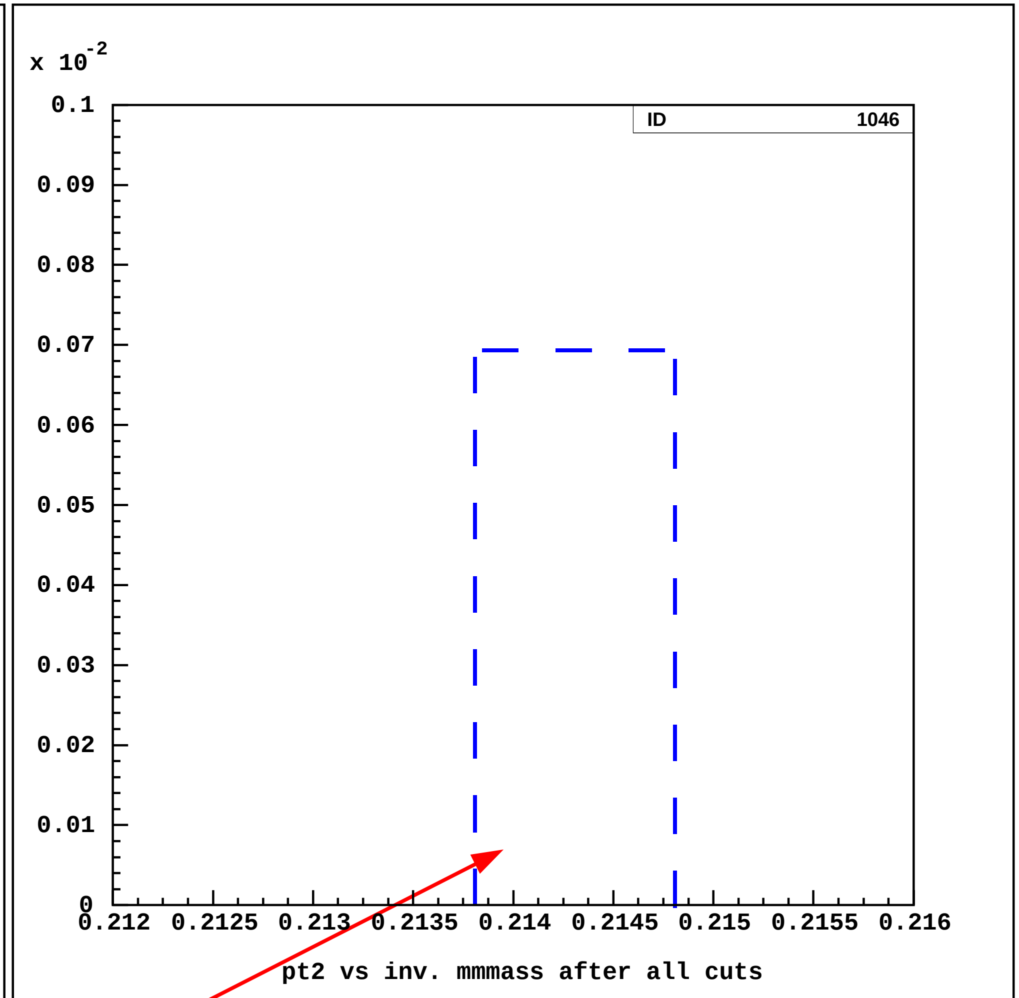


1997 $K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ MC

~ Box Dimensions ~

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

$p_T^2 \leq 700$ MeV^2



1997 KTeV Data

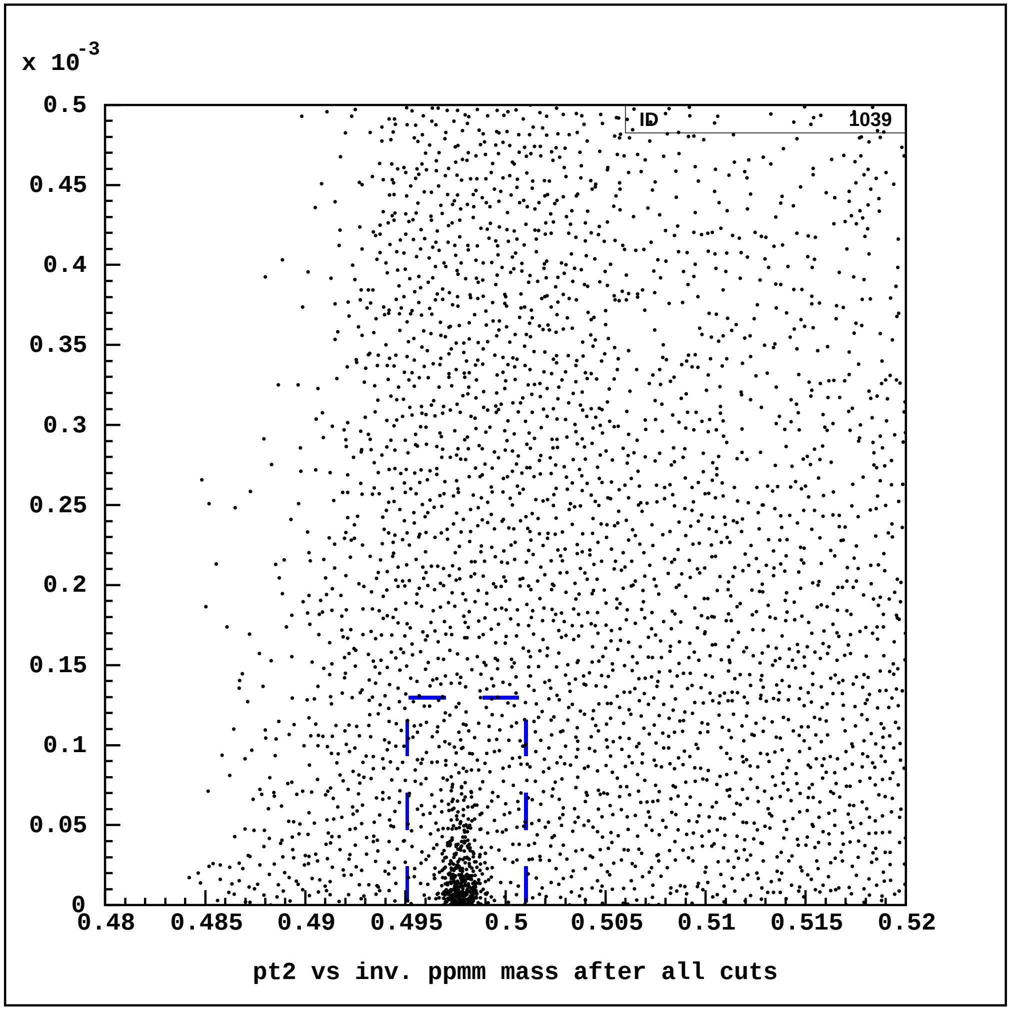
~ Box Dimensions ~

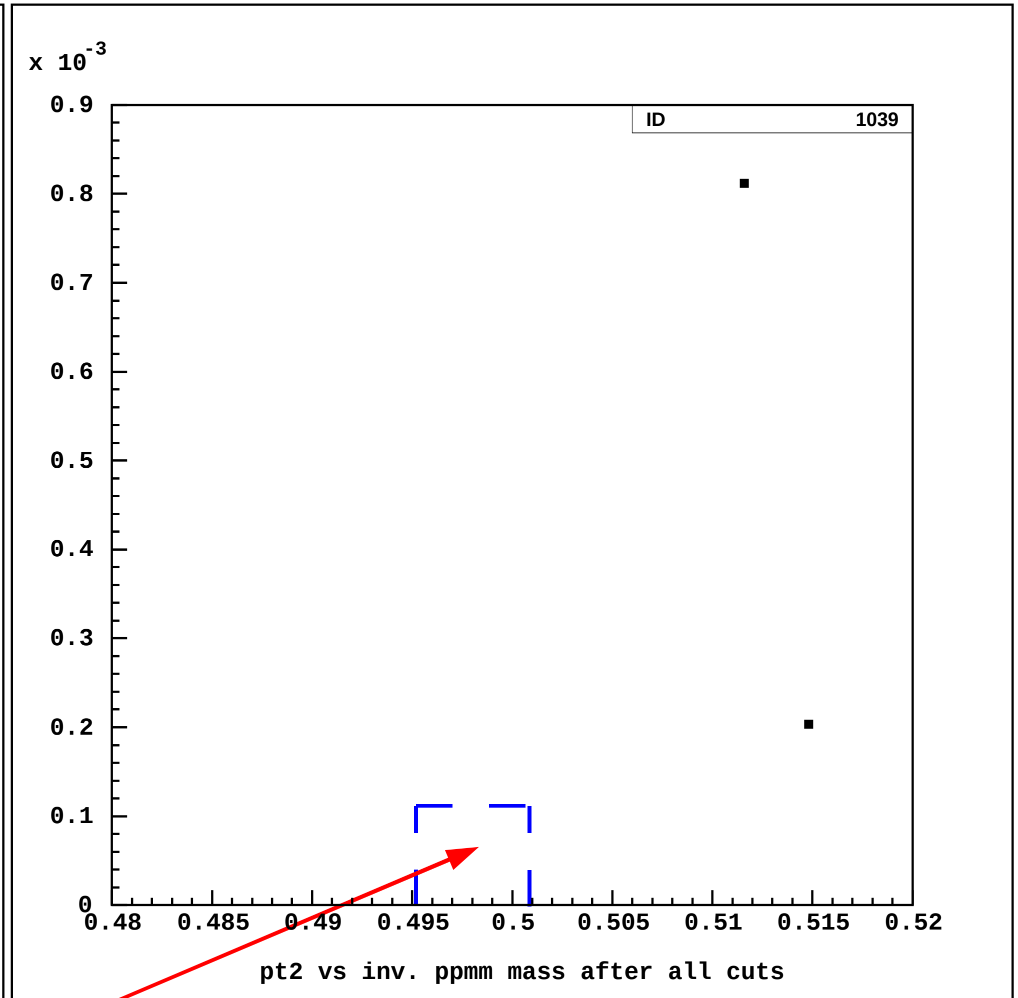
213.8 MeV $\leq M_{\mu\mu} \leq$ 214.8 MeV

$p_T^2 \leq 700$ MeV^2

X^0 Signal Box Opened and is EMPTY!

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 ≤ 130 MeV^2

K_L Signal Box Opened and is EMPTY!

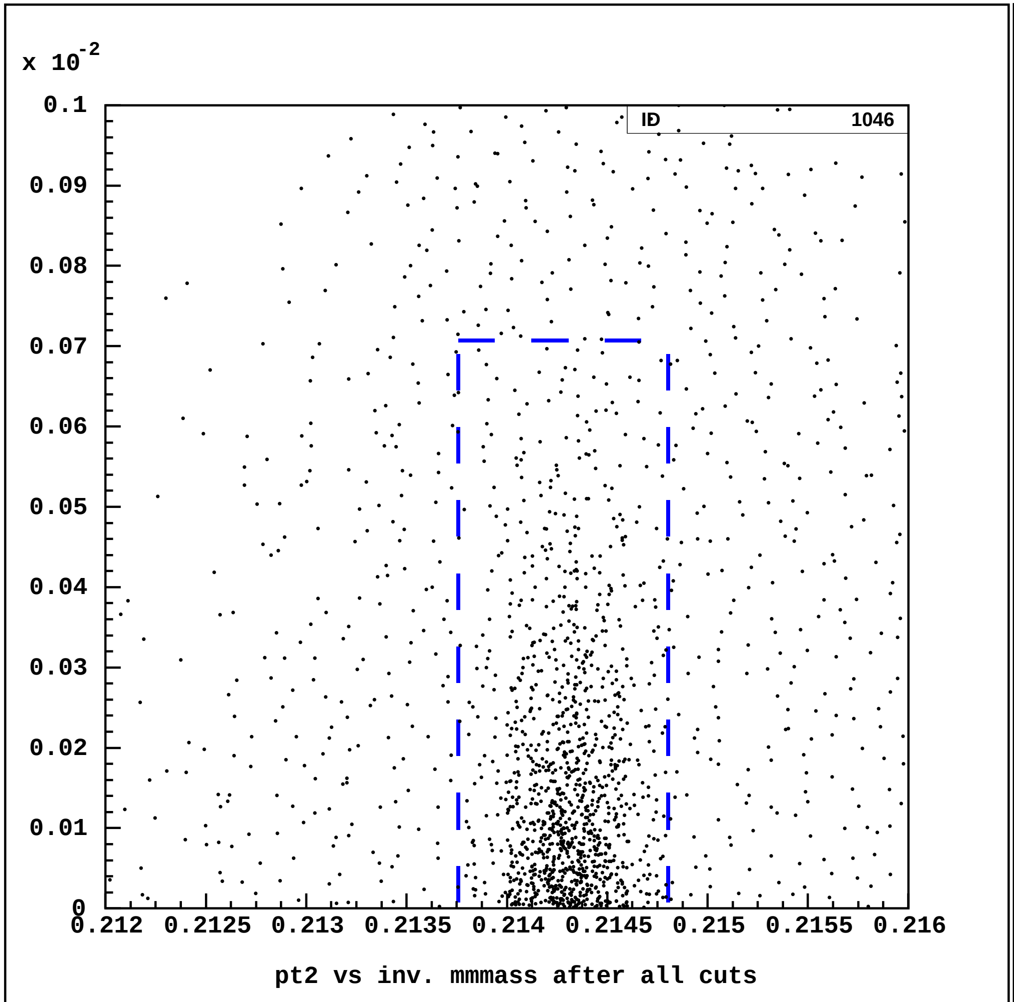
1999 KTeV Data

~ Box Dimensions ~

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

p_T^2 ≤ 130 MeV^2

Opening of the 1999 X^0 Box!

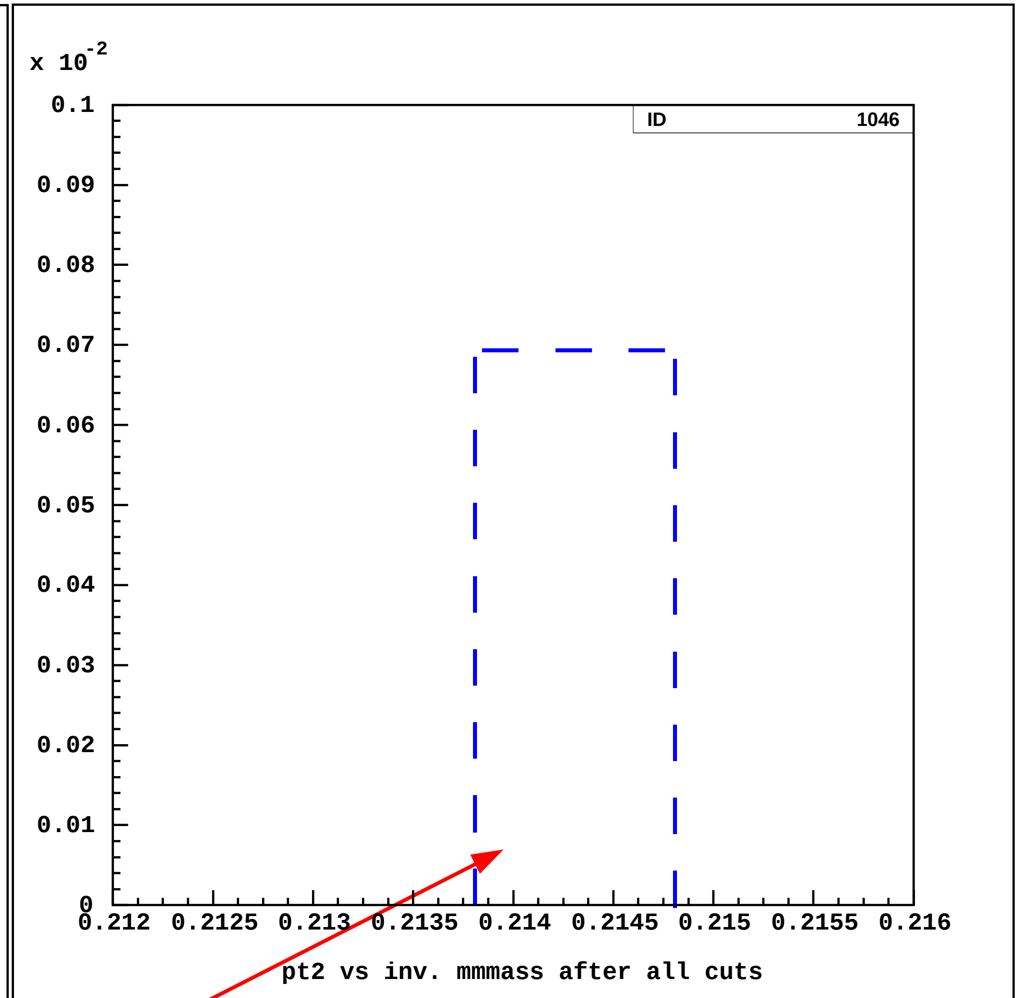


1999 $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ MC

~ 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!

Normalization Mode ($K_L \rightarrow \pi^0\pi^0\pi^0_D$) *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
$0.95 \leq E_{cl}(track) / p_{track} \leq 1.05$	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

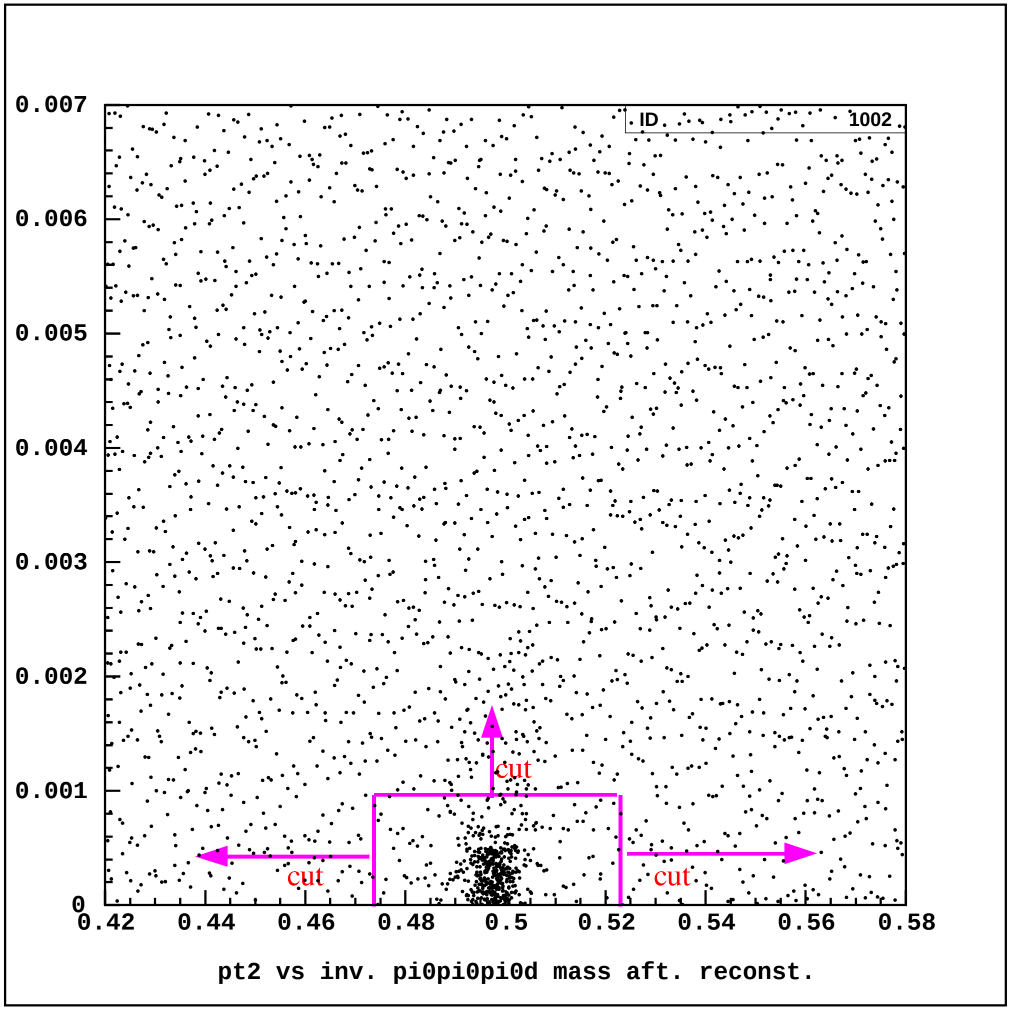
183,131 events

* = *cuts listed in chronological order,*

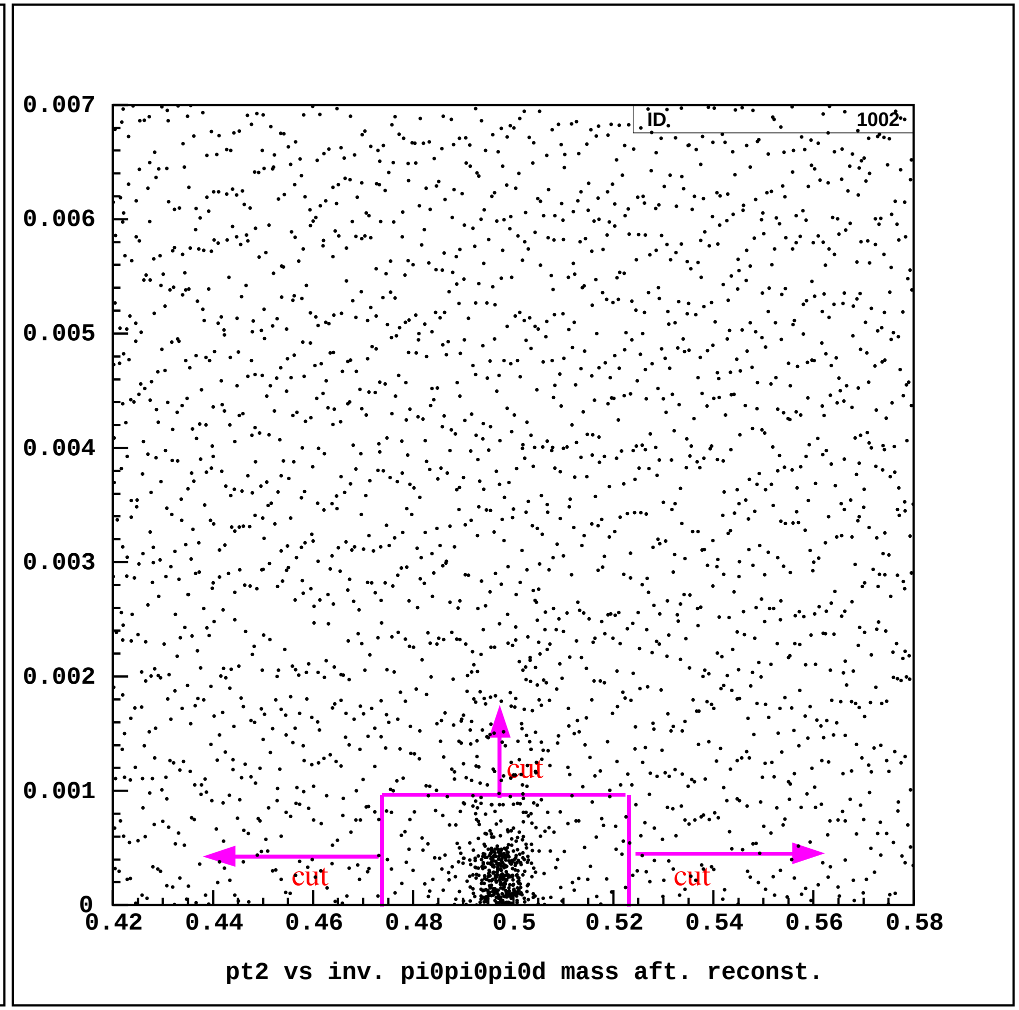
♫ = *initial # data events was ~47.2 M (# generated MC events was ~1.41 G),*

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

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



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



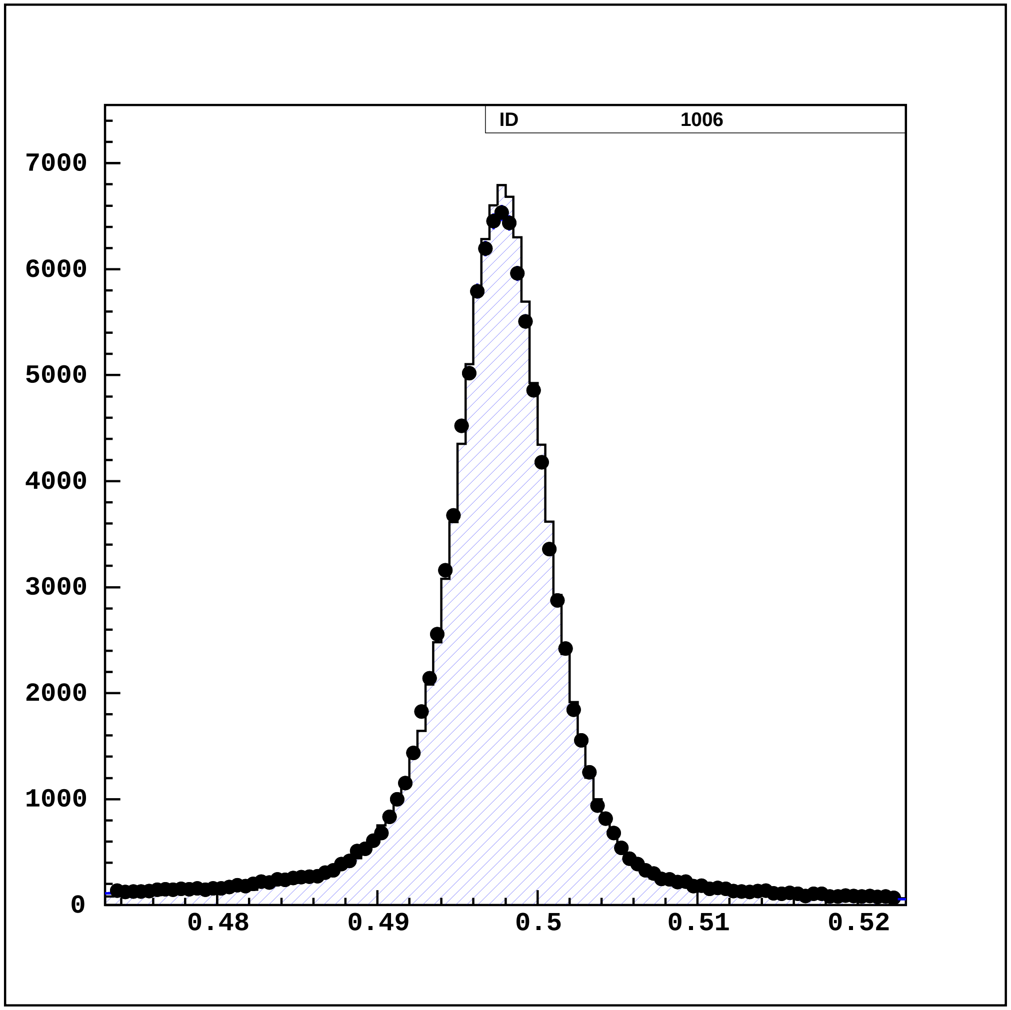
1997 KTeV Data

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

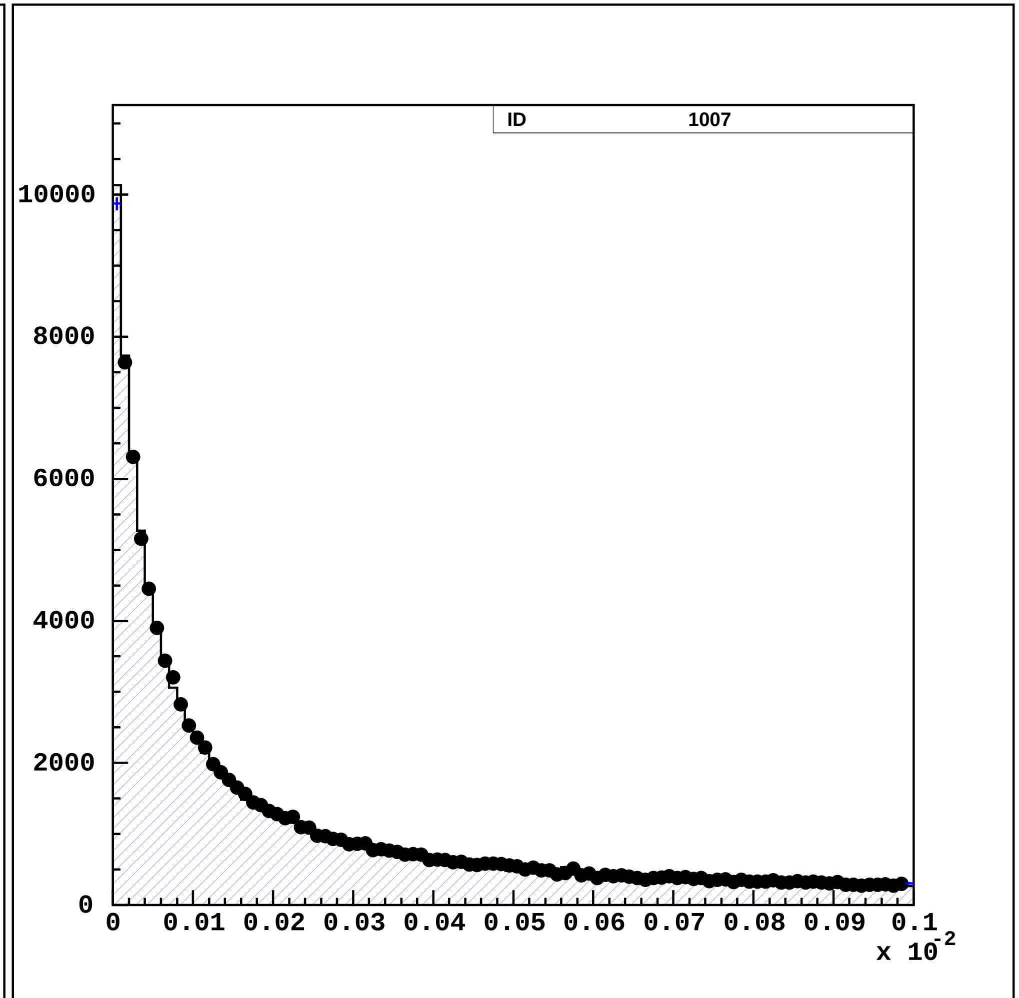
473 MeV $\leq M_{\gamma\gamma\gamma\gamma ee} \leq$ 523 MeV

$p_T^2 \leq 0.001$ GeV^2

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

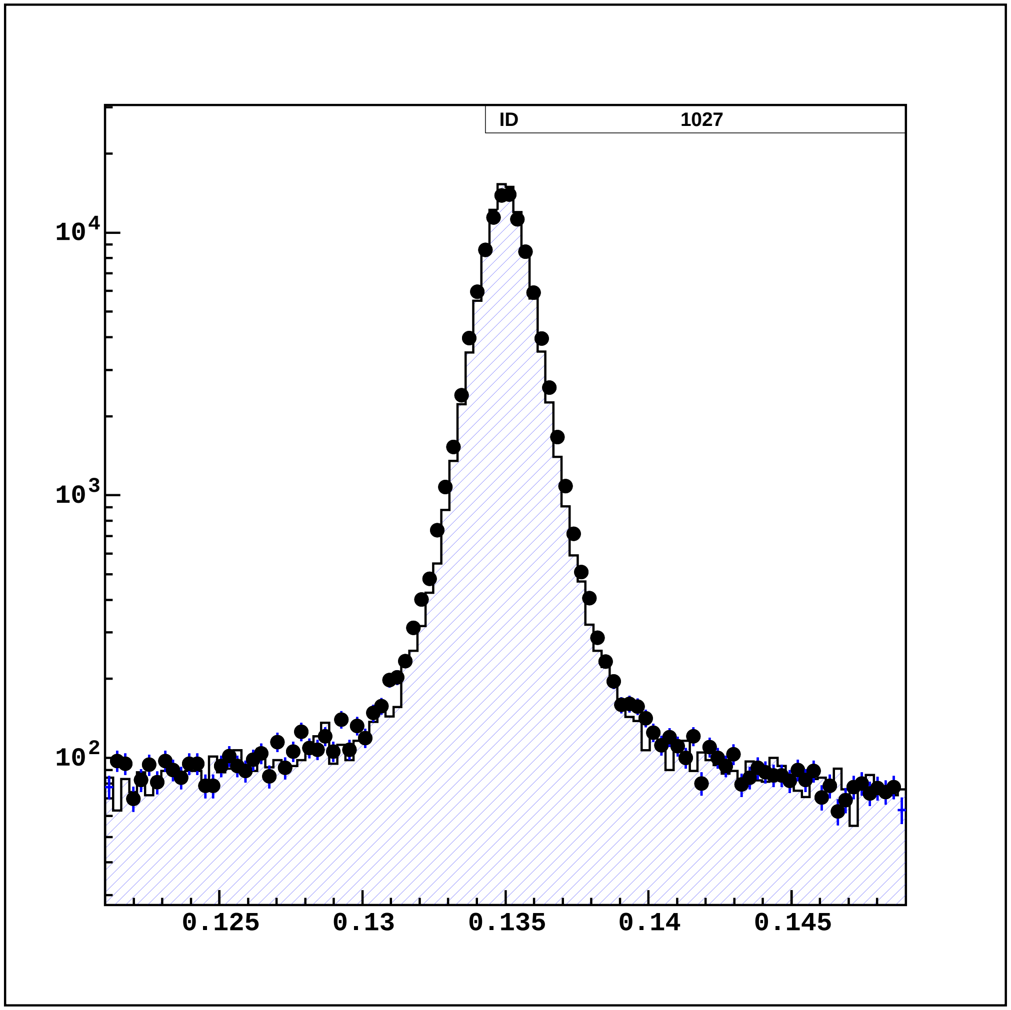


1997 $\pi^0\pi^0\pi^0_D$ P_T^2

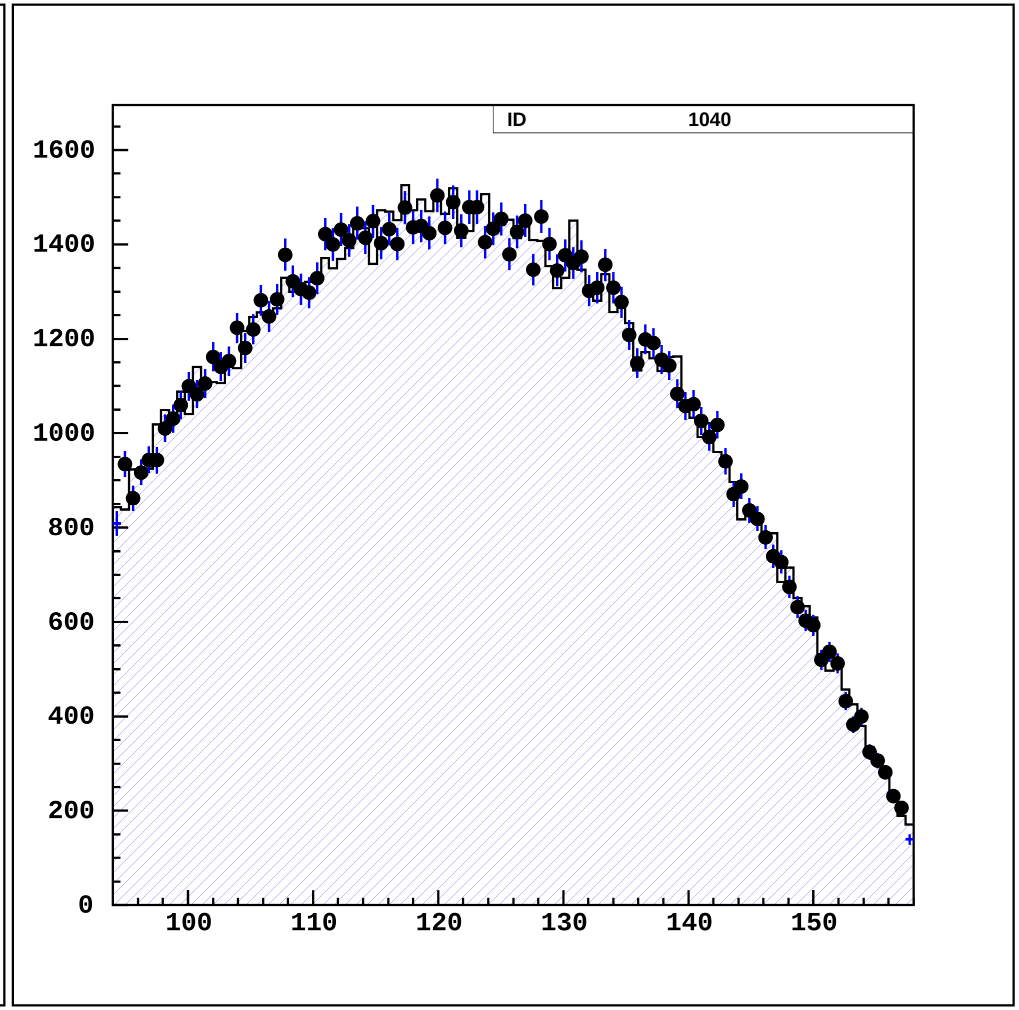
● = Data

□ = 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

K_L Flux Calculation

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

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

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

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

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

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

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

Putting everything together yields →

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

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

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

Source of Systematic Error	$\frac{\Delta F_{Norm,1997}}{F_{Norm,1997}}$	$\frac{\Delta F_{Norm,1999}}{F_{Norm,1999}}$
$(473 \mp 1)\ \text{MeV} \le M_{ee\gamma\gamma\gamma\gamma} \le (523 \pm 1)\ \text{MeV}$	+0.04% -0.05%	+0.05% -0.06%
$\lvert M_{rec.pi0} - M_{pi0} \rvert \le (14 \pm 1)\ \text{MeV}$	+0.02% -0.03%	+0.02% +0.01%
$(94.0 \mp 1.0)\ \text{m} \le Z_{VTX} \le (158.0 \pm 1.0)\ \text{m}$	+0.16% +0.02%	+0.20% -0.10%
$P_T^2 \le (1.0 \pm 0.1) \times 10^{-3}\ \text{GeV}^2$	+0.11% +0.02%	+0.06% -0.08%
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	+0.91% - 0.89%	+2.08% - 2.07%

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

$$\Delta F_{Norm} = \frac{N^{Data}_{Norm} \pm \Delta N}{A_{Norm} \pm \Delta A} - F_{Norm}$$

Systematic from E/p 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]

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

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!!!
(Systematic Error from E/p still under study)

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

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

Compare with:

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

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

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.

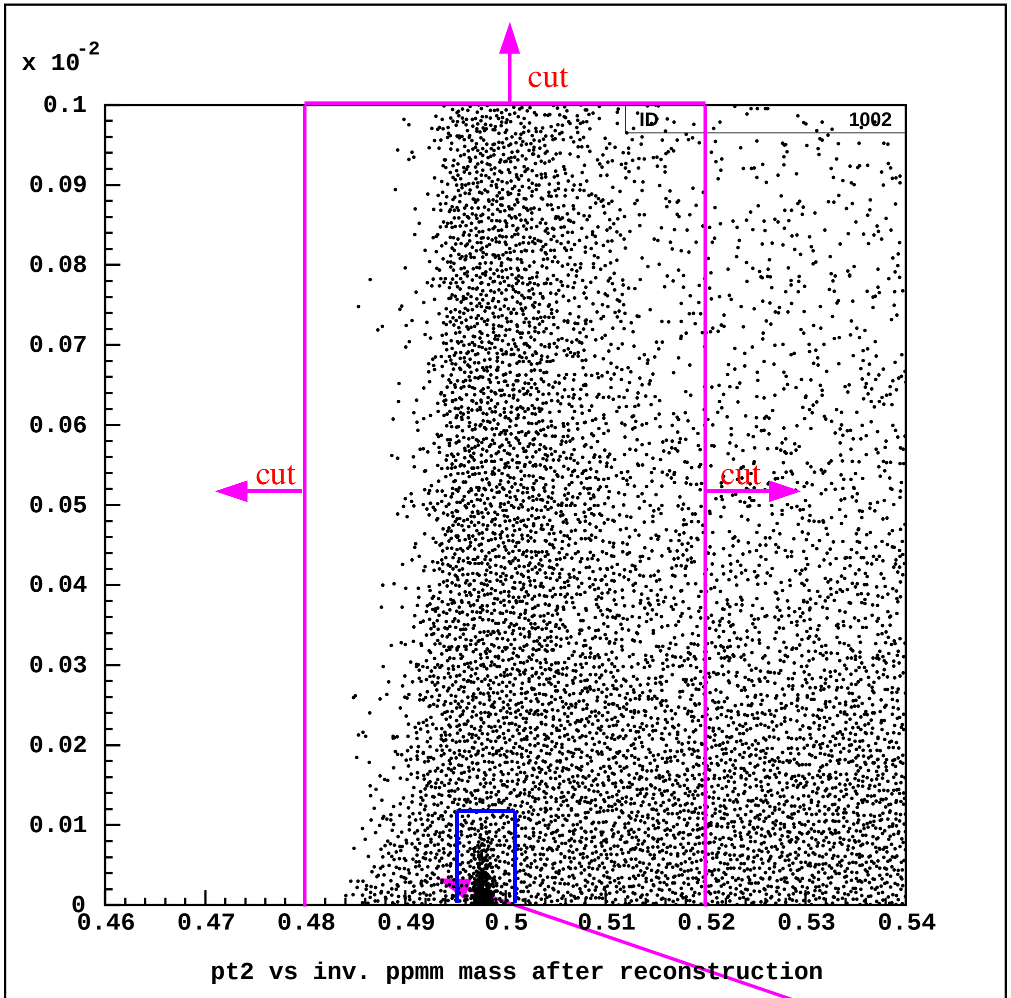
- based on these preliminary results, the pseudoscalar X^0 candidate has been ruled out as an explanation for the neutral boson X^0 observed by HyperCP. However, an axial vector X^0 candidate has not been ruled out.

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

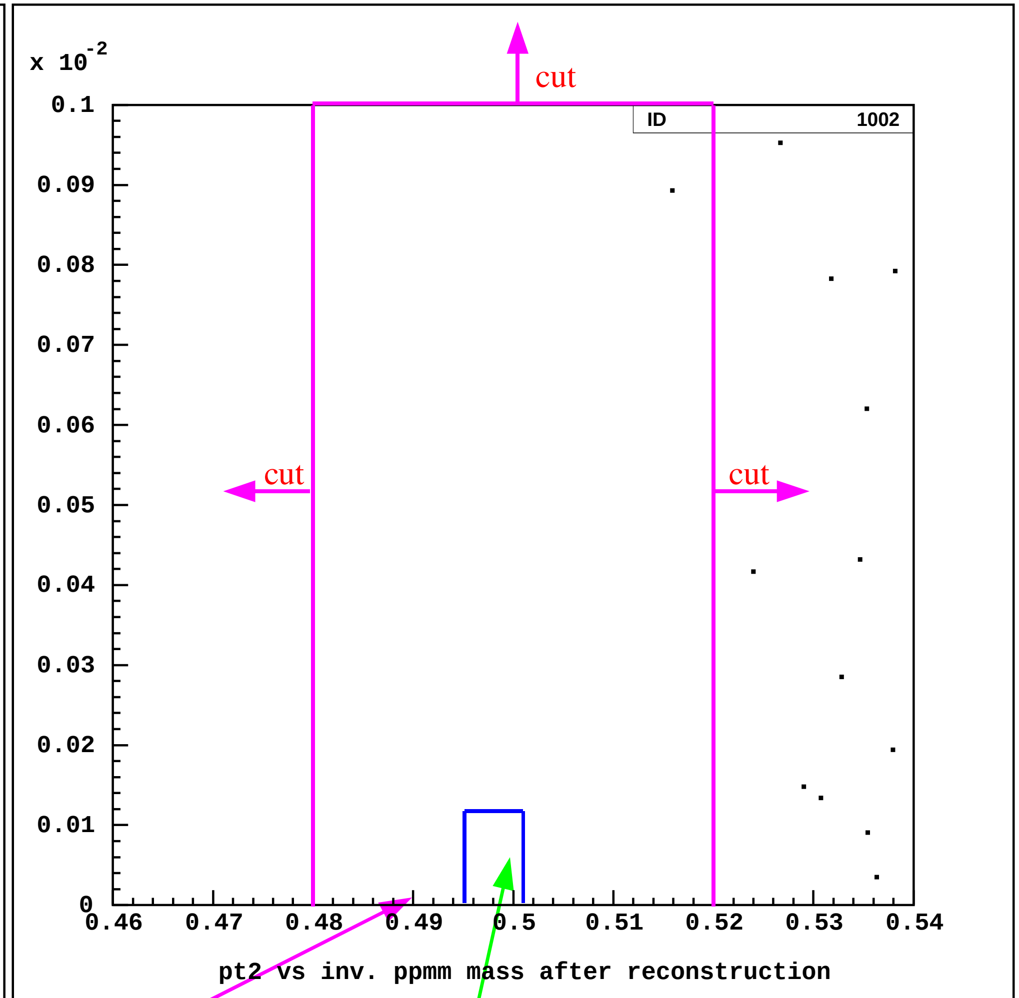
~ Backup Slides ~

Cut on P_T^2 vs. Inv. K_L Mass

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



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



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

~ Box Dimensions ~

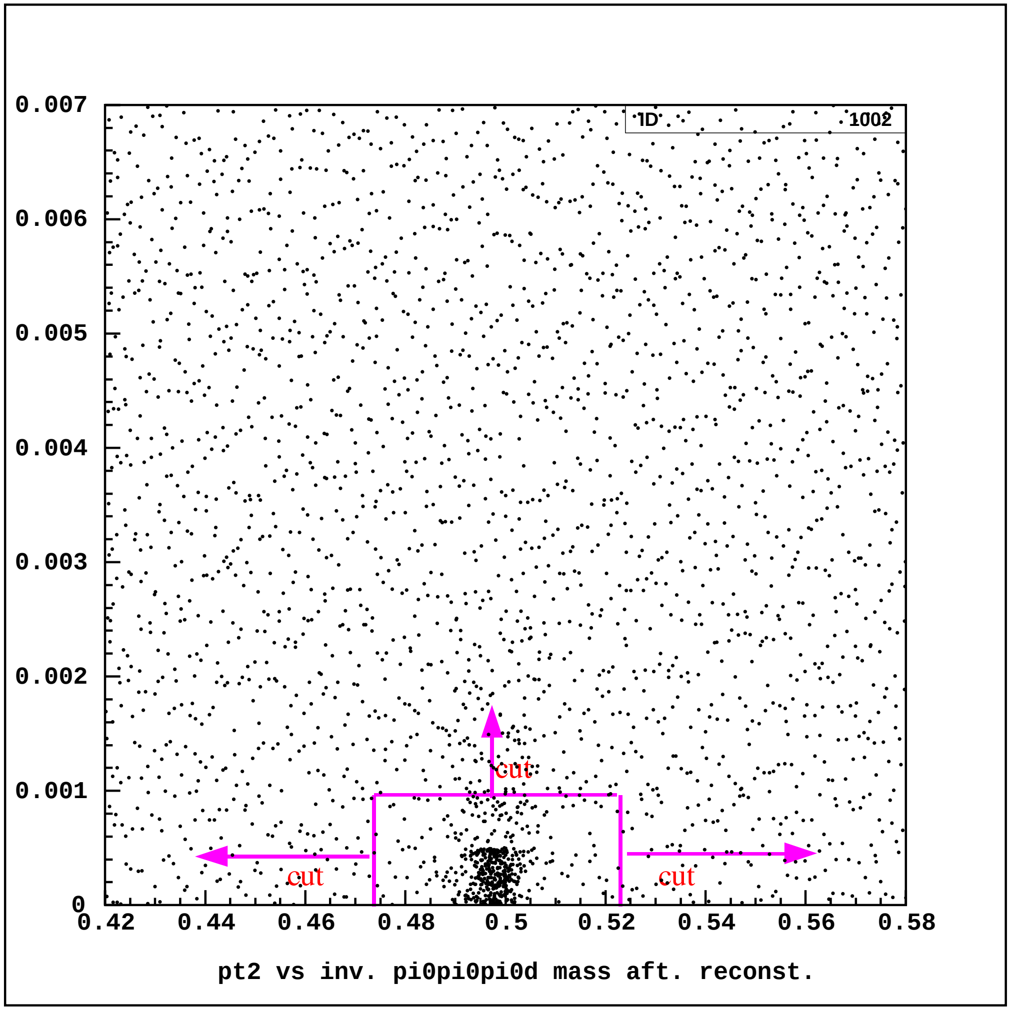
$495\ \mathrm{MeV} \leq M_{\gamma\gamma\gamma\gamma\mu\mu} \leq 501\ \mathrm{MeV}$

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

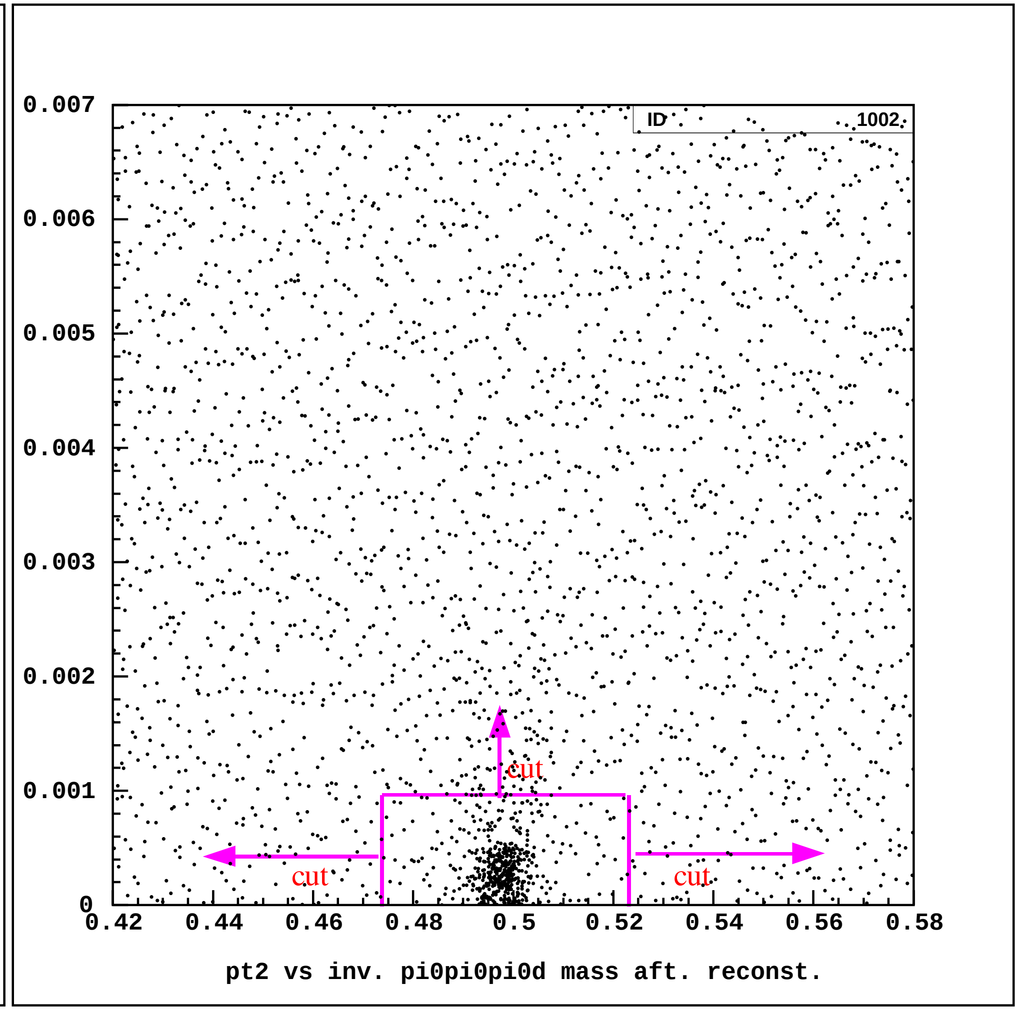
Signal box for MC is open, but for Data remains closed!

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

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



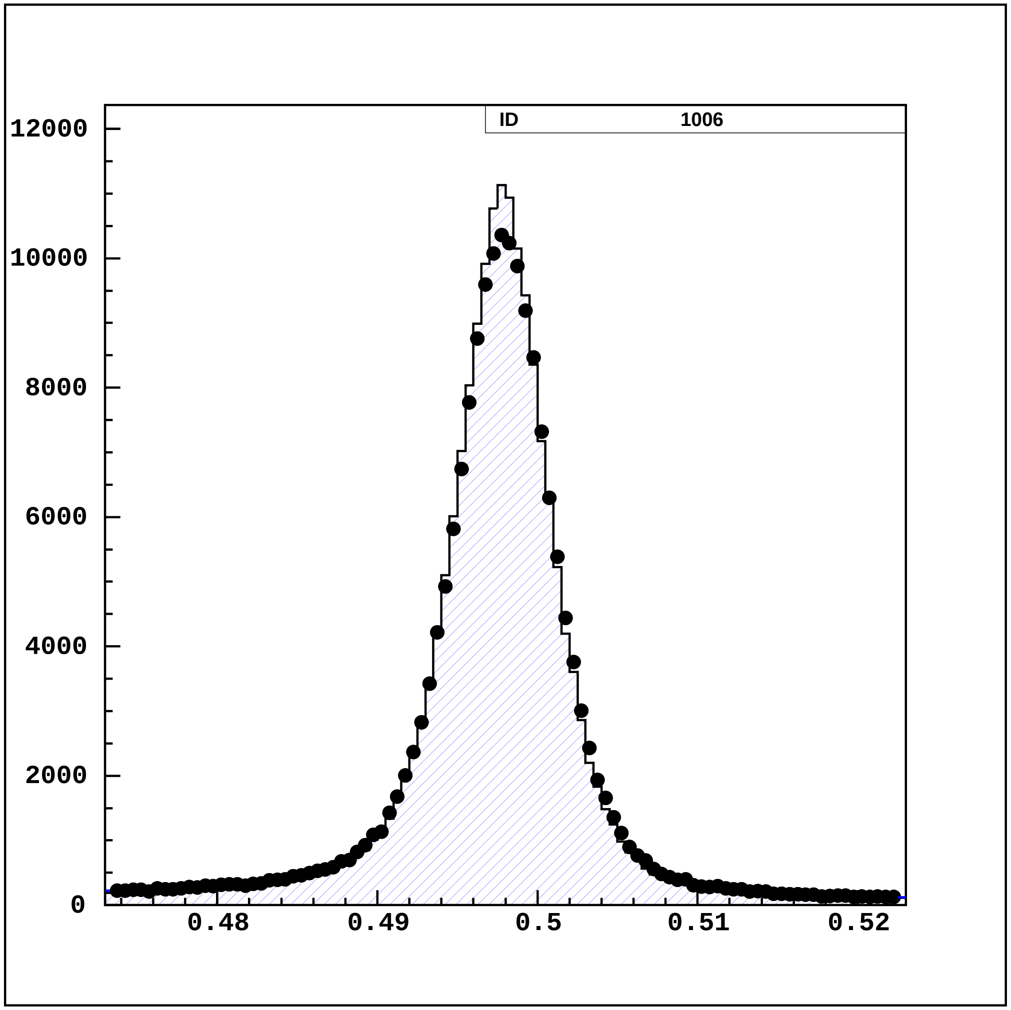
1999 KTeV Data

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

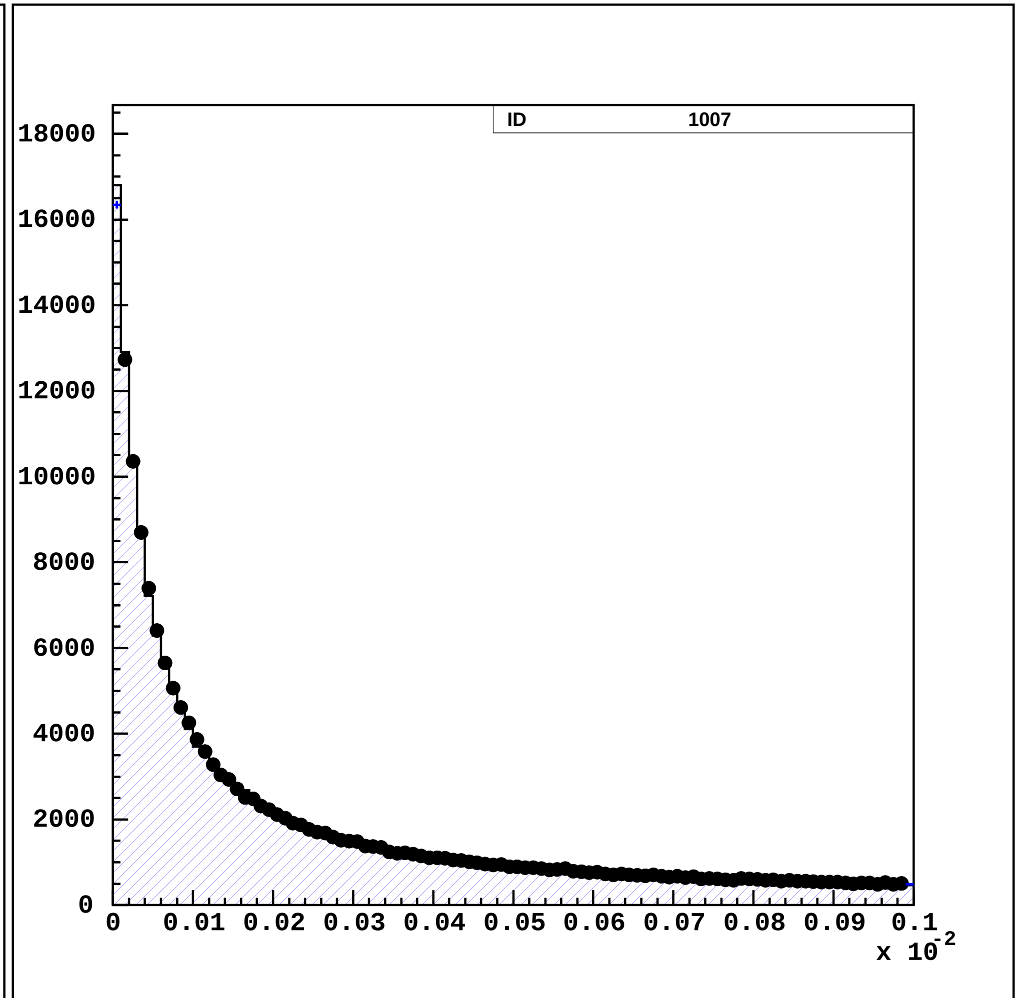
473 MeV $\leq M_{\gamma\gamma\gamma\gamma ee} \leq$ 523 MeV

$p_T^2 \leq 0.001$ 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

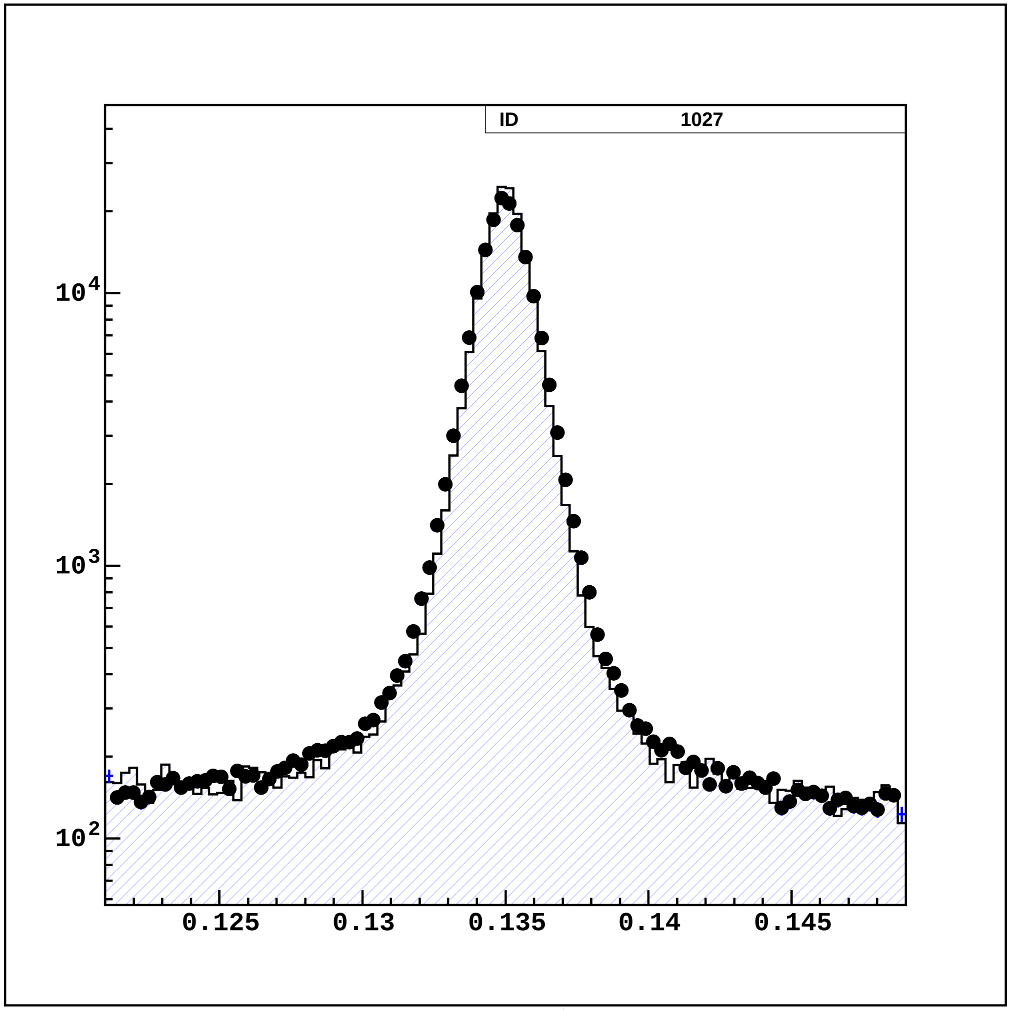


1999 $\pi^0\pi^0\pi^0_D$ P_T^2

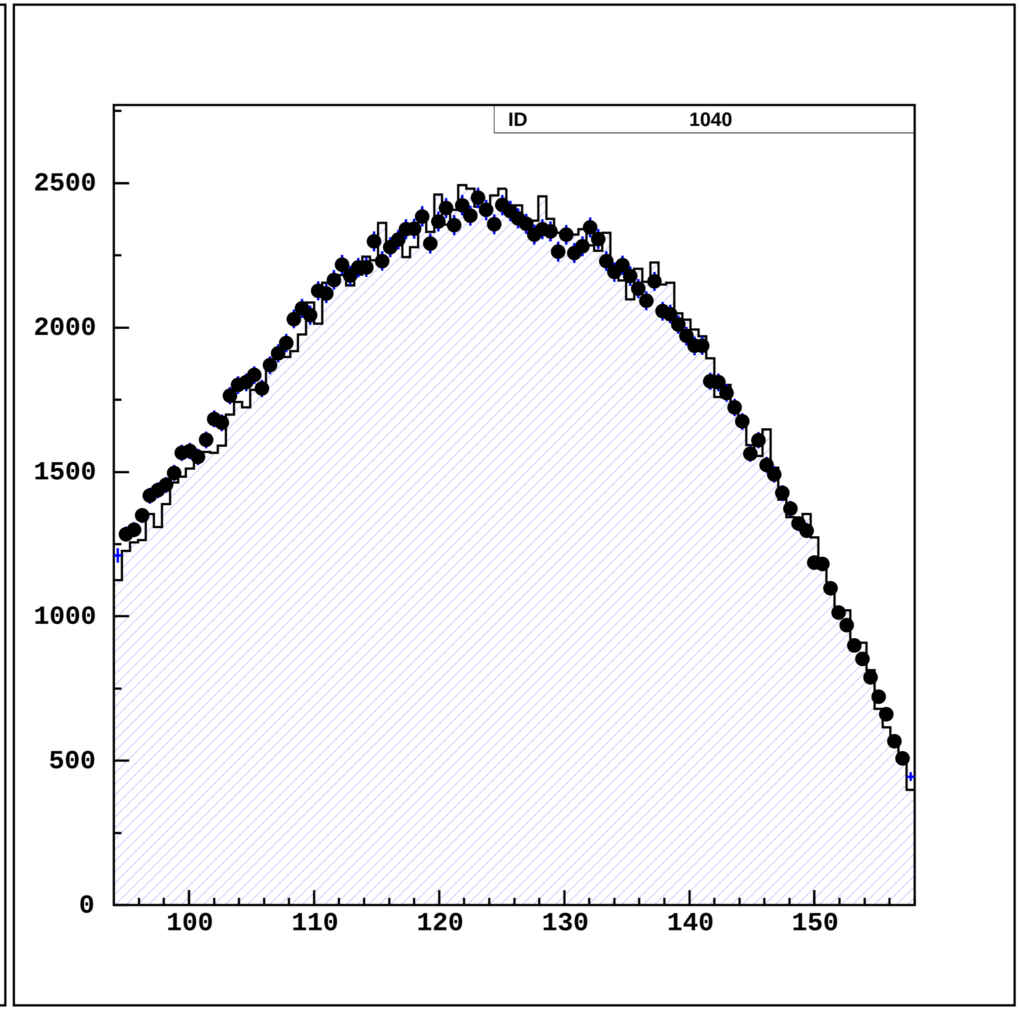
● = Data

□ = MC

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



1999 $\pi^0\pi^0\pi^0_D$ 1st π^0 Mass



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

● = Data

□ = MC

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.

What Is A 'Blind Analysis'?

- a 'blind analysis' is a technique of hiding some part of the data to prevent experimenter's bias, or that bias which stems from someone "unconsciously working toward a certain value."

- in this analysis, we could be setting ourselves up for a truly dangerous bias scenario, since we're looking for a signal that's at the edge of phase space.

- Why? 1) One could choose cuts to remove individual events, thereby possibly yielding a better upper limit than is deserved.
  2) Or one could choose cuts to retain individual events, which could potentially produce a signal where none is warranted.

Why Do We Need A 'Box'??

- we need to define our signal region in terms of two experimental parameters that will separate signal from backgrounds.

- since we can simulate the signal, determine its' efficiency and estimate the size of the background in the signal region using the invariant K_L mass and P_T^2, then a 2D signal box using these variables does the job well.