The Search for $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\mu^+\mu^-$

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High Energy Physics Seminar

May 2, 2007

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Introduction & Motivation

- a preliminary KTeV study on $K_L \to \pi^0 \pi^0 \mu^+ \mu^-$ was performed in late 2005.

- currently, there's no published calculation inside the Standard Model for $Br(K_L \to \pi^0 \pi^0 \mu^+ \mu^-)$, although the decay is possible via γ^*.

- however, HyperCP reports a *'potential'* new neutral boson X^0 observed via $\Sigma^+ \to p X^0 \to p \mu^+ \mu^-$. They determined the following branching ratios:

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

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

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

Previous Studies

~Theorist Brainstorming~

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

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

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

$$Br(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) = 8.02\,x10^{-9} \qquad \text{(\textit{Deshpande et al.}, 2005)}$$

- 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:

$$Br[\mathrm{K}^+ \to \pi^+\mu^+\mu^-] = (8.1 \pm 1.4)\, x10^{-8} \qquad (PDG,\ 2004)$$

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

$$Br(\Sigma^+ \to pX^0{}_{\mathrm{S}} \to p\mu^+\mu^-) < 6\, x10^{-11}, \quad Br(\Sigma^+ \to pX^0{}_{\mathrm{V}} \to p\mu^+\mu^-) < 3\, x10^{-11}$$

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

- they then use existing constraints on pseudoscalar or axial vector X^0's to predict the pseudoscalar and axial vector X^0 contributions to the $K_L \to \pi^0\pi^0\mu^+\mu^-$ decay mode:

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

(*Valencia et al.*, 2005)

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

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

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 $K_L \rightarrow \pi^0\pi^0e^+e^-$.

- the amplitude of $K_L \rightarrow \pi^0\pi^0e^+e^-$ 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 $K_L \rightarrow \pi^0\pi^0\gamma$.

- even in the narrow phase space of $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$, the direct γ^* production will only yield a background in the $\mu^+\mu^-$ mass band around 214 MeV.

Previous KTeV Studies

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

- 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 $1.4\,x10^{-10}$

~signal of less than 2.3 events

90% C.L. $\rightarrow$

~partial width for 'new physics' estimated to be $< 4.0\,x10^{-24}\,MeV$

- the aforementioned analysis does however have some potential shortcomings that need to be addressed, such as the following:

  ~identification and estimation of background.

  ~selection and completion of a normalization analysis.

  ~systematics in the sensitivity!

  ~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.

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

- KTeV thesis on $K_L \rightarrow \pi^0 \mu^+ \mu^-$ was completed in early 1999.

- this decay is particularly interesting since it contains a direct CP violating contribution within the Standard Model.

- two events were observed with an expected background of 0.87 ± 0.15 events from MC simulation. The upper limit was set at:

$$Br(K_L \rightarrow \pi^0 \mu^+ \mu^-) < 3.8\, x10^{-10}$$ ← 90% C.L. (*PRL*, June 2000)

- the above analysis was performed on the KTeV E799 1997 data set only.
An analysis on the 1999 data set has yet to be performed.

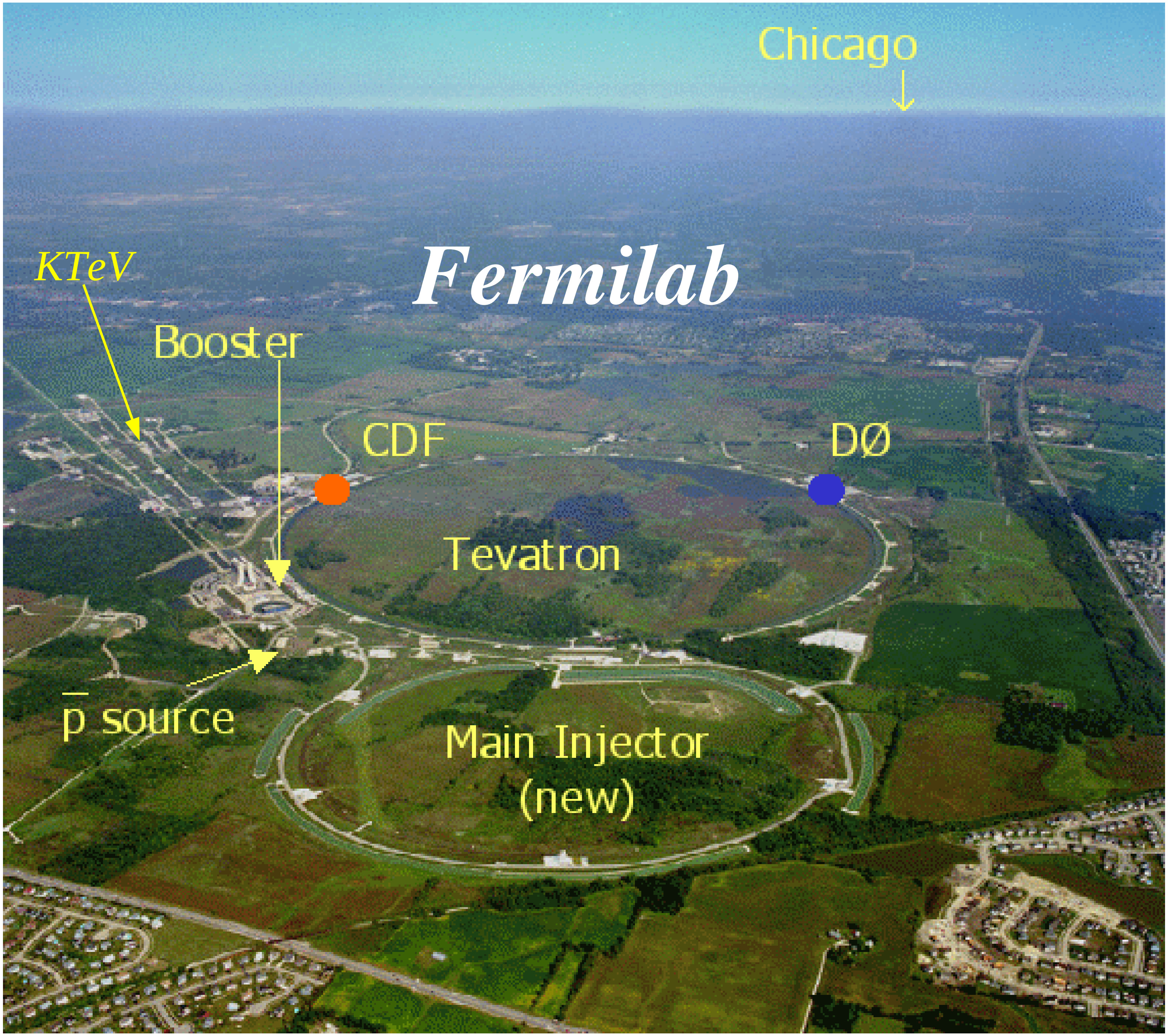
What Is The KTeV Experiment???

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

- 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 is to detect and measure rare K_L decays, especially CP-violating processes.

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


Chicago
Fermilab
KTeV
Booster
CDF
DØ
Tevatron
p̄ source
Main Injector
(new)

Creation of the Neutral Kaon Beam

- neutral kaons are 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 $\sim$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

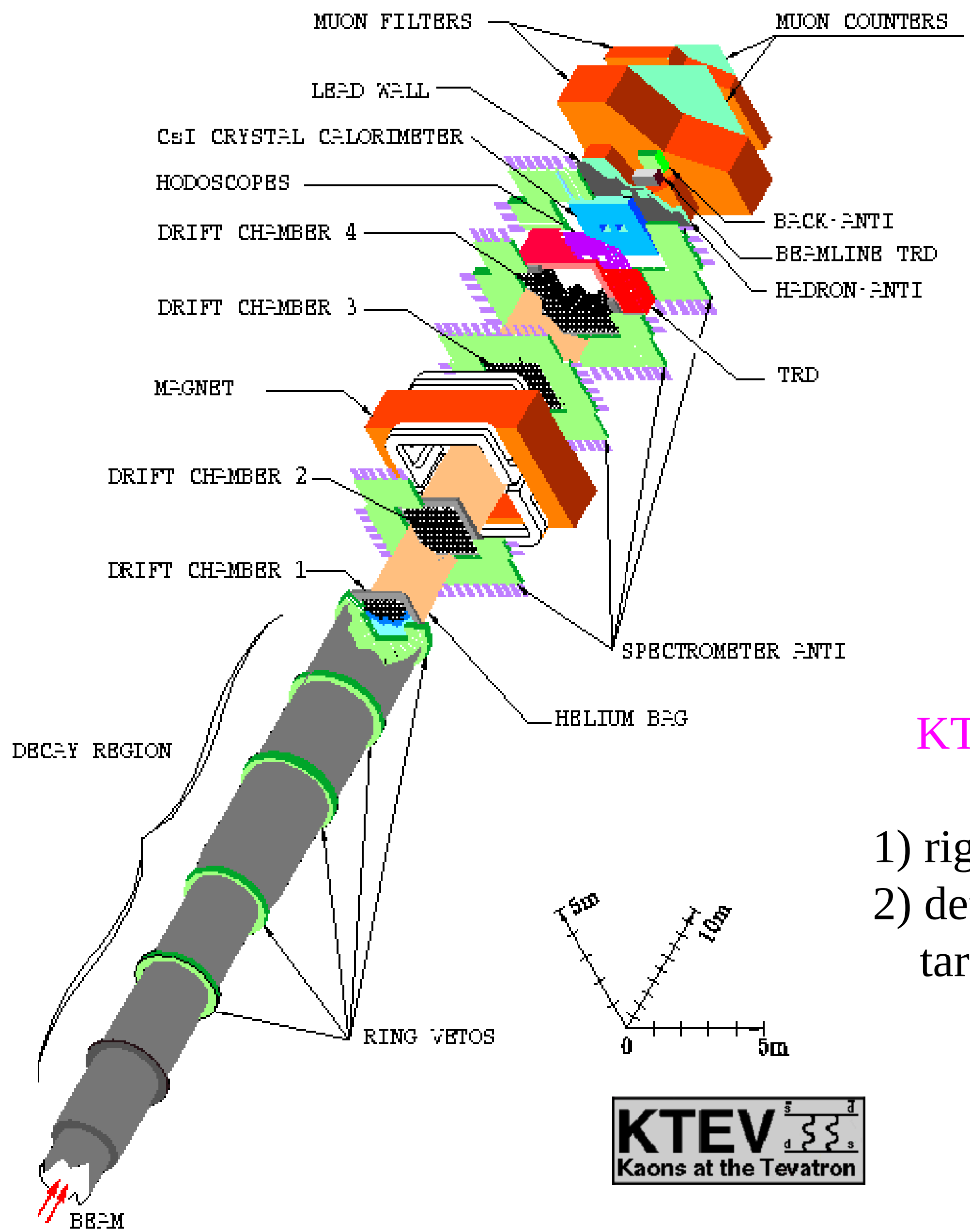
- KTeV uses two parallel neutral kaon beams to produce K_L and K_S decays.
  - ~ E799 uses two identical K_L beams.
    (Note: nearly all of the K_S's and hyperons produced at the target decay before they reach the decay region, which is ~90 m from the target.)
  - ~ E832 also has two K_L beams, but one of them passes through a plastic regenerator to produce K_S's.

- This novel technique is beneficial, because it enables us to collect 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

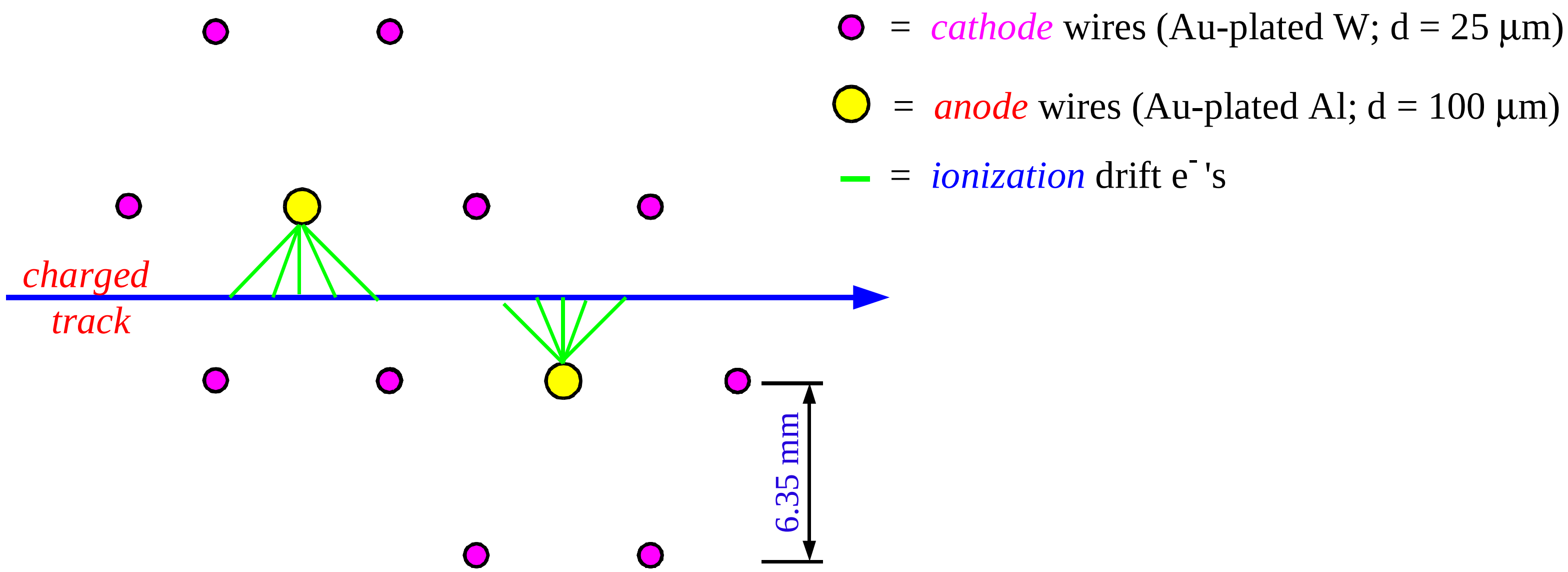


KTeV's coordinate system is:

1) right-handed
2) defined such that the target is at the origin.

The KTeV Spectrometer

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



- Drift Chamber Wire Geometry -

- each drift chamber has a pair of *Y-view* anode wire planes followed by a pair of *X-view* anode wire planes; there are a total of ***1972*** anode wires in the four drift chambers.

- 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.

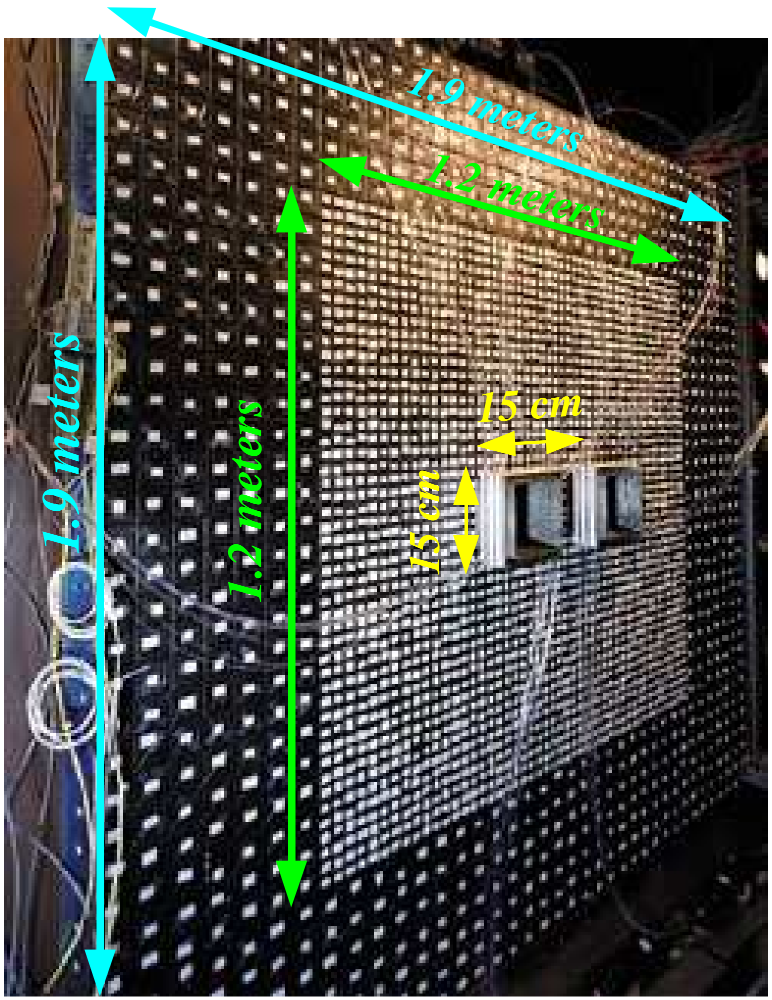
- helium bags were placed before, behind and between each drift chamber to reduce photon conversions, multiple scattering and beam interactions.

- the magnet has a strength of ~0.5 T, produces a field that's uniform to better than 1% and imparts a 0.41 GeV/c kick in the horizontal plane.

- the *momentum resolution* of the spectrometer is:

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

The KTeV Electromagnetic Calorimeter



- the **KTeV ECAL** is 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:

$$\sigma_E / E = (0.4 \oplus 2/\sqrt{E})\ \%, \text{ where } E \text{ is in GeV.}$$

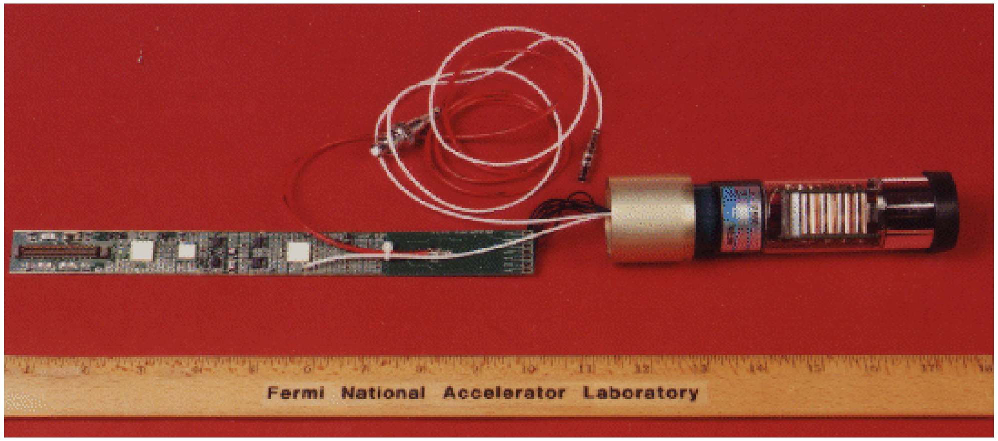
- the position resolution was ~1 mm.

- the π^0 mass resolution (for $K_L \rightarrow \pi^+ \pi^- \pi^0$) was ~1.3 MeV/c^2.

KTeV CsI Crystals & PMTs

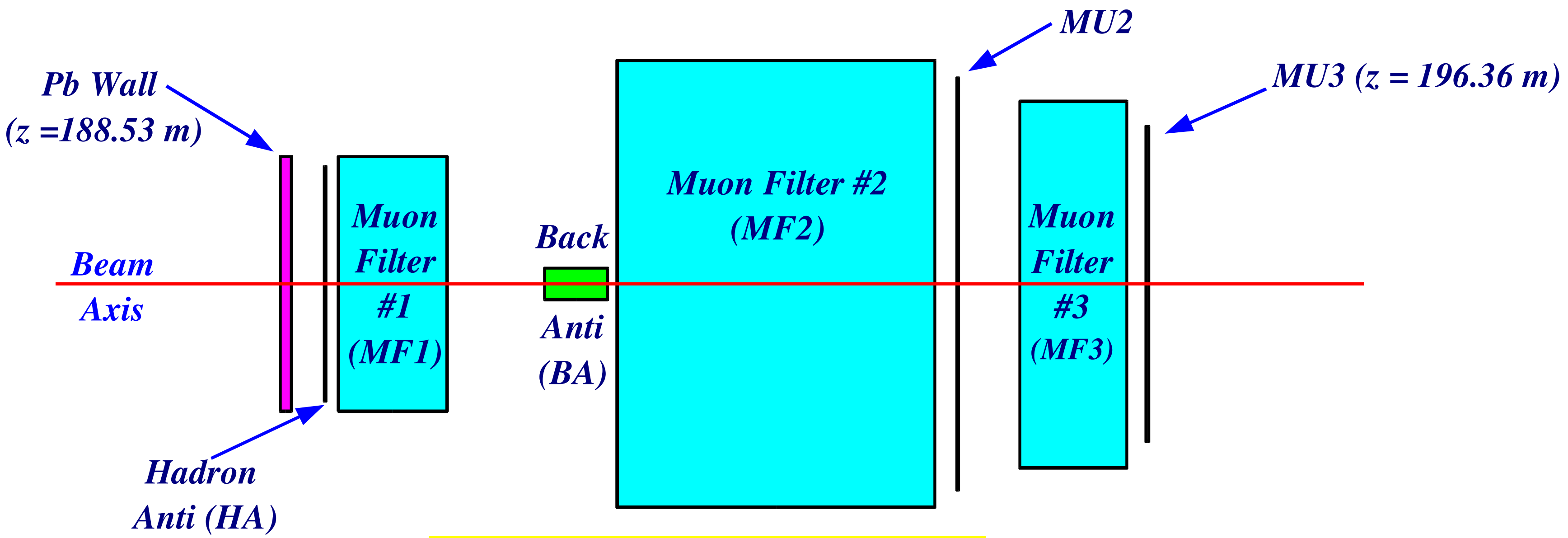
- the CsI crystals all have a unique outer wrapping designed to produce a uniform scintillation response along the length of the crystals.

- in order to maximize the uniformity, the crystals were wrapped in 13 μm thick black and/or reflective mylar coverings; the ratio of black and reflective wrappings as well as the boundary between the two is different for every crystal.



- affixed to each crystal was a photomultiplier (PMT) with a DPMT (digital PMT) board. The DPMT board was created to digitize and buffer the anode signal from the PMT's.

The KTeV Muon ID System



- Muon ID System Schematic -

- the ***Muon ID System*** is a series of particle filters and scintillator planes that are 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 protected 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 150cmx15cmx1.5cm 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.

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

- a 'crunch' has been performed on 130 data storage tapes...these tapes contained approximately *1.73 TeraBytes* of data.

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

- two potential candidates for the *normalization* mode are $K_L \to \mu^+ \mu^- \gamma$ and $K_L \to \mu^+ \mu^- \gamma\gamma$.

<-'97 def'n

TRIG5[2MU-LD] =
GATE*2V*DC12*2MU3*PHVBAR1*2HCY_LOOSE*HCC_GE1

2V = 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 DCOR 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 $\geq$ 500 MeVin the RC's and $\geq$ 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: $\geq$ 1 hardware cluster.

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

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

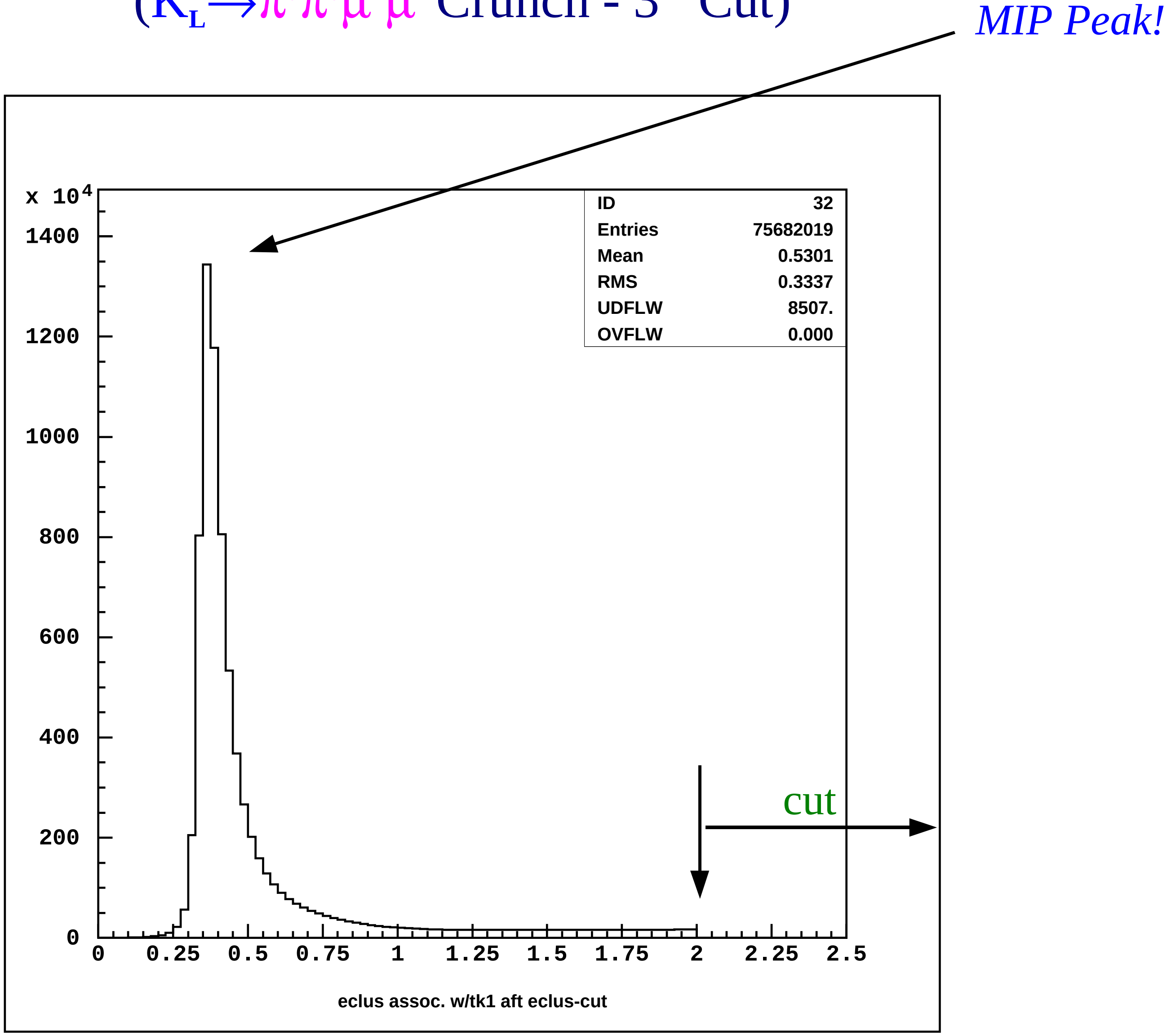
-Crunch Cuts-

$K_L \to \pi^0\pi^0\mu^+\mu^-$ Crunch Cut*	Data♬	MC ♪	Data♬	MC ♪	$K_L \to \pi^0\mu^+\mu^-$ Crunch Cut*
Require 2 tracks	0.700	0.992	0.700	0.996	Require 2 tracks
$C_{track1} = -C_{track2}$	0.999	1.000	0.999	1.000	$C_{track1} = -C_{track2}$
E_{cl}(track) $\leq$ 2.0 GeV	0.391	0.942	0.391	0.982	E_{cl}(track) $\leq$ 2.0 GeV
E_{cl}(track) / $p_{track} \leq 0.9$	0.999	1.000	0.999	1.000	E_{cl}(track) / $p_{track} \leq 0.9$
# γ clusters ≥ 4	0.056	0.629	0.366	0.720	# γ clusters ≥ 2
# hits in μ planes ≥ 1	0.980	1.000	0.982	1.000	# hits in μ planes ≥ 1
$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq$ 15 MeV	0.196	0.983	0.480	0.985	$\lvert M_{rec.pi0} - M_{pi0} \rvert \leq$ 15 MeV
90.0 m $\leq Z_{VTX} \leq$ 160.0 m	0.265	0.985	0.987	0.999	90.0 m $\leq Z_{VTX} \leq$ 160.0 m
			0.887	0.997	400 MeV $\leq K_{\gamma\gamma\mu\mu} \leq$ 600 MeV
$p_T^2 \leq 0.06$ GeV^2/c^2	0.569	0.999	0.678	0.993	$p_T^2 \leq 0.0025$ GeV^2/c^2
Total Acceptance	0.00044	0.569	0.028	0.687	Total Acceptance

** = cuts listed in chronological order, ♪ = initial # events was ~20K, ♬ = initial # events was ~277 M*

Cut On E_{cl} Associated w/the Track

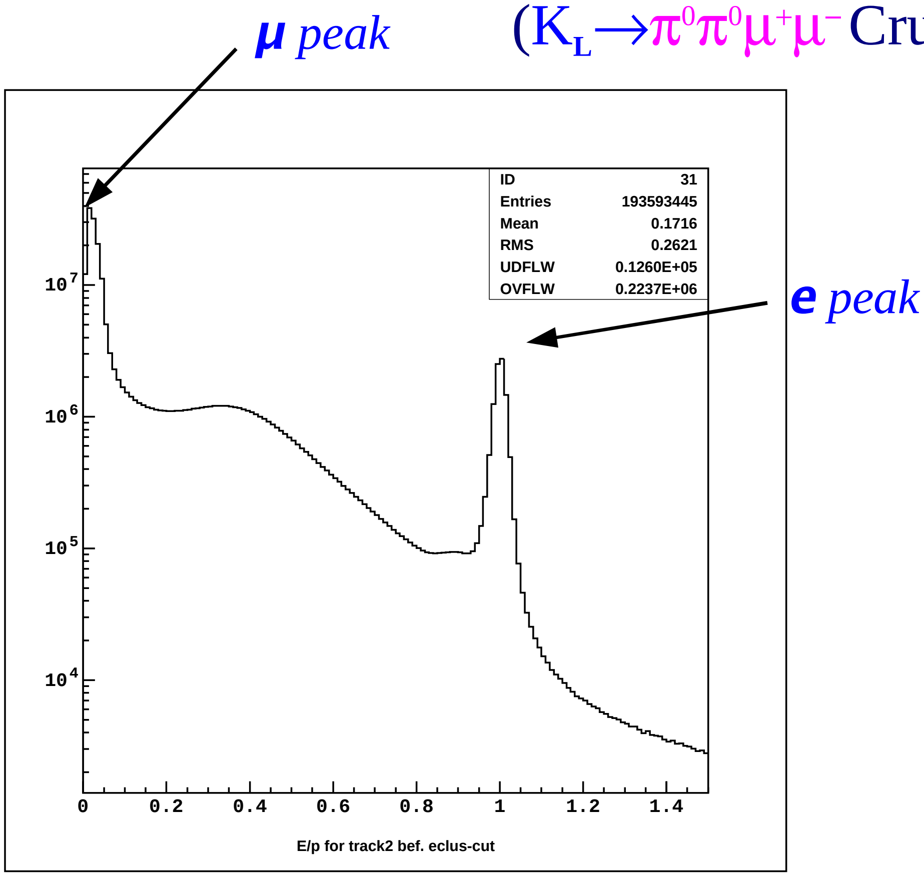
($K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Crunch - 3rd Cut)



Data

Cut On E_{cl}(track)/p_{track}

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



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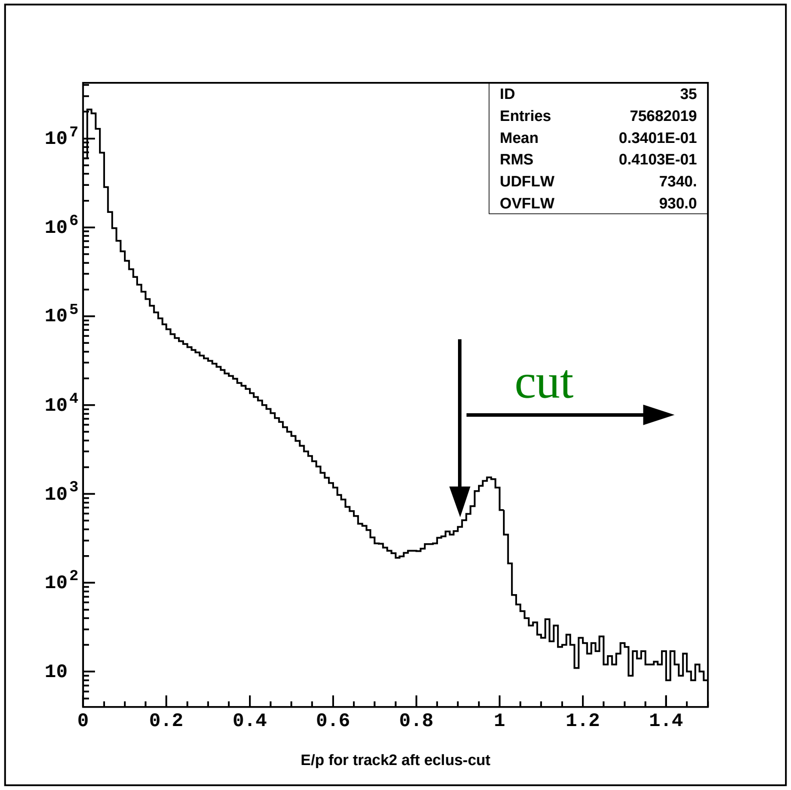
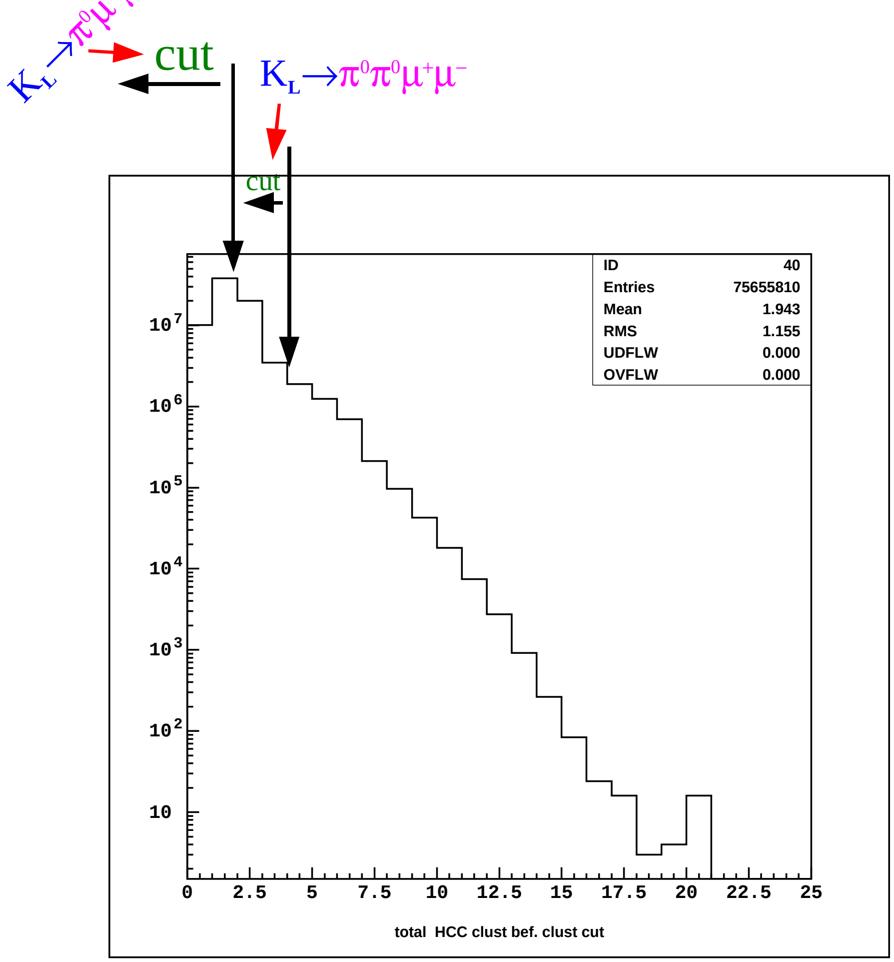


Data

Cut On Number of γ Clusters

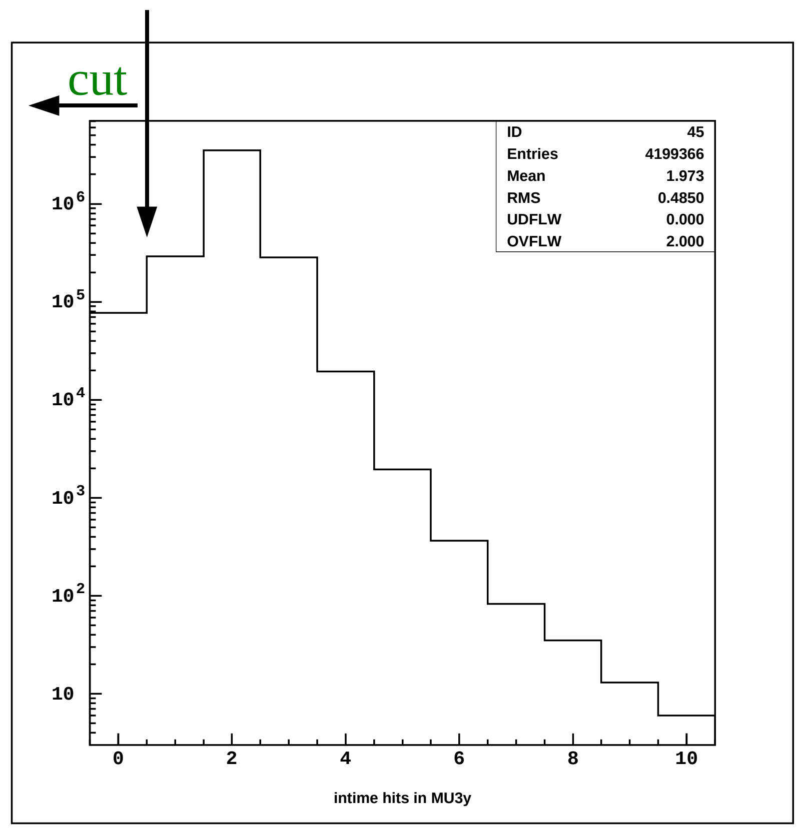
($K_L \to \pi^0\pi^0\mu^+\mu^-$ Crunch - 5th Cut)



Data

Cut On Number of Hits in μ Counting Planes

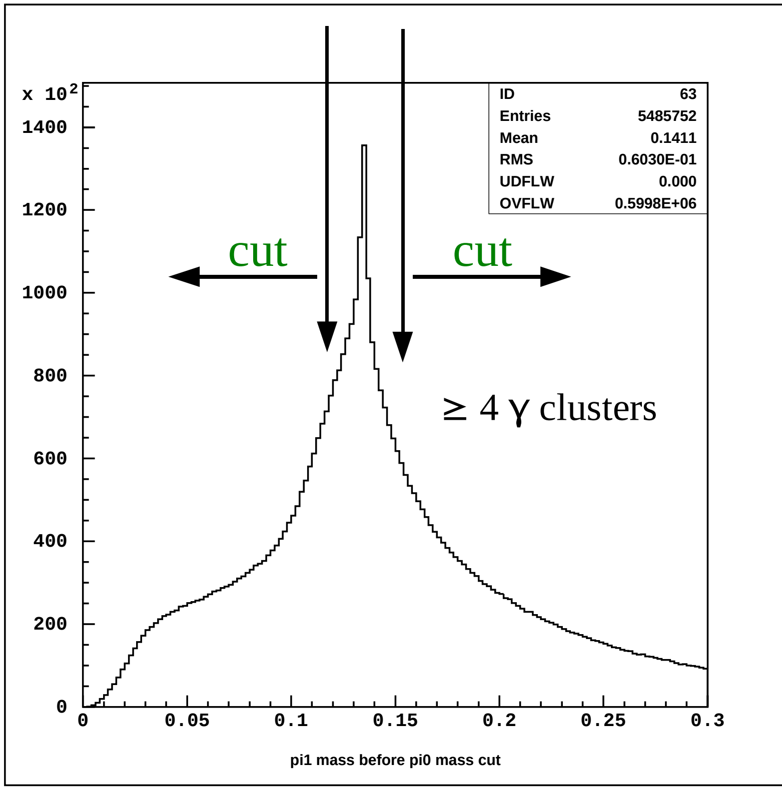
($K_L \to \pi^0\pi^0\mu^+\mu^-$ Crunch - 6th Cut)



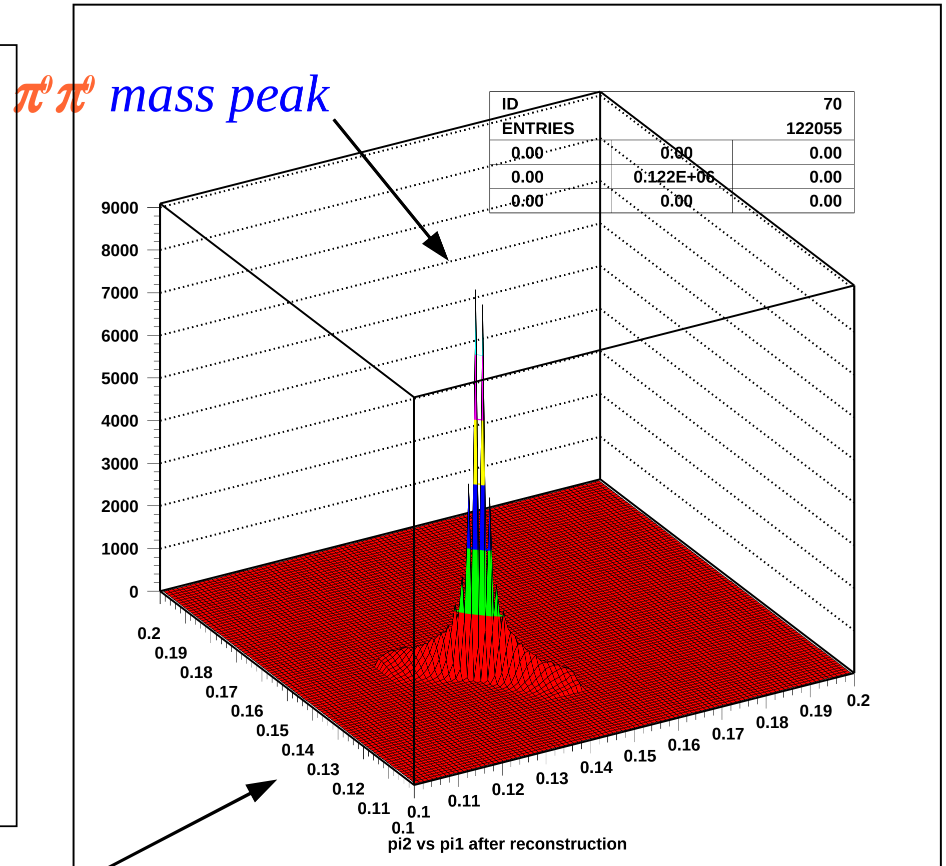
Data

Cut On Reconstructed π^0 Mass

($K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ Crunch - 7th Cut)



Data



Data

This mass peak could be from the following possible backgrounds:

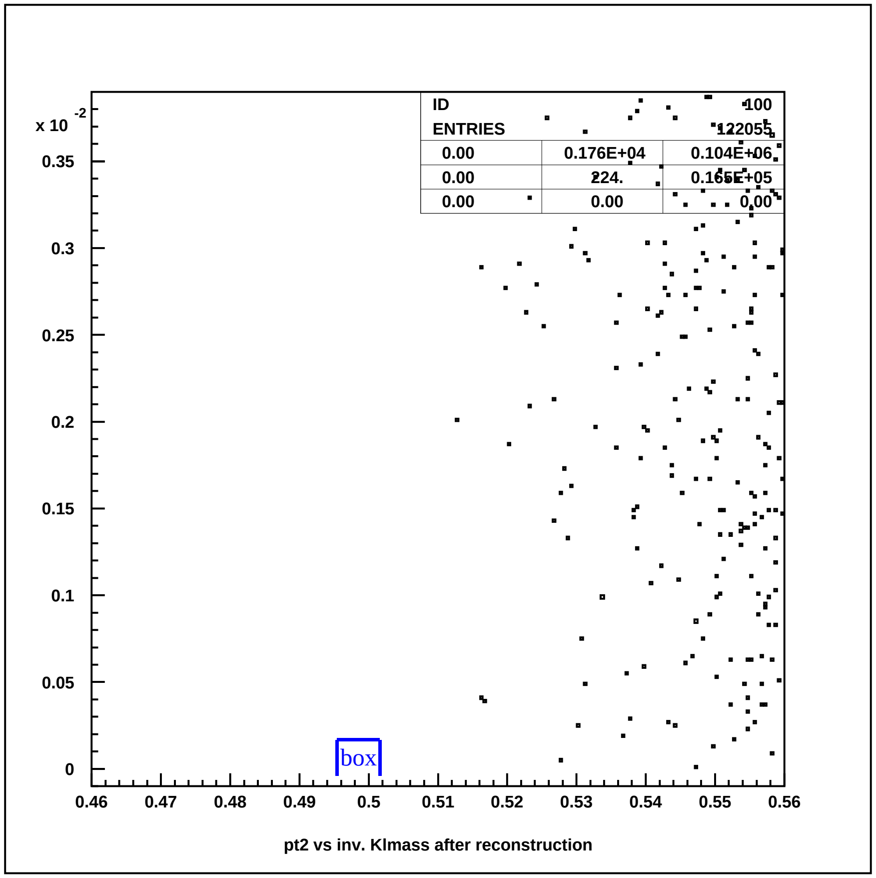
$K_L \rightarrow \pi^0\pi^0 + acc.$

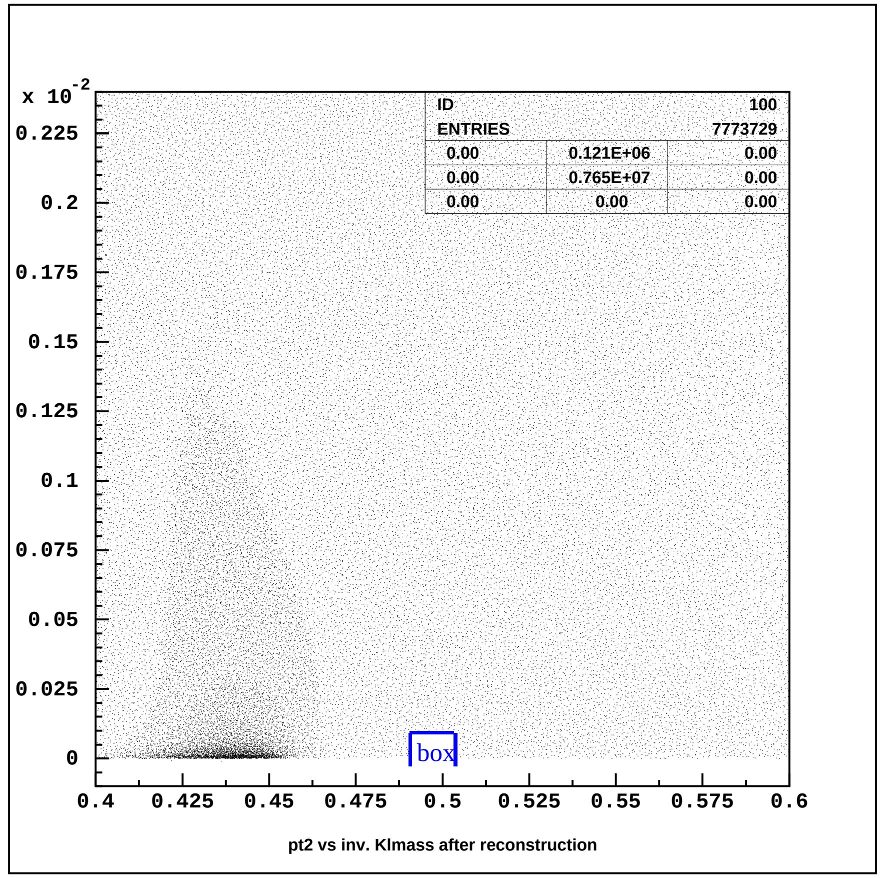
$K_L \rightarrow 3\pi^0$

$K_L \rightarrow 3\pi^0_D$

Results From Crunch of All Tapes

(P_T^2 vs. Inv. K_L Mass)





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

~ Box Dimensions ~

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

$p_T^2 \leq 130$ MeV^2

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

~ Box Dimensions ~

491 MeV $\leq M_{\gamma\gamma\mu\mu} \leq$ 505 MeV

$p_T^2 \leq 100$ MeV^2

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."

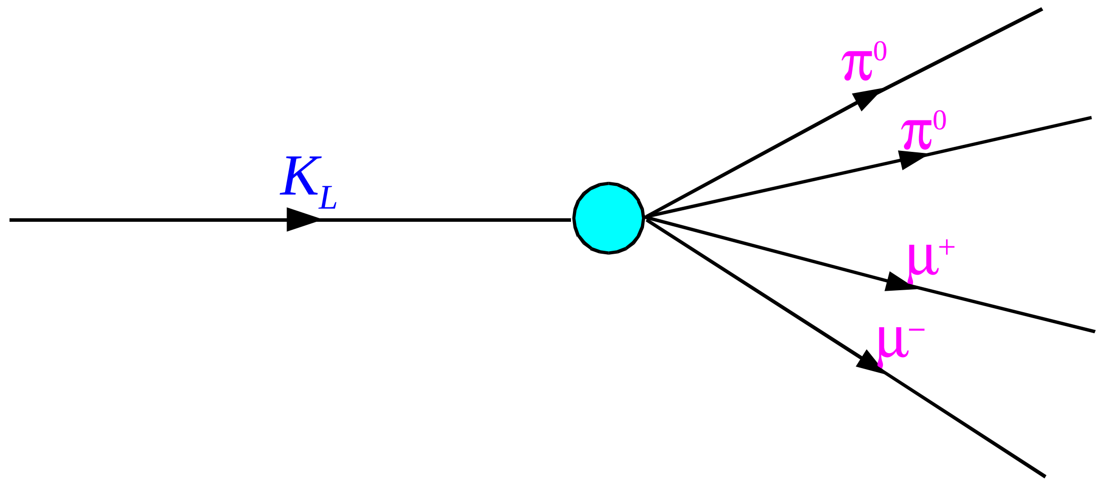
- in this analysis, we could be setting ourselves up for a truly dangerous bias scenario, since we're looking for a signal that's at the edge of phase space.

- *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'??

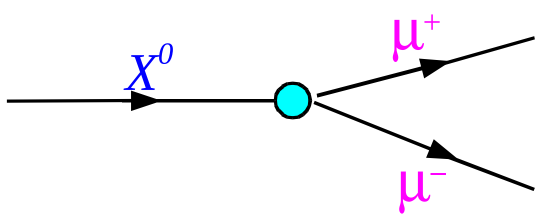
- we need to define our signal region in terms of two experimental parameters that will separate *signal* from *backgrounds*.

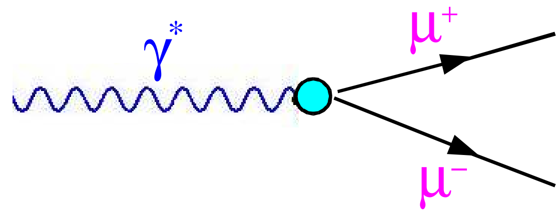
- since we can simulate the signal, determine its' efficiency and estimate the size of the background in the signal region using the *invariant* K_L *mass* and P_T^2, then a 2D signal box using these variables does the job well.



$$P_{T,kaon}^2 = \left(\vec{P}_{T,\mu\mu vtx} + \vec{P}_{T,\pi 1} + \vec{P}_{T,\pi 2}\right)^2,$$ where $\vec{P}_{T,\mu\mu vtx}$,

$\vec{P}_{T,\pi 1}$ and $\vec{P}_{T,\pi 2}$ are measured relative to the K_L direction.

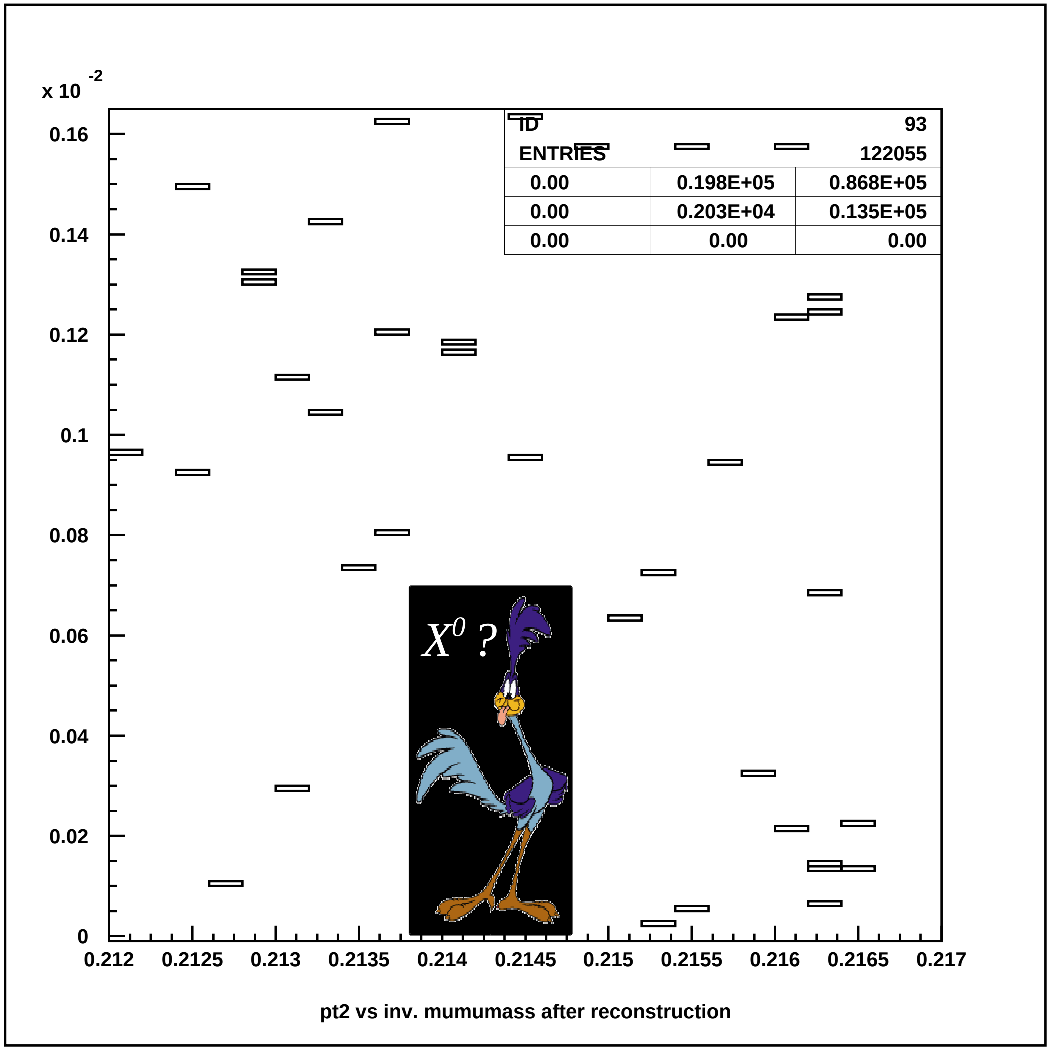




$$P_{T,\mu\mu vtx}^2 - \left(\underbrace{\vec{P}_{T,kaon}}_{=0} - \vec{P}_{T,\pi 1} - \vec{P}_{T,\pi 2}\right)^2 = 0,$$ where $\vec{P}_{T,\mu\mu vtx}$,

$\vec{P}_{T,\pi 1}$ and $\vec{P}_{T,\pi 2}$ are measured relative to the K_L direction.

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



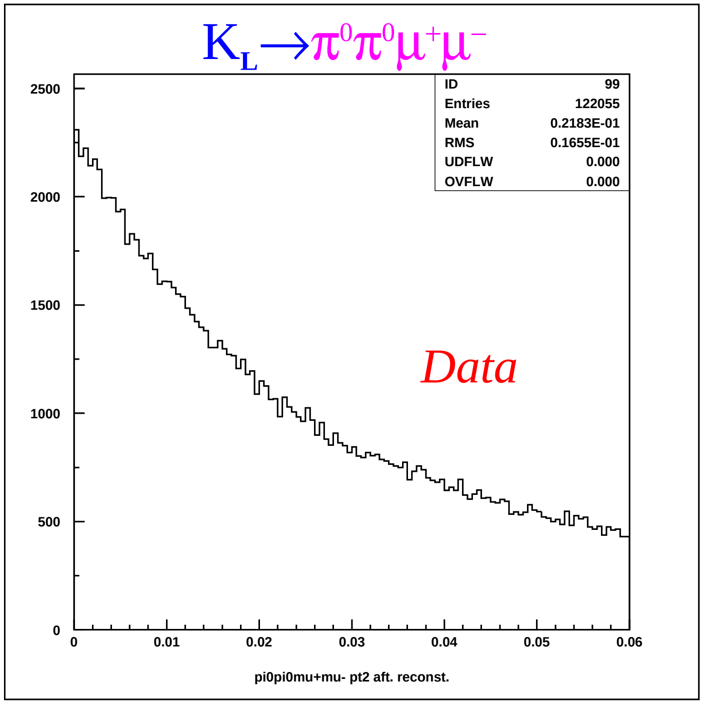
$K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ *Data*

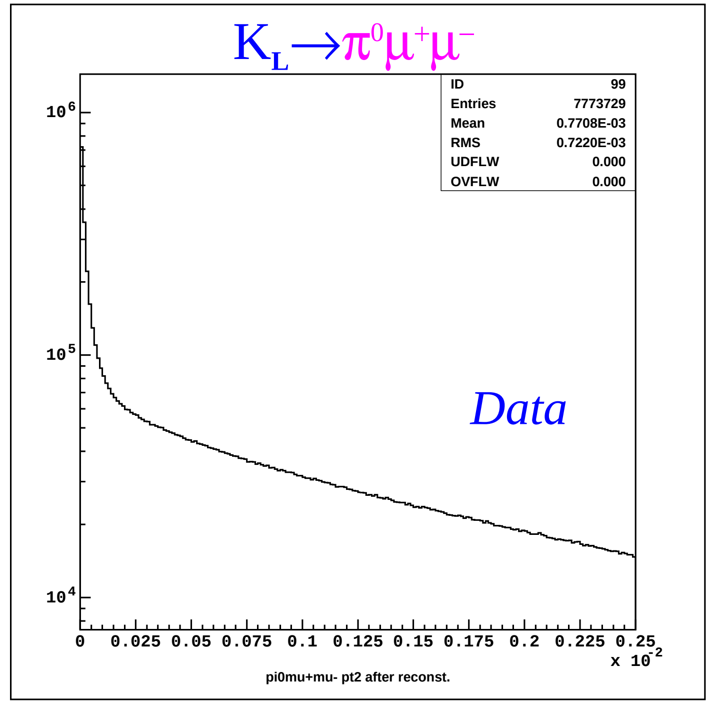
~ Box Dimensions ~

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

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

$P_T^{\,2}$


$K_L \to \pi^0\pi^0\mu^+\mu^-$
ID 99
Entries 122055
Mean 0.2183E-01
RMS 0.1655E-01
UDFLW 0.000
OVFLW 0.000
Data
2500
2000
1500
1000
500
0
0 0.01 0.02 0.03 0.04 0.05 0.06
pi0pi0mu+mu- pt2 aft. reconst.


$K_L \to \pi^0\mu^+\mu^-$
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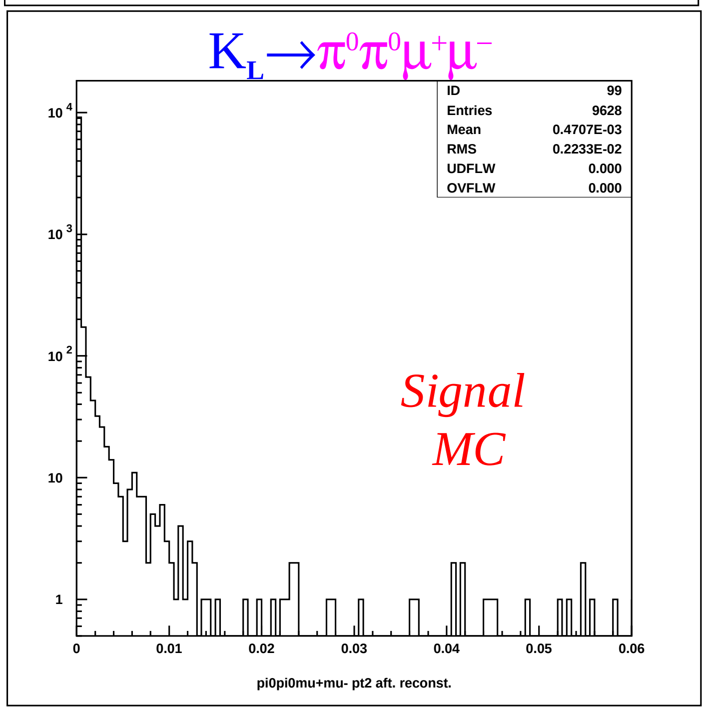
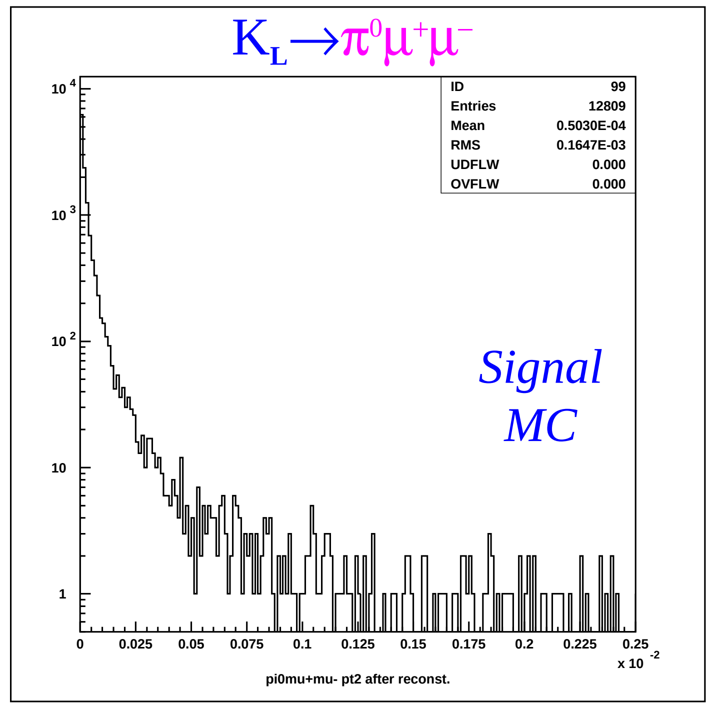
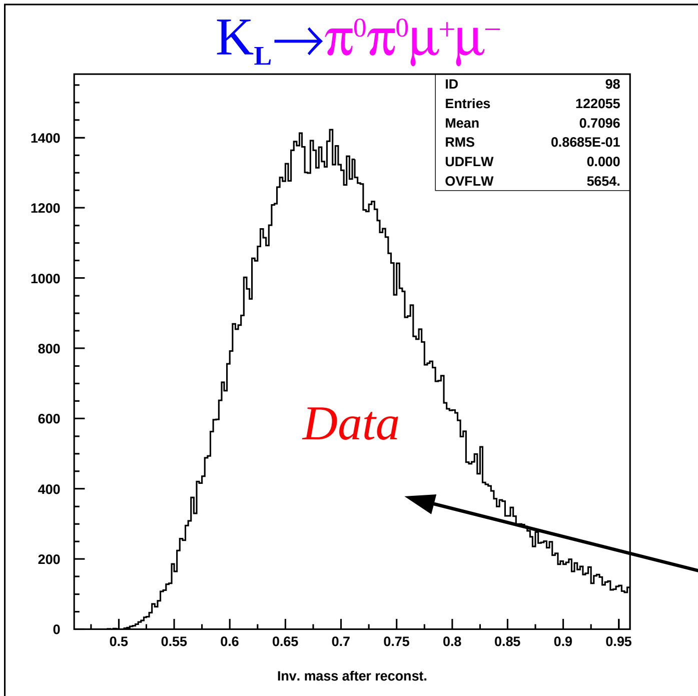
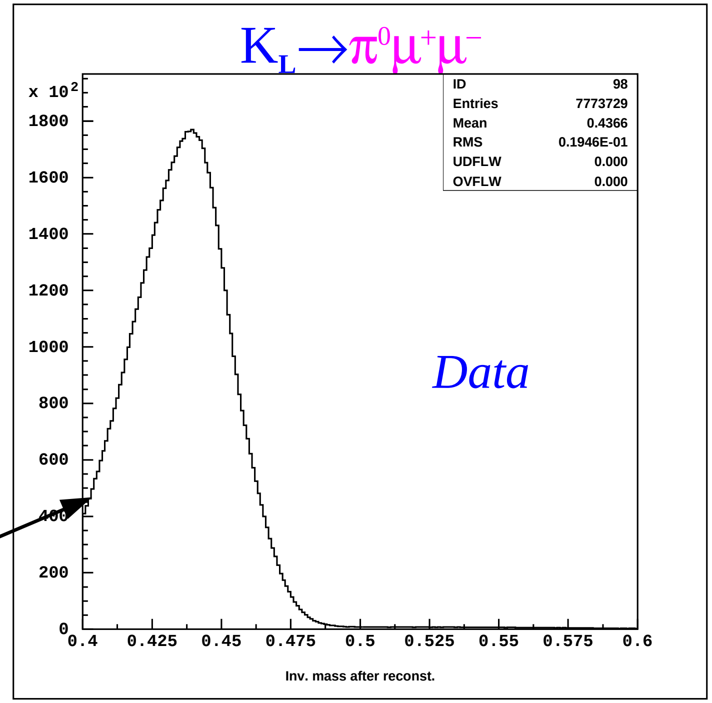
Mean 0.7708E-03
RMS 0.7220E-03
UDFLW 0.000
OVFLW 0.000
Data
10^6
10^5
10^4
0 0.025 0.05 0.075 0.1 0.125 0.15 0.175 0.2 0.225 0.25
x 10^{-2}
pi0mu+mu- pt2 after reconst.


$K_L \to \pi^0\pi^0\mu^+\mu^-$
ID 99
Entries 9628
Mean 0.4707E-03
RMS 0.2233E-02
UDFLW 0.000
OVFLW 0.000
Signal MC
10^4
10^3
10^2
10
1
0 0.01 0.02 0.03 0.04 0.05 0.06
pi0pi0mu+mu- pt2 aft. reconst.

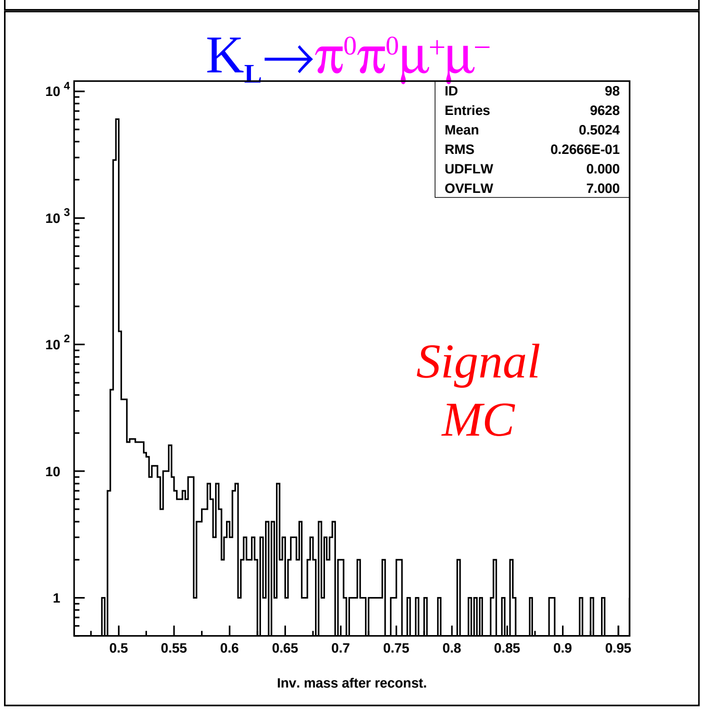

$K_L \to \pi^0\mu^+\mu^-$
ID 99
Entries 12809
Mean 0.5030E-04
RMS 0.1647E-03
UDFLW 0.000
OVFLW 0.000
Signal MC
10^4
10^3
10^2
10
1
0 0.025 0.05 0.075 0.1 0.125 0.15 0.175 0.2 0.225 0.25
x 10^{-2}
pi0mu+mu- pt2 after reconst.

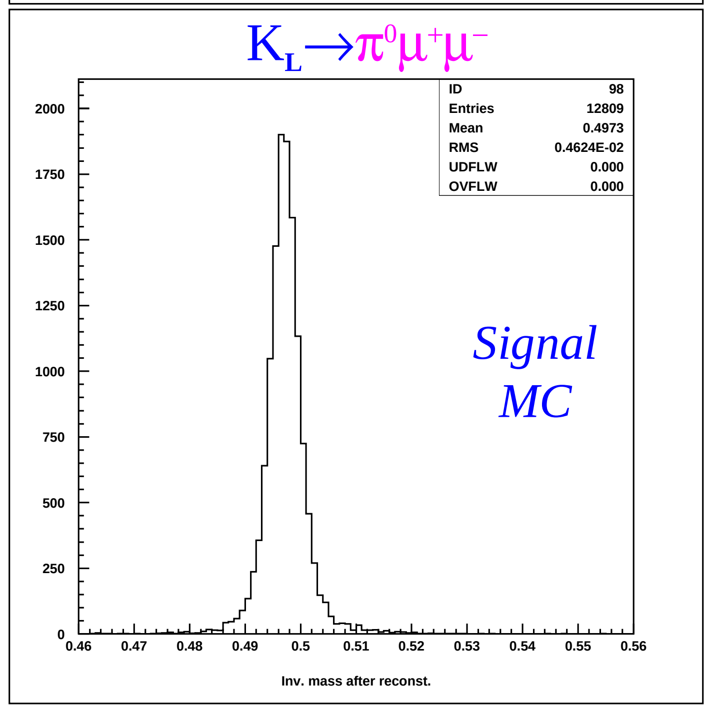
Inv. K_L Mass



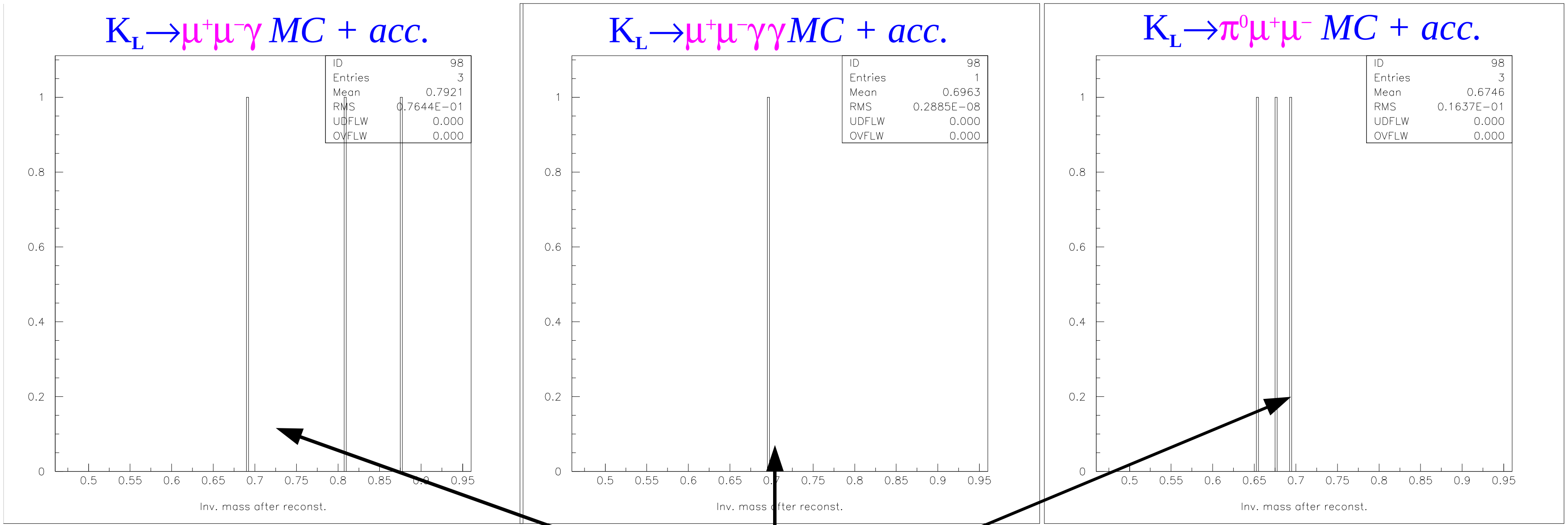


what's all this background??





MC Studies on High Mass Signal Mode Background



After feeding the above MC Samples (~20 K events)
into the $K_L \to \pi^0\pi^0\mu^+\mu^-$ Crunch Code, this is
what we were left over with after all cuts.

- We can relate the above plots to the High Mass Background Spectrum in the Inv. K_L Mass Plot for $K_L \to \pi^0\pi^0\mu^+\mu^-$ by extrapolation:

7 events /(20 K *MC events*) ≃ x /(277 M *Data events*) → x ≃ 96800 background events

- So, our *MC Estimate* says that ~ 96800 events in the high mass signal mode background are due to the above three decays. This accounts for ~ 80 % of the background.
- Another potential background to be studied is $K_{\mu 3}\gamma$ + acc.

Normalization Mode Studies**

-Crunch Cuts-

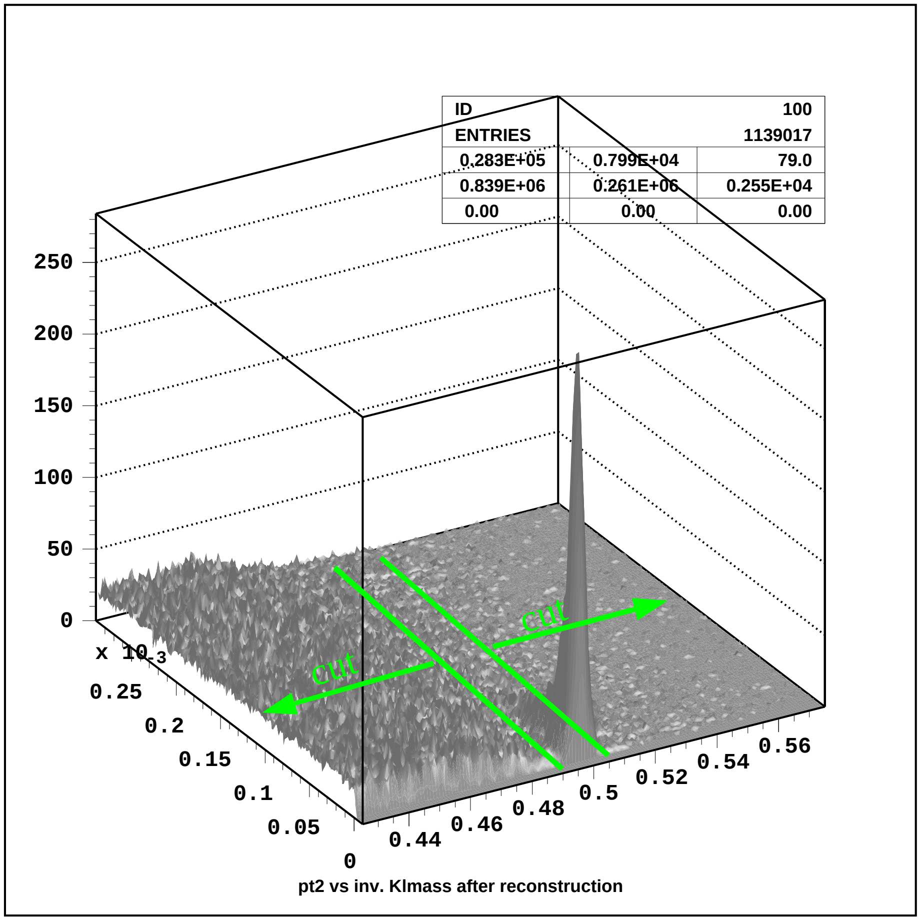
$K_L \to \mu^+\mu^-\gamma\gamma$ Crunch Cut*	Data♫	MC ♪	Data♫	MC ♪	$K_L \to \mu^+\mu^-\gamma$ Crunch Cut*
Require 2 tracks	0.700	0.998	0.700	0.998	Require 2 tracks
$C_{track1} = -C_{track2}$	0.999	1.000	0.999	1.000	$C_{track1} = -C_{track2}$
E_{cl}(track) $\leq$ 2.0 GeV	0.391	0.980	0.391	0.990	E_{cl}(track) $\leq$ 2.0 GeV
$E_{cl}(\text{track}) / p_{track} \leq 0.9$	0.999	1.000	0.999	1.000	$E_{cl}(\text{track}) / p_{track} \leq 0.9$
# γ clusters = 2	0.265	0.158	0.501	0.937	# γ clusters = 1
# hits in μ planes $\geq$ 1	0.983	1.000	0.988	1.000	# hits in μ planes $\geq$ 1
90.0 m $\leq Z_{VTX} \leq$ 160.0 m	0.973	1.000	0.977	0.999	90.0 m $\leq Z_{VTX} \leq$ 160.0 m
$p_T^2 \leq 0.0003\ \text{GeV}^2/c^2$	0.161	0.947	0.031	0.949	$p_T^2 \leq 0.0003\ \text{GeV}^2/c^2$
			0.025	0.917	492 MeV $\leq K_{\mu\mu\gamma} \leq$ 504 MeV
Total Acceptance	0.011	0.147	0.0001	0.806	Total Acceptance

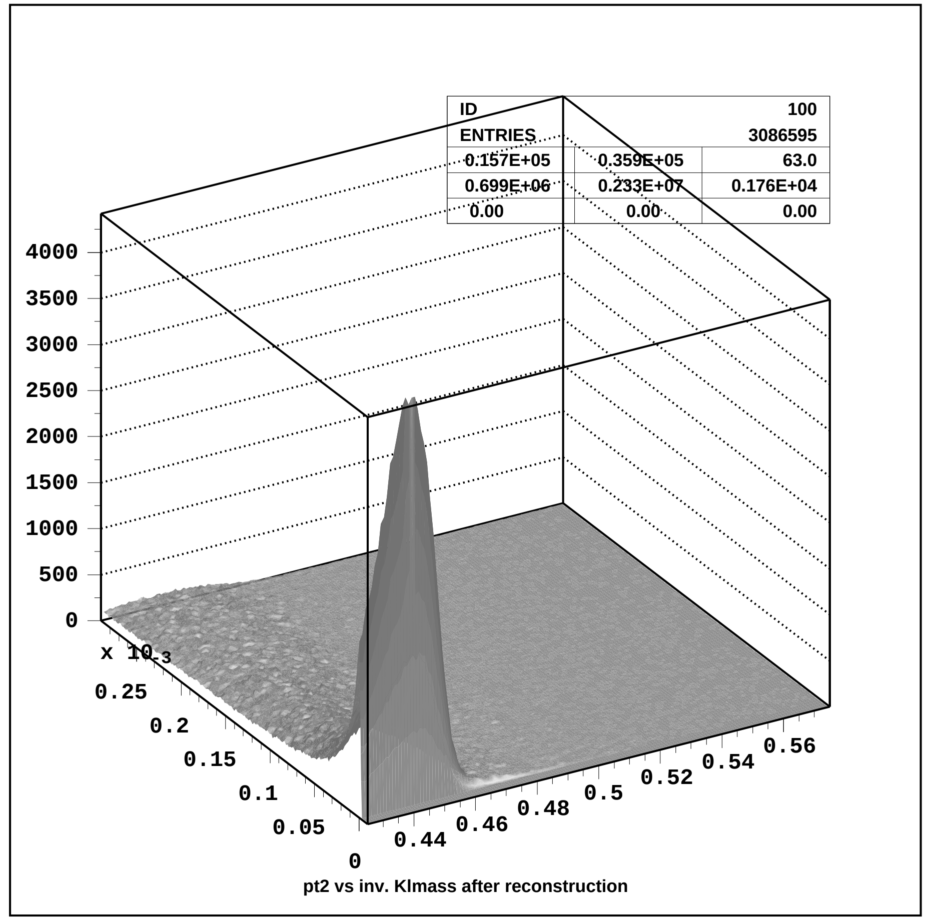
* = *cuts listed in chronological order,* ♪ = *initial # events was ~20K,* ♫ = *initial # events was ~277 M*

** = *have not decided on a normalization mode yet*

Normalization Modes:

$P_T^{\,2}$ vs. Inv. K_L Mass

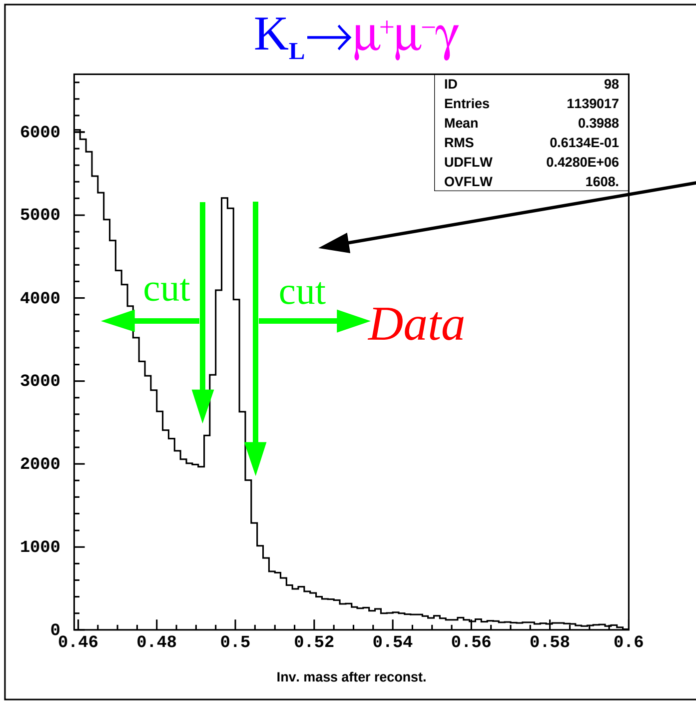




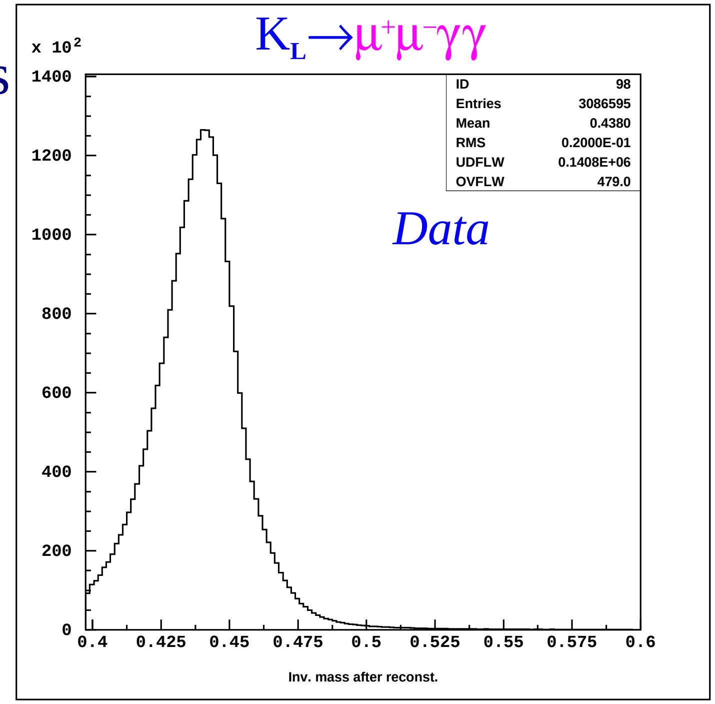
$K_L \to \mu^+\mu^-\gamma$ *Data*

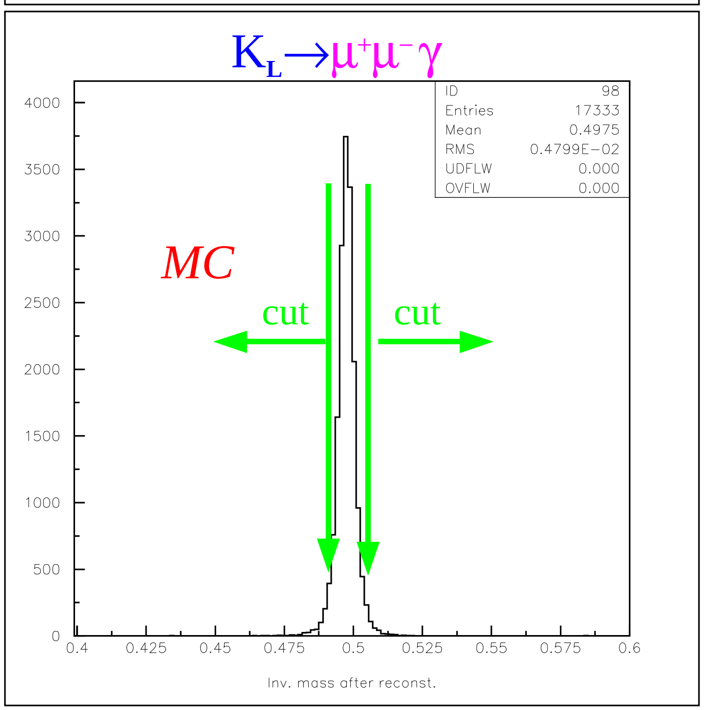
$K_L \to \mu^+\mu^-\gamma\gamma$ *Data*

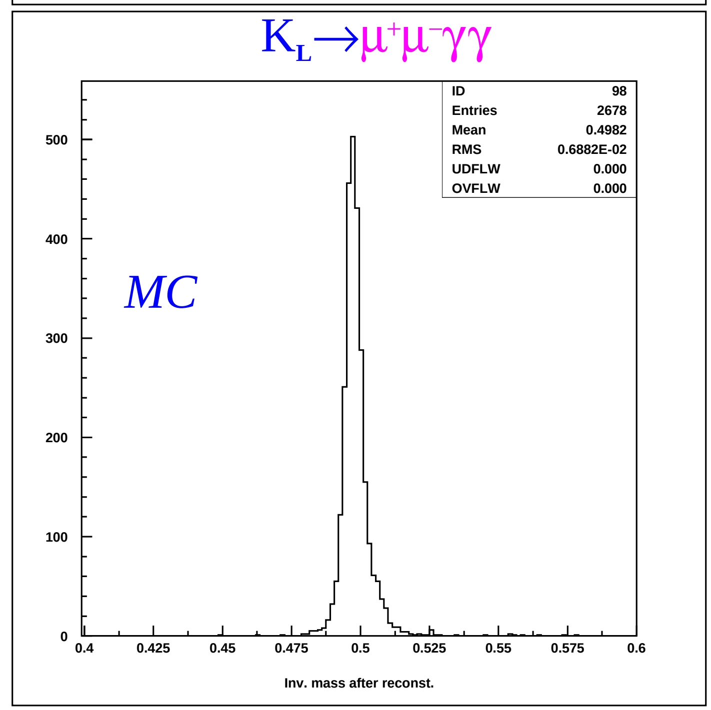
Inv. K_L Mass

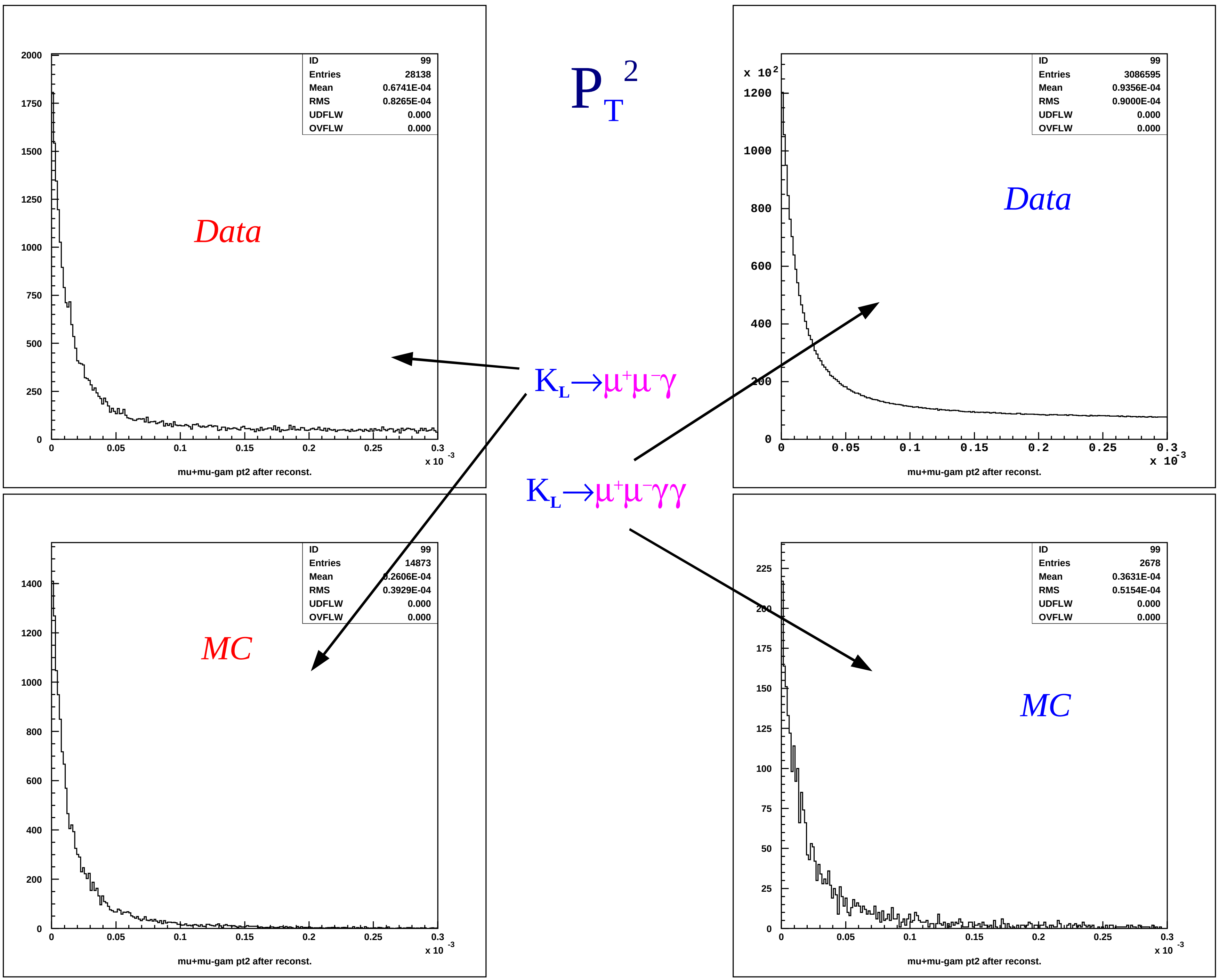


$\mu^+\mu^-\gamma$ *peak!*









P_T^2
K_L→μ+μ−γ
K_L→μ+μ−γγ
Data
MC
Data
MC
ID 99
Entries 28138
Mean 0.6741E-04
RMS 0.8265E-04
UDFLW 0.000
OVFLW 0.000
ID 99
Entries 3086595
Mean 0.9356E-04
RMS 0.9000E-04
UDFLW 0.000
OVFLW 0.000
ID 99
Entries 14873
Mean 0.2606E-04
RMS 0.3929E-04
UDFLW 0.000
OVFLW 0.000
ID 99
Entries 2678
Mean 0.3631E-04
RMS 0.5154E-04
UDFLW 0.000
OVFLW 0.000
x 10^-3
x 10^2
mu+mu-gam pt2 after reconst.
mu+mu-gam pt2 after reconst.
mu+mu-gam pt2 after reconst.
mu+mu-gam pt2 after reconst.

Future Plans

- HyperCP uses a uniform matrix element for $\Sigma^+ \rightarrow pX^0 \rightarrow p\mu^+\mu^-$. This would not be advisable for $K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ since the K_L decay is momentum dependent.

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

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

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

- with the tools listed above, we should be able to construct a suitable matrix element for $K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ and improve MC generation!

- in short, this analysis has been started from scratch and I will be analyzing the data *with the box closed* and with my own cuts.

- still need to decide on my *backgrounds*, which would reside at the edge of phase space.