Recent Results on Rare K_L Decays from KTeV

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(for KTeV Collaboration)

XIV Rencontres de Blois - June 2002

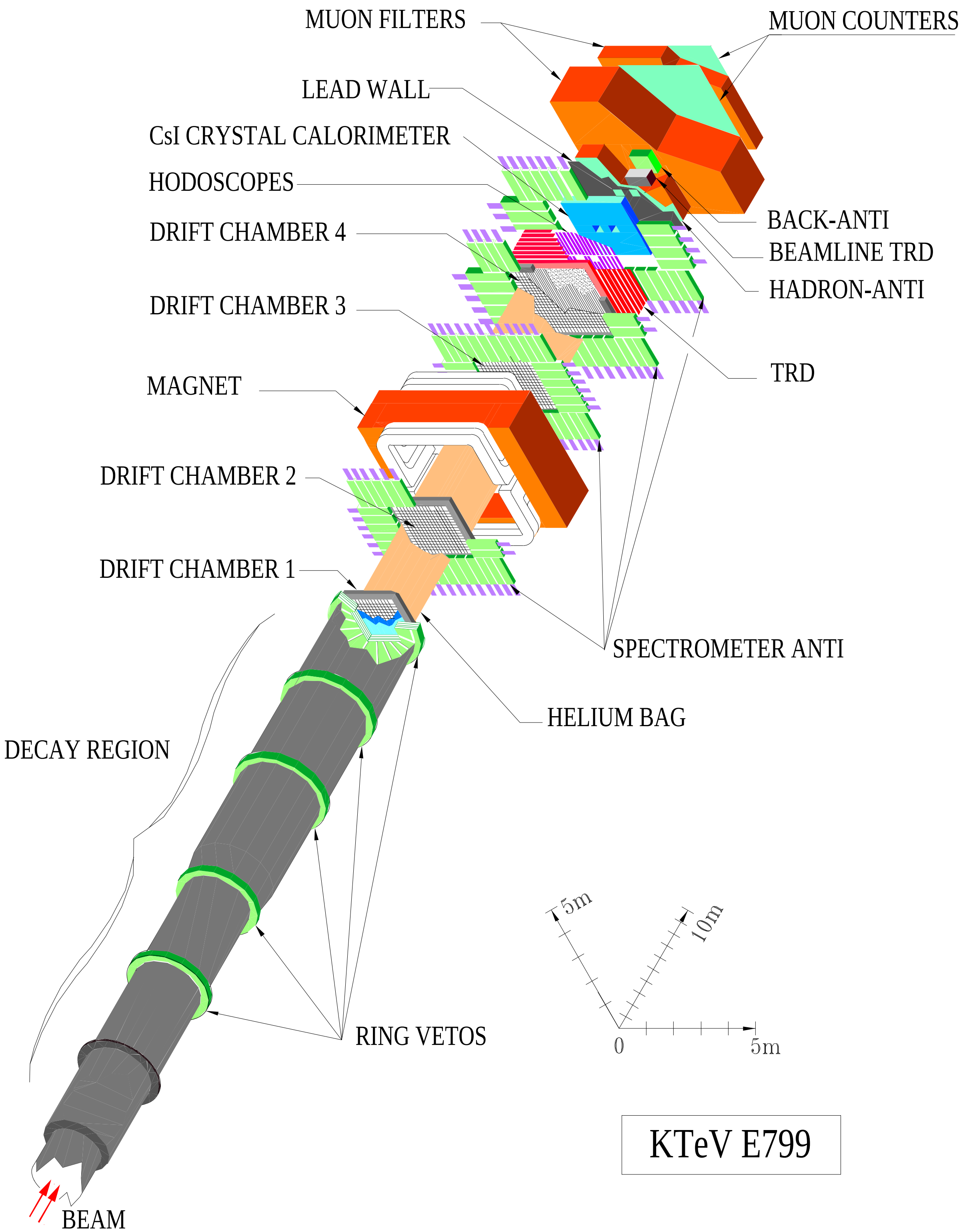
These results were presented at DPF 2002, Williamsburg Virginia, May 24 - 28, 2002. For more details look at individual talks on www.dpf20002.org

- CP violation in $K_L \to \pi^+\pi^-e^+e^-$ from full 1997 and 1999 data sets.
- Measurement of branching fraction and form factor in the decay $K_L \to e^+e^-\gamma$
- Measurement of $K_L \to e^+e^-\mu^+\mu^-$ from full 1997 and 1999 data sets
- Measurements of $\pi^0 \to e^+e^-e^+e^-$
- Search for the lepton number violating decay $K_L \to \pi^0\mu^\pm e^\mp$.

Present KTeV Collaboration

University of Arizona
University of California, Los Angeles
University of California, San Diego
University of Campinas, Brazil
University of Chicago
University of Colorado, Boulder
Elmhurst College
Fermi National Accelerator Laboratory
Osaka University
Rice University
Rutgers University
University of Sao Paulo, Brazil
University of Virginia
University of Wisconsin

KTeV Spectrometer (E799-II)



The Decay $K_L \to \pi^+\pi^-e^+e^-$

Work by Sasha Golossanov, University of Virginia

This decay was first seen by KTeV in 1998, and branching fraction measured from 2% of the data.

Current branching fraction from entire 1997 data set is (still preliminary, submitted for publication soon):

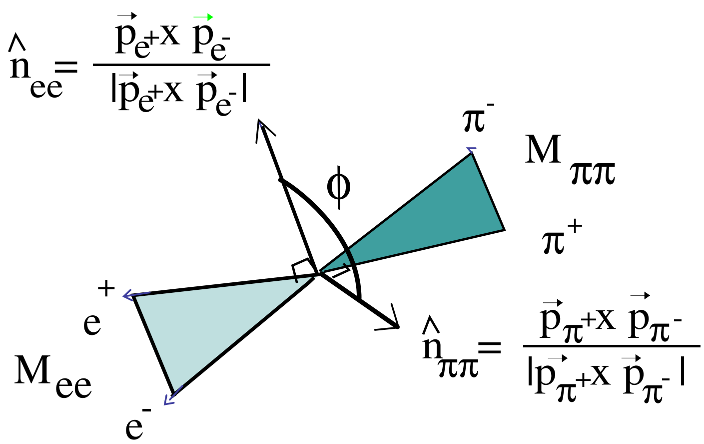
$$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}.$$

$K_L \to \pi^+\pi^-e^+e^-$ shows a new indirect CP violating effect as an asymmetry in a T-odd angular variable.

These asymmetry results from the 1997 run have been published in A.Alavi-Harati **et.al.** Physical Review Letters **84**, 408 (2000).

We are continuing to analyse other physics that may be extracted from this decay

CP-odd and T-odd angle ϕ



$$\hat{z} = \frac{\vec{p}_{\pi^+} + \vec{p}_{\pi^-}}{|\vec{p}_{\pi^+} + \vec{p}_{\pi^-}|}$$

$$\sin\phi\cos\phi = (\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \bullet \hat{z}(\hat{n}_{ee} \bullet \hat{n}_{\pi\pi})$$

$$CP(\hat{n}_{ee}) \to \hat{n}_{ee} \qquad T(\hat{n}_{ee}) \to \hat{n}_{ee}$$
$$CP(\hat{n}_{\pi\pi}) \to \hat{n}_{\pi\pi} \qquad T(\hat{n}_{\pi\pi}) \to \hat{n}_{\pi\pi}$$
$$CP(\hat{z}) \to -\hat{z} \qquad T(\hat{z}) \to -\hat{z}$$
$$CP(\phi) \to -\phi \qquad T(\phi) \to -\phi$$

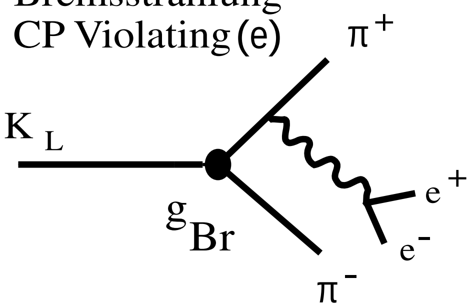
Definition of the asymmetry:

$$A(\phi) \equiv \frac{N_{sin\phi cos\phi} > 0.0 - N_{sin\phi cos\phi} < 0.0}{N_{sin\phi cos\phi} > 0.0 + N_{sin\phi cos\phi} < 0.0}$$

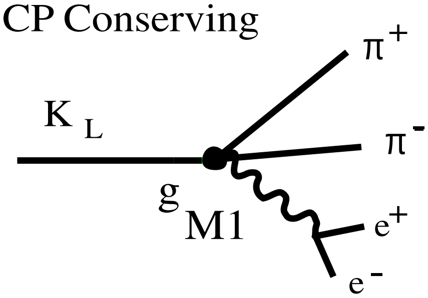
Theoretical Model (Sehgal and Wanninger)

K->ππee Processes

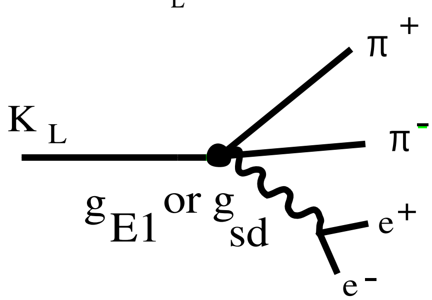
a) Bremsstrahlung
CP Violating (e)



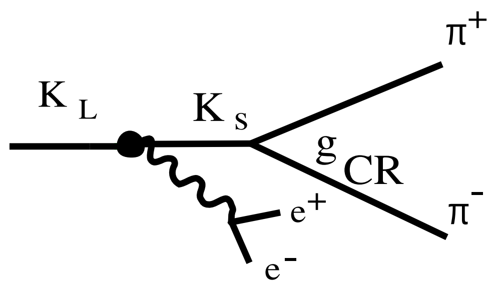
b) M1 Direct Photon Emission
CP Conserving



c) E1 Direct Photon Emission
CP Violating or Direct CP(e')
(e from K_L)



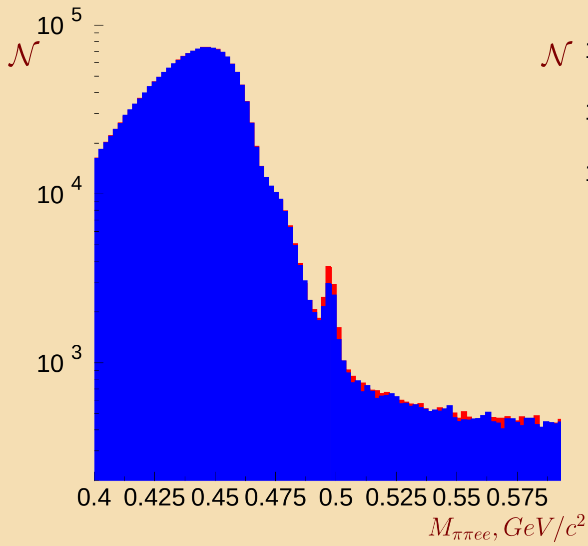
d) KO Charge Radius
CP Conserving

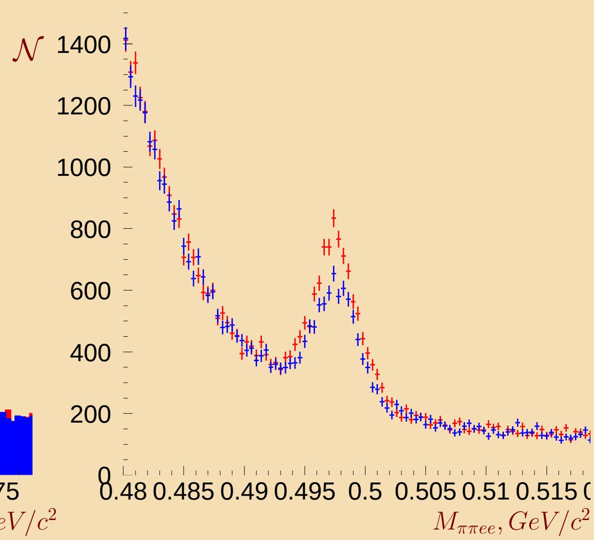


Total raw data

3.2. Observation of the Asymmetry

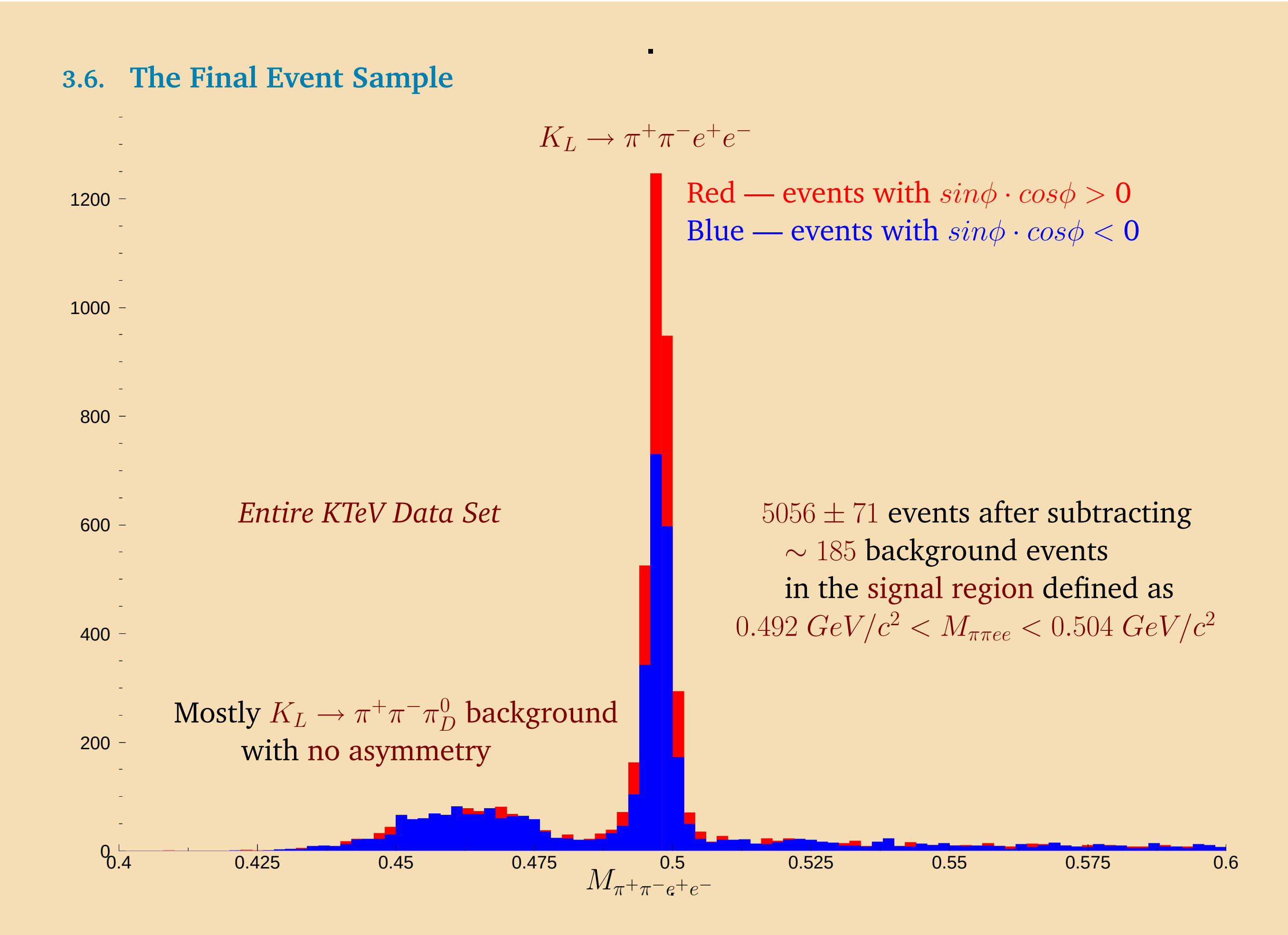
After reconstruction (described on the previous slide) we can already see the $\mathbf{K_L} \to \pi^+\pi^-\mathbf{e^+e^-}$ signal and observe the asymmetry!





Red Histogram — events with $\sin\phi\cos\phi > \mathbf{0}$
Blue " — " $\sin\phi\cos\phi < \mathbf{0}$

Total 1997 and 1999 Data Set



5. The Summary

All Results are Preliminary !

- Identified $\mathbf{5056 \pm 71\ K_L \to \pi^+\pi^-e^+e^-}$ events.
- Reported New Preliminary Measurements
  - CP Violating Asymmetry in the ϕ angular variable.
    - ⋆ $\mathcal{A} = (\mathbf{13.3 \pm 1.4(stat) \pm 1.0(syst)})\,\%$
  - Vector Form Factor Parameters
    - ⋆ $\frac{\mathbf{a_1}}{\mathbf{a_2}} = \mathbf{-0.75 \pm 0.03(stat) \pm 0.02(syst)}$
    - ⋆ $\mathbf{\tilde{g}_{M_1} = 1.10 \pm 0.10(stat) \pm 0.06(syst)}$
- These results are in agreement with the previously published measurements and theoretical predictions.
- Plans and Future Prospectives:
  - Measure new value for the Branching Ratio
  - Fit for the parameter $\mathbf{g_{CR}}$ related to the K^0 Charge Radius
  - Attempt to fit for the parameter $\mathbf{g_{E_1}}$ to search for CP Violating E_1 direct emission.

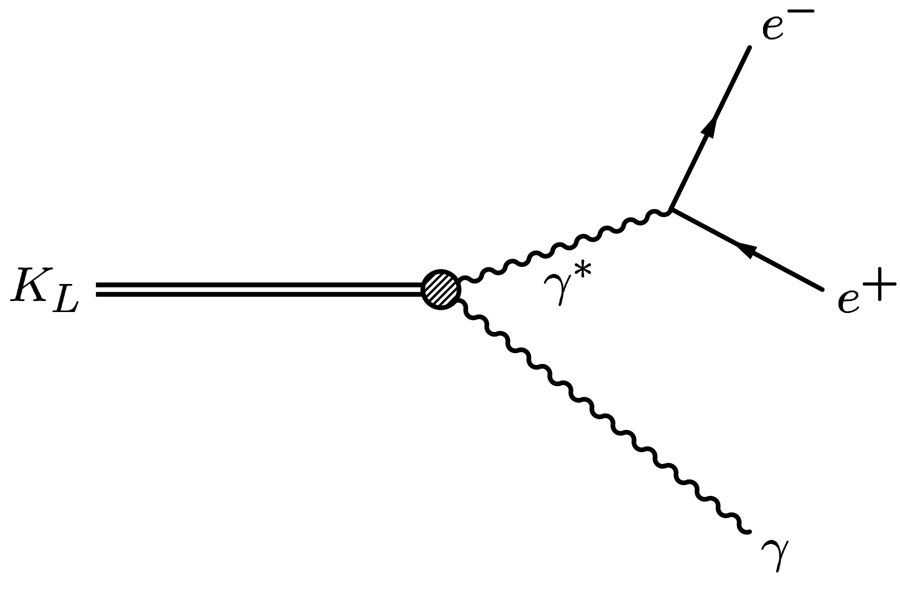
Measurements of the decay $K_L \to e^+e^-\gamma$

Work of Jason Ladue, University of Colorado

Motivation

The form factor from $K_L \to e^+e^-\gamma$ can be used to calculate the "long-distance" contribution to the $K_L \to \mu^+\mu^-$ decay. The interesting "short-distance" weak contribution, which is sensitive to V_{td} can then be obtained by subtracting the long-distance contribution from the total rate for $K_L \to \mu^+\mu^-$.

The decay $K_L \to e^+e^-\gamma$ proceeds through $K_L \to \gamma^*\gamma$, where the virtual photon converts internally into an e^+e^- pair (also called a Dalitz decay).



Theory

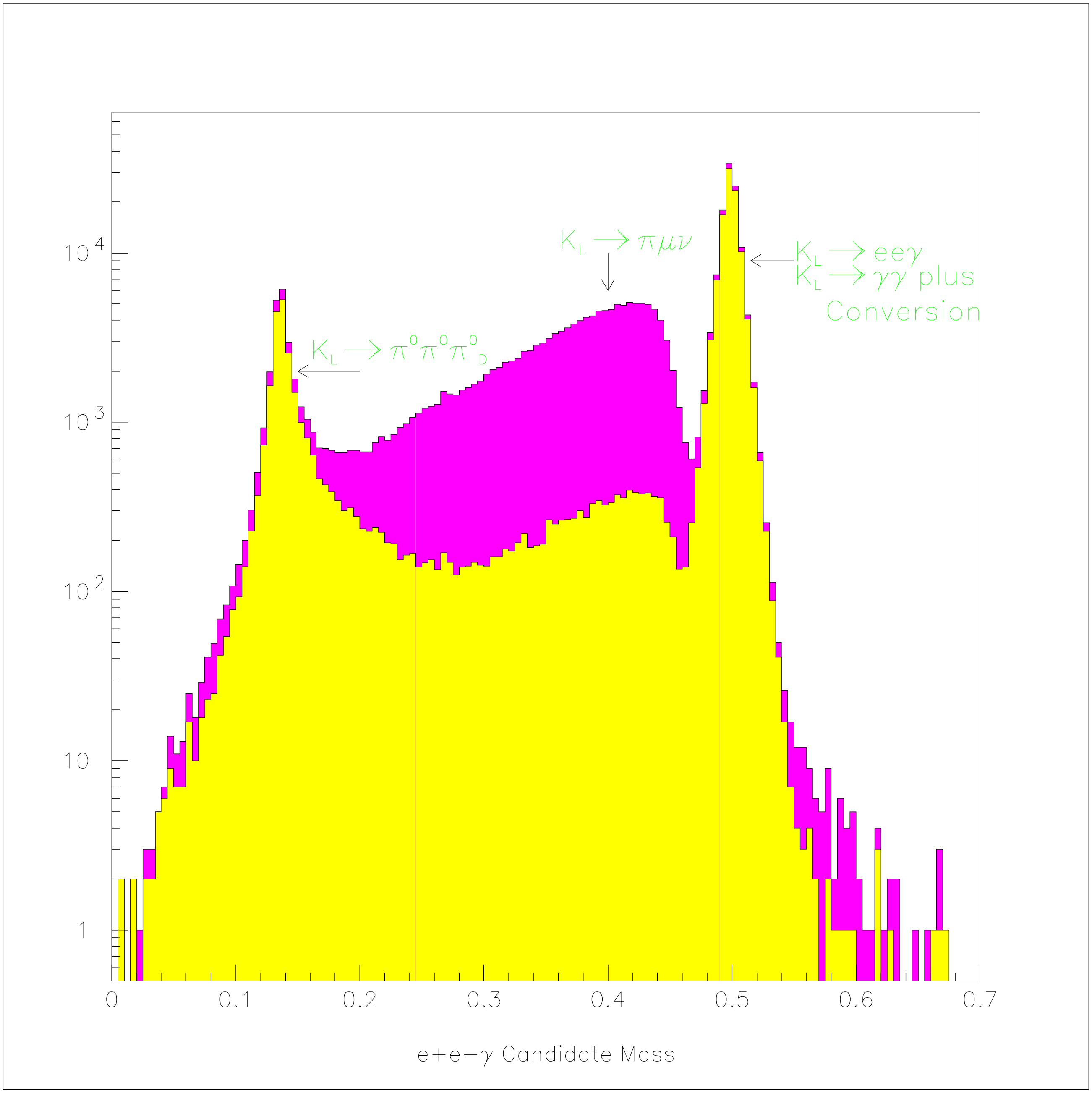
The form factor function depends on photon $q^2 = M^2_{e^+e^-}$ in a complex way. The simplest model involves a simple linear approximation,

$$f(x) = 1 + \beta x$$
$$x = \frac{q^2}{M^2_{K_L}}.$$

A more complex model proposed by Bergström, Massó, and Singer (BMS) uses a vector-meson dominance model to express the form factor as a function of a parameter α_{K^*}.

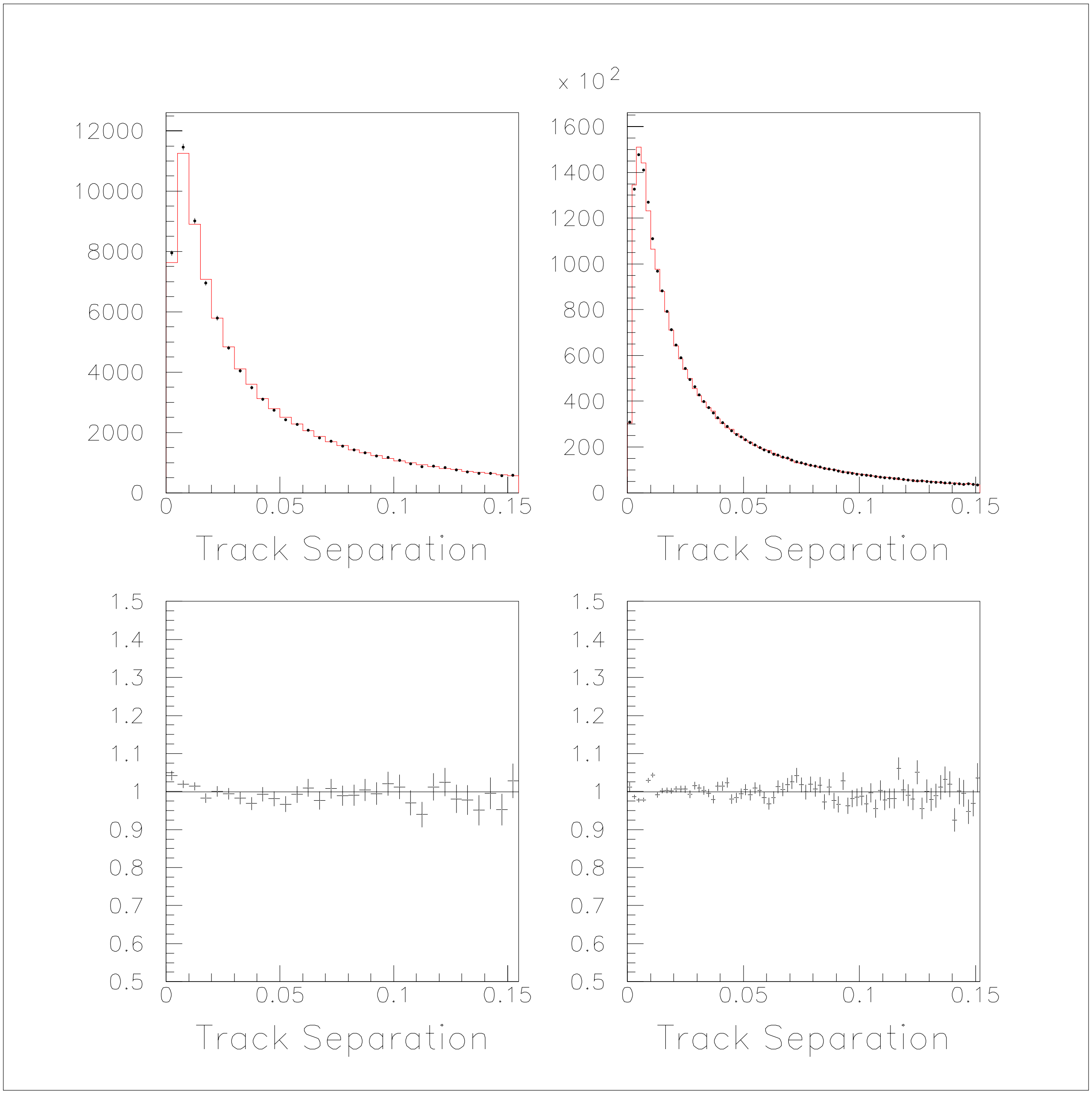
$$f(q^2,0) = \frac{1}{1-q^2/M^2_\rho} + \frac{2.5\alpha_{K^*}}{1-q^2/M^2_{K^*}}.$$
$$\left(\frac{4}{3} - \frac{1}{1-q^2/M^2_\rho} - \frac{1}{9}\frac{1}{1-q^2/M^2_\omega} - \frac{2}{9}\frac{1}{1-q^2/M^2_\phi}\right)$$

$$f(x,0) = \frac{1}{1-0.418x} + \frac{2.5\alpha_{K^*}}{1-0.311x}.$$
$$[\frac{4}{3} - \frac{1}{1-0.418x} - \frac{1}{9(1-0.405x)} - \frac{2}{9(1-0.238x)}]$$



$e^+e^-\gamma$ candidate Mass after all cuts except the TRD cut(Final Set).

Track Separation at Chamber 1



Left is Signal($K_L \rightarrow e^+e^-\gamma$)
Right is Normalization($K_L \rightarrow \pi^0\pi^0\pi^0_D$)

$K_L \to e^+e^-\gamma$ Branching Ratio

Best published result: NA48

$BR(K_L \to e^+e^-\gamma) =$

$[10.6 \pm 0.2(\text{stat}) \pm 0.2(\text{sys}) \pm 0.4(\text{extsys})] \times 10^{-6}$

$K_L \to e^+e^-\gamma$ events observed (N_{Sig}): 93383

$K_L \to \pi^0\pi^0\pi^0_D$ events observed (N_{Norm}): 5306073

$K_L \to e^+e^-\gamma$ Acceptance (ϵ_{Sig}): 0.03422(4)

$K_L \to \pi^0\pi^0\pi^0_D$ Acceptance (ϵ_{Norm}): 0.00266(2)

$$\frac{BR(K_L \to e^+e^-\gamma)}{BR(K_L \to \pi^0\pi^0\pi^0_D)} = \frac{N_{Sig}}{N_{Norm}} \cdot \frac{\epsilon_{Norm}}{\epsilon_{Sig}}$$

Flux: $(2.69 \pm 0.08) \times 10^{11}$

$BR(K_L \to e^+e^-\gamma) = [10.13 \pm 0.04(\text{stat})] \times 10^{-6}$

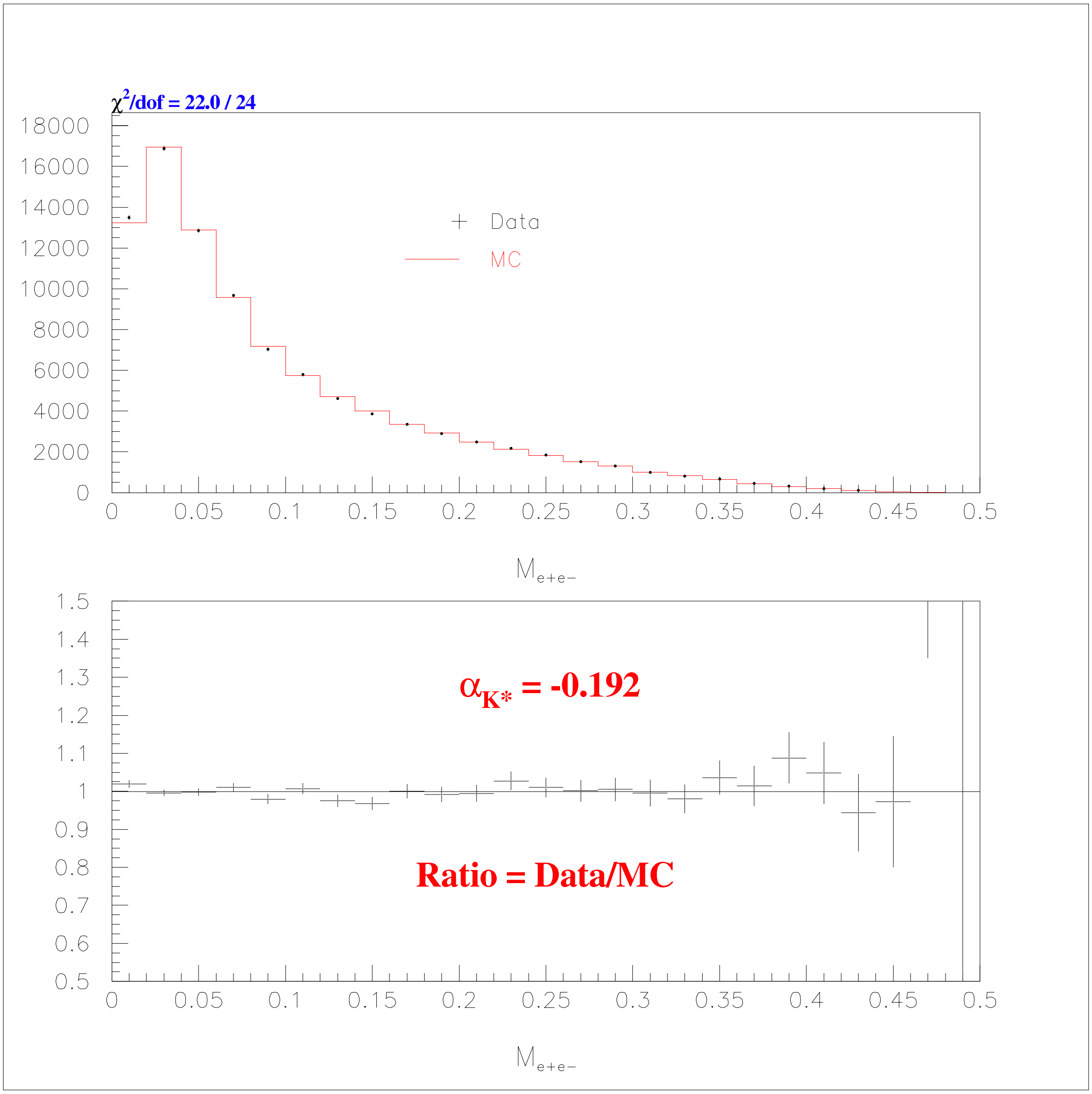
Statistical Uncertainty	0.36%
Internal Systematic Uncertainty	
Drift Chamber Inefficiencies	0.37%
Vary Cuts	0.33%
Energy Slope	0.23%
Energy Resolution	0.14%
Background	0.08%
Upstream Material	0.07%
Track Position Resolution	0.04%
Form Factor Uncertainty	0.03%
$\mathcal{O}(\alpha^3)$ Radiative Corrections	0.03%
Total Internal Systematic	0.57%
External Systematic Uncertainty	2.84%

$BR(K_L \to e^+e^-\gamma) =$

$[10.13 \pm 0.04(\text{stat}) \pm 0.06(\text{sys}) \pm 0.29(\text{ext sys})] \times 10^{-6}$

$$\frac{\Gamma(K_L \to e^+e^-\gamma)}{\Gamma(\pi^0 \to e^+e^-\gamma)} \cdot \frac{\Gamma(\pi^0 \to \gamma\gamma)}{\Gamma(K_L \to \gamma\gamma)} =$$

$1.426 \pm 0.006(\text{stat}) \pm 0.009(\text{sys}) \pm 0.028(\text{ext sys})$



The mass of the e^+e^- system, histogram is the Monte Carlo with the best fit α_{K^*} and dots are the data. The ratio of the two is shown second.

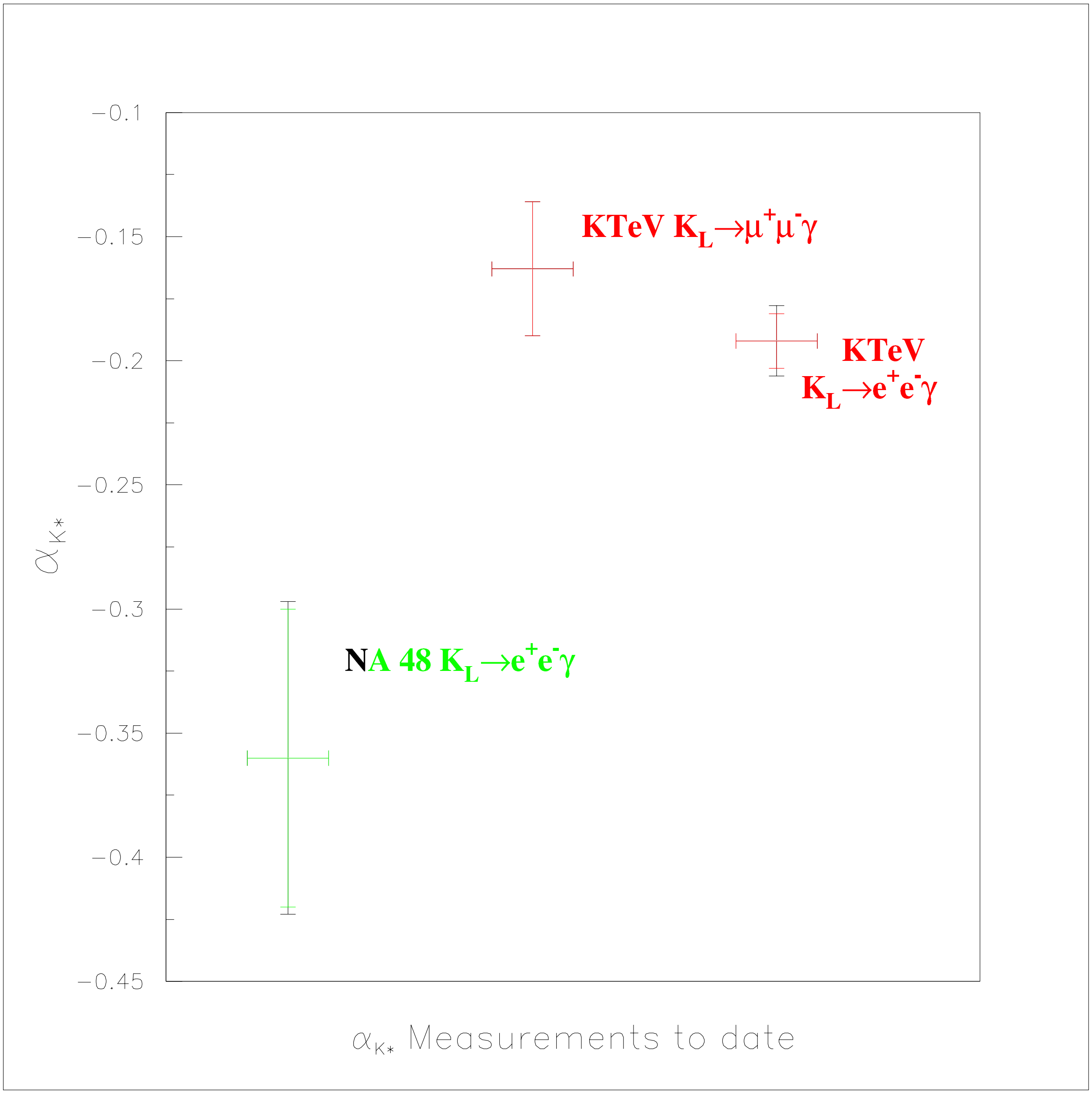
χ^2 Method:

$\alpha_{K^*} = -0.192 \pm 0.011(stat)$

Systematic Uncertainty

Vary Cuts	0.0052
Energy Slope	0.0045
Drift Chamber Inefficiencies	0.0036
Upstream Material	0.0030
$\mathcal{O}(\alpha^3)$ Radiative Corrections	0.0030
Trigger Verification	0.0011
Track Position Resolution	0.0008
Energy Resolution	0.0003
Total	0.0089

$\alpha_{K^*} = -0.192 \pm 0.011(\text{stat}) \pm 0.009(\text{sys})$



The BMS form factor parameter α_{K^*} as determined from the most recent experiments. Difference between this result and NA48 result is $\Delta = 0.168 \pm 0.062$, $\sim 2.7\sigma$.

Measurements of $K_L \to e^+e^-\mu^+\mu^-$

work of Jason Hamm, University of Arizona

Latest Proposal for $K_L\gamma^*\gamma^*$ Form Factor:

D'Ambrosio, Isidori, Portolés
Phys. Lett. B **423**, 385 (1998)

$$f\left(q_1^2, q_2^2\right) = 1 + \alpha\left(\frac{q_1^2}{q_1^2 - m_\rho^2} + \frac{q_2^2}{q_2^2 - m_\rho^2}\right) + \beta\left(\frac{q_1^2\, q_2^2}{\left(q_1^2 - m_\rho^2\right)\left(q_2^2 - m_\rho^2\right)}\right)$$

- General long–distance parameterization compatible with chiral expansion to $\mathcal{O}(p^6)$
- Coefficients α, β can be tied directly to ρ
- KTeV measurements of α:

$K_L \longrightarrow \mu^+\mu^-\gamma$	-1.54 ± 0.10	(2001)
$K_L \longrightarrow e^+e^-e^+e^-$	-1.1 ± 0.6	(2001)

- To date, no measurement of β

Current Status of $K_L \longrightarrow e^+e^-\mu^+\mu^-$ at KTeV

- First observation by $E799-I$: 1 event

$$\text{BR} = (2.9^{+6.7}_{-2.4}) \times 10^{-9}$$

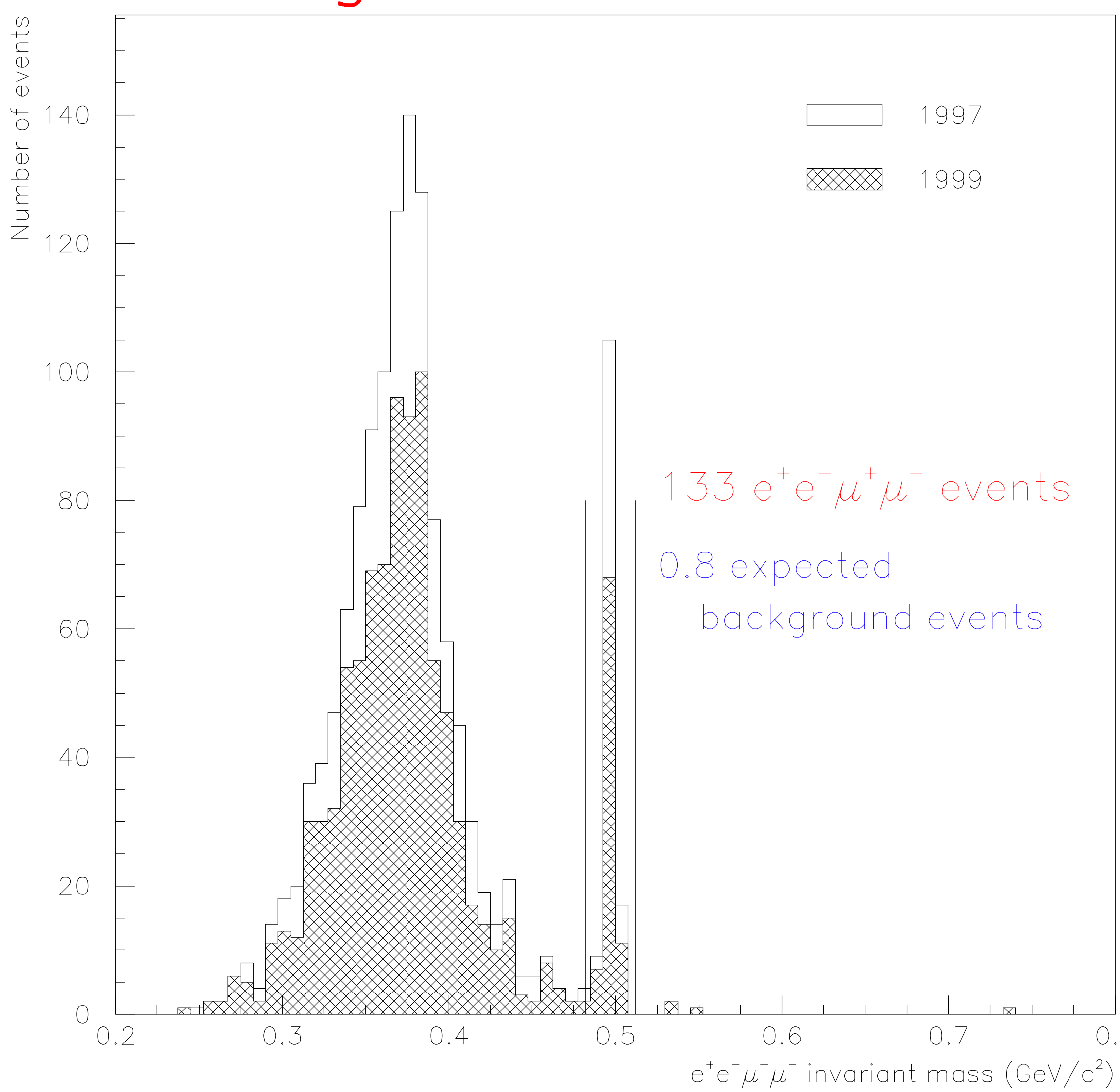
- KTeV, 1997 run: 43 events

$$\text{BR} = (2.62 \pm 0.40_{stat} \pm 0.17_{syst}) \times 10^{-9}$$

- Trigger optimization, detector upgrades increased signal acceptance $\approx 25\%$ for 1999 run

- New combined (1997 + 1999) BR to be presented here

Signal After All Cuts



After all cuts, 133 events remain, with a background of:

$\mu^+\mu^-\gamma$ conversions	0.68 ± 0.01
$K_{\mu 3}$ double decays	0.08 ± 0.01
$\pi^+\pi^-\pi^0_D$ punchthroughs/decays	0.06 ± 0.03
Total	0.82 ± 0.04

These numbers lead to a branching ratio of:

$$\mathcal{B}(K_L \longrightarrow e^+e^-\mu^+\mu^-) = (2.61 \pm 0.23_{stat} \pm 0.18_{syst}) \times 10^{-9}$$

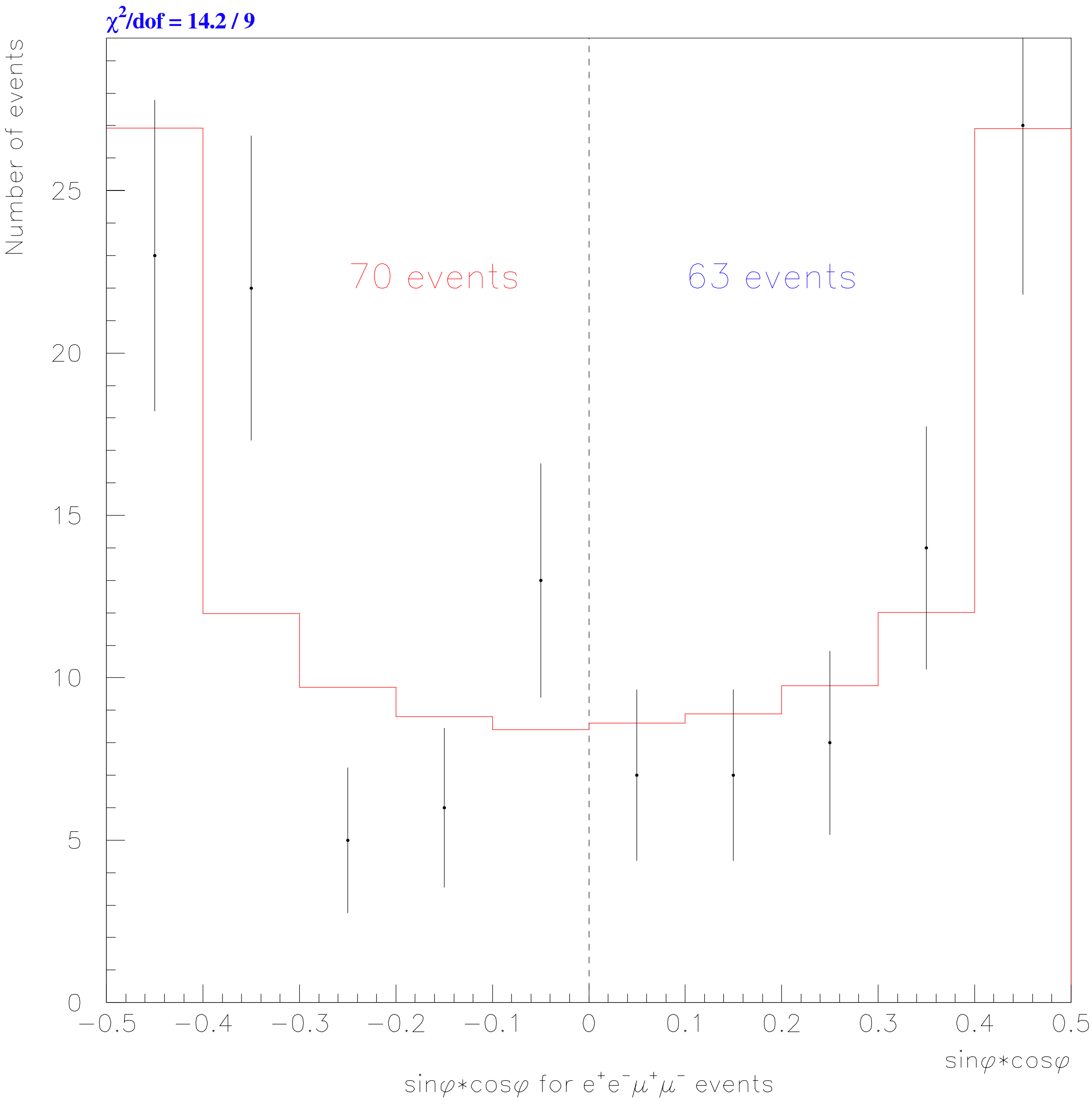
- Total KTeV sample has *tripled* in size

- Systematic error dominated by uncertainty on $K_L \longrightarrow \pi^+\pi^-\pi^0_D$ branching ratio

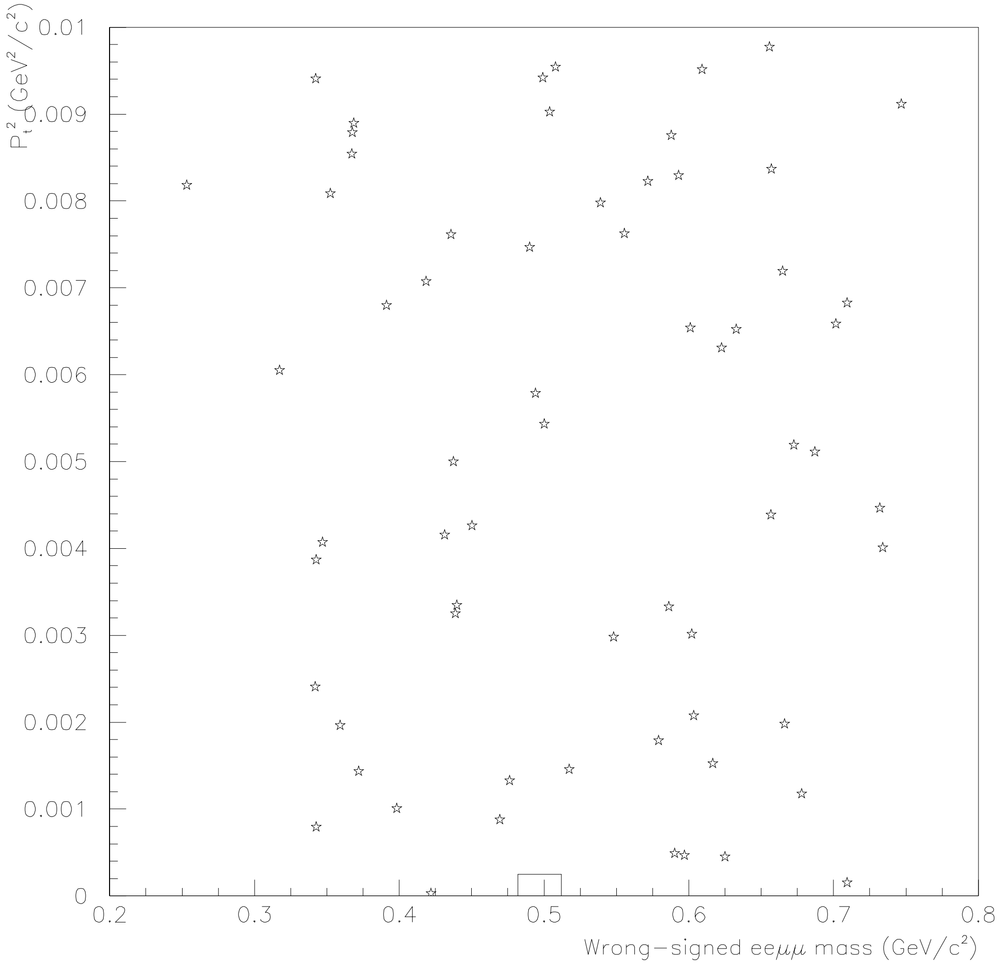
- Branching ratio consistent with VMD prediction of 2.34×10^{-9}

- Prediction of $(1.3 \pm 0.2) \times 10^{-9}$ seems to be ruled out

No CP–violating effects evident in angular distribution



Search For LFV $K_L \longrightarrow e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$



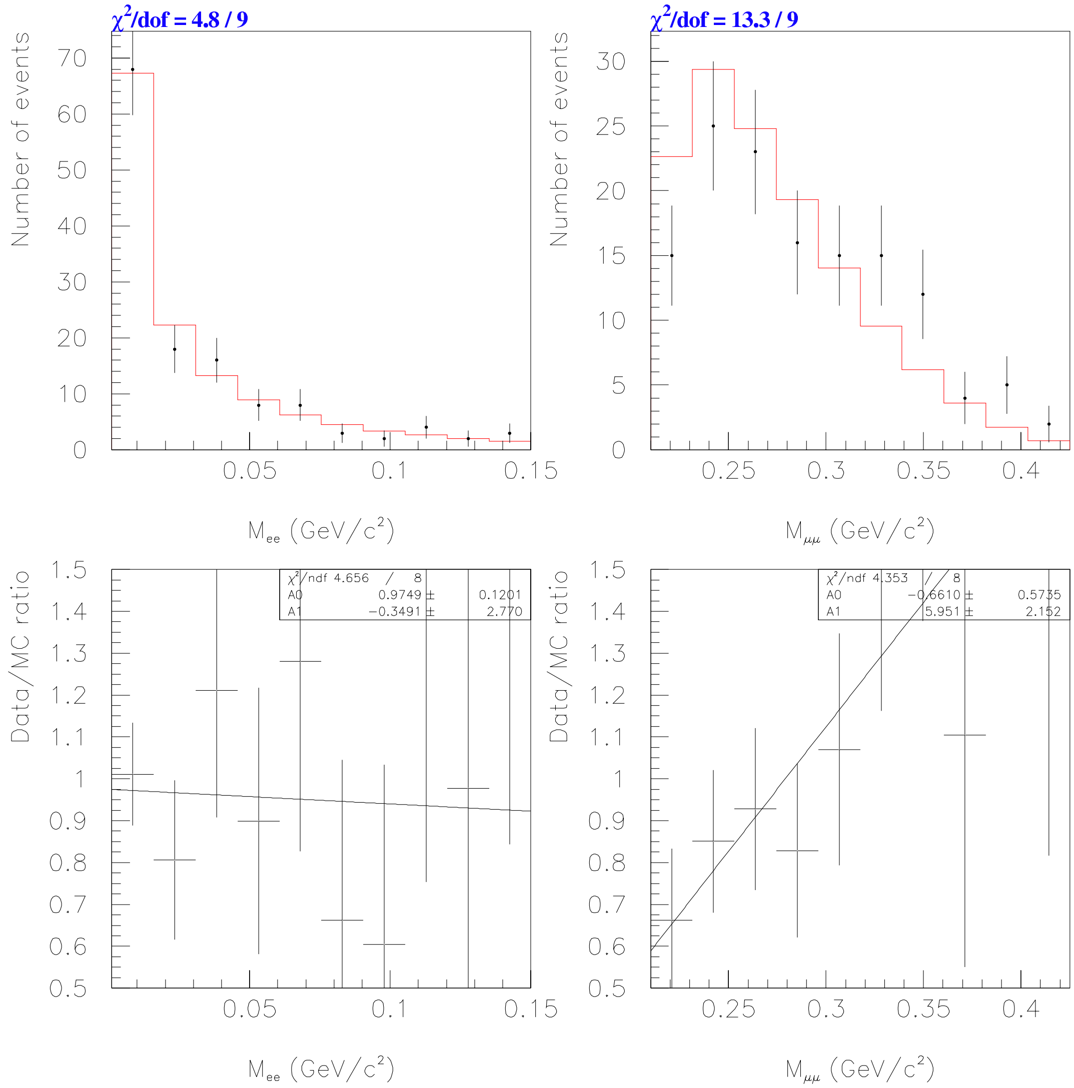
- Identical cuts to $K_L \longrightarrow e^+e^-\mu^+\mu^-$

- New 90% C.L. limit on branching ratio:

$$\mathcal{B}(K_L \longrightarrow e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}) < 4.12 \times 10^{-11}$$

- *Factor of 3* improvement over previous (KTeV) limit

DIP Form Factor Fit for α and β

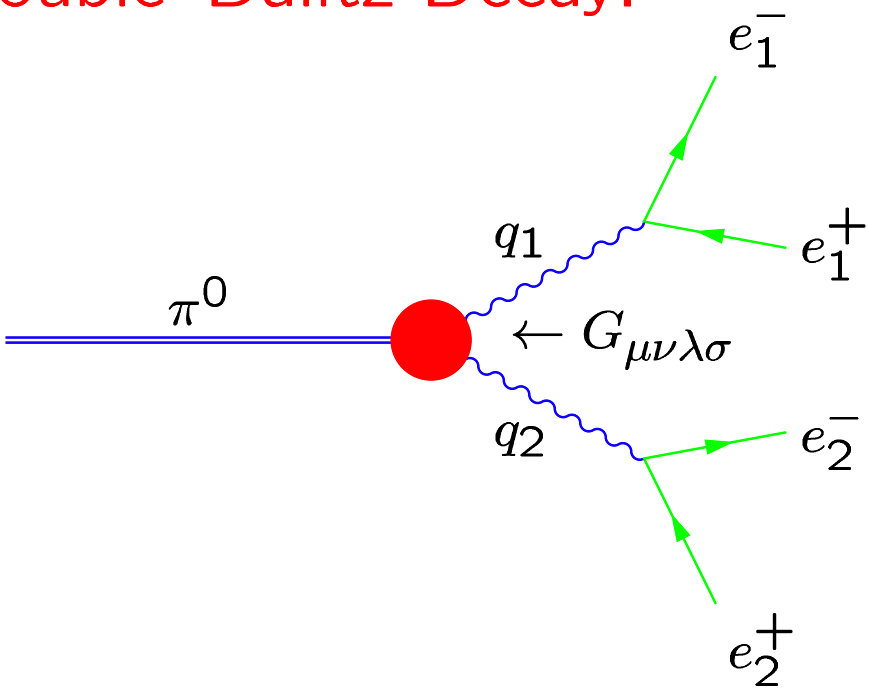


- MC overlays in M_{ee}, $M_{\mu\mu}$ for $\alpha = \beta = 0$ shown above
- Evidence of a non–trivial form factor
- Fits for α and β are in progress. . .

Measurements of $\pi^0 \to e^+e^-e^+e^-$

work by Patrick Toale, University of Colorado

The Double–Dalitz Decay:



$$G_{\mu\nu\lambda\sigma} \sim F_{ps}\ \epsilon_{\mu\nu\lambda\sigma} + F_s \left[g_{\mu\lambda} g_{\nu\sigma} - g_{\mu\sigma} g_{\nu\lambda} \right]$$

- Final State angular distribution sensitive to Scalar/Pseudoscalar coupling
- Form Factor affects Distribution of ee Masses:

$$F\left(q_1^2, q_2^2\right) = F_0 \cdot f\left(q_1^2, q_2^2\right)$$

where

$$f\left(q_1^2, q_2^2\right) = 1 + \frac{a}{M_\pi^2}\left(q_1^2 + q_2^2\right) + \mathcal{O}\left(q_i^2 q_j^2\right)$$

Previous Measurement:

N. P. Samios, *et al*, Phys. Rev. **126**, 1844 (1962). Based on 146 Events :

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to \gamma\gamma)} = (3.18 \pm 0.30) \times 10^{-5}$$

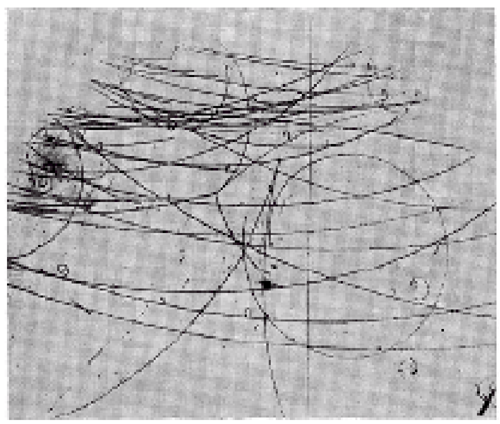


FIG. 1. Photograph of a typical double internal conversion.

$$\frac{\partial\Gamma}{\partial\phi} \sim 1 + \alpha\,(\cos 2\phi + C \sin 2\phi)$$

$\phi \sim$ Angle b/w ee planes

$$\begin{aligned} \alpha &= -0.12 \pm 0.15 \\ C &= 0.77 \pm 0.53 \end{aligned}$$

Combined Result:

	DD	2D
97	10,506	52,446
99	17,448	79,640
Combo	27,954	132,086

97:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.2277 \pm 0.0024$$

99:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.2233 \pm 0.0019$$

Combined:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.2252 \pm 0.0015$$

Combined Result:

Old 97 Preliminary Result:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.228 \pm 0.003 \pm 0.006$$

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to \gamma\gamma)} = (3.31 \pm 0.04 \pm 0.22)\times 10^{-5}$$

New Combined Preliminary Result:

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to e^+e^-\gamma)^2} = 0.2252 \pm 0.0015 \pm 0.0059$$

$$\frac{B(\pi^0 \to e^+e^-e^+e^-)}{B(\pi^0 \to \gamma\gamma)} = (3.274 \pm 0.022 \pm 0.197)\times 10^{-5}$$

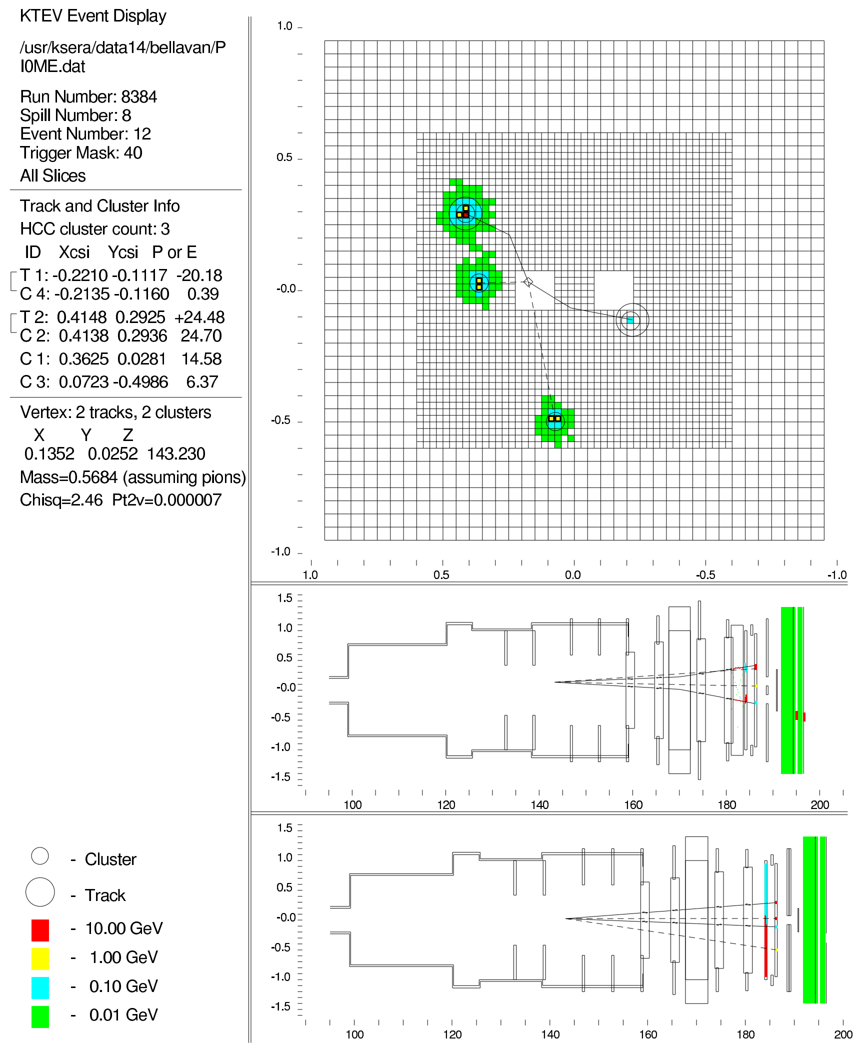
Conclusions:

- Branching Ratio:
  - $\frac{B(\pi^0 \to 4e)}{B(\pi^0 \to ee\gamma)^2} = 0.2252 \pm 0.0015 \pm 0.0074$
  - Agrees with expectations
  - Radiative Corrections are now available
  - Systematic error can be reduced with further work
- Form Factor:
  - Radiative Corrections are a larger effect
  - Corrections will be included soon
- ϕ Distribution:
  - Tree–Level MC predicts general features of ϕ distribution in Data
  - No indication of CP violation

Search for Lepton Number Violating Decay $K_L \to \pi^0 \mu^\pm e^\mp$

Work of Angela Bellavance, Rice University

Example ($K_L \to \pi^0 \mu^\pm e^\mp$) MC Event



Main Backgrounds:

$K_L \to \pi^+\pi^-\pi^0$ (K3pi)

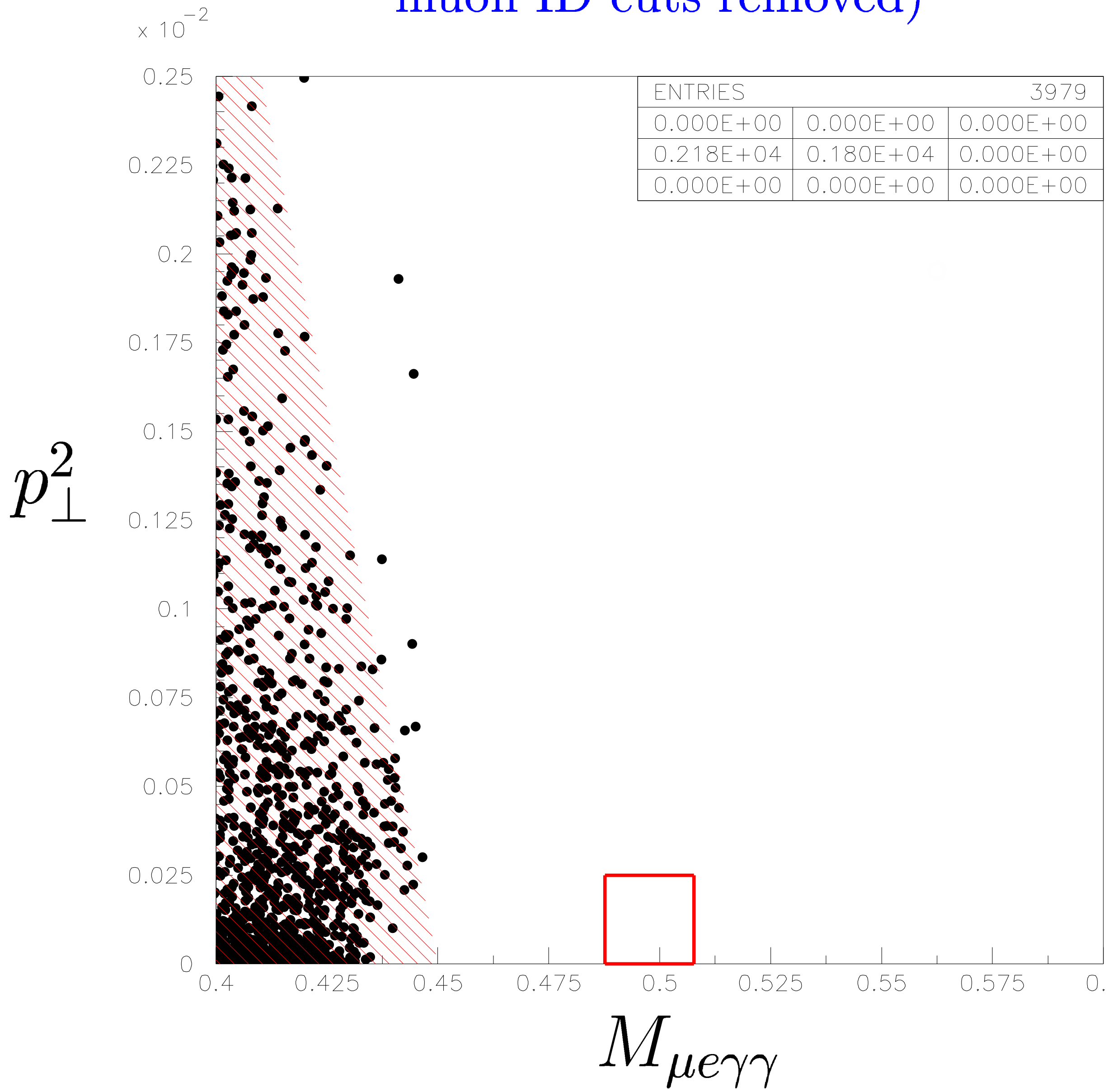
$K_L \to \pi^0\pi^\pm e^\mp \nu_e$ (Ke4)

$K_L \to \pi^\pm e^\mp \nu_e$ (Ke3)

Normalization Mode:

$K_L \to \pi^+\pi^-\pi^0$ (K3pi)

K3pi Background
(normalization data, $5{\times}10^{-5}$ times flux, muon ID cuts removed)

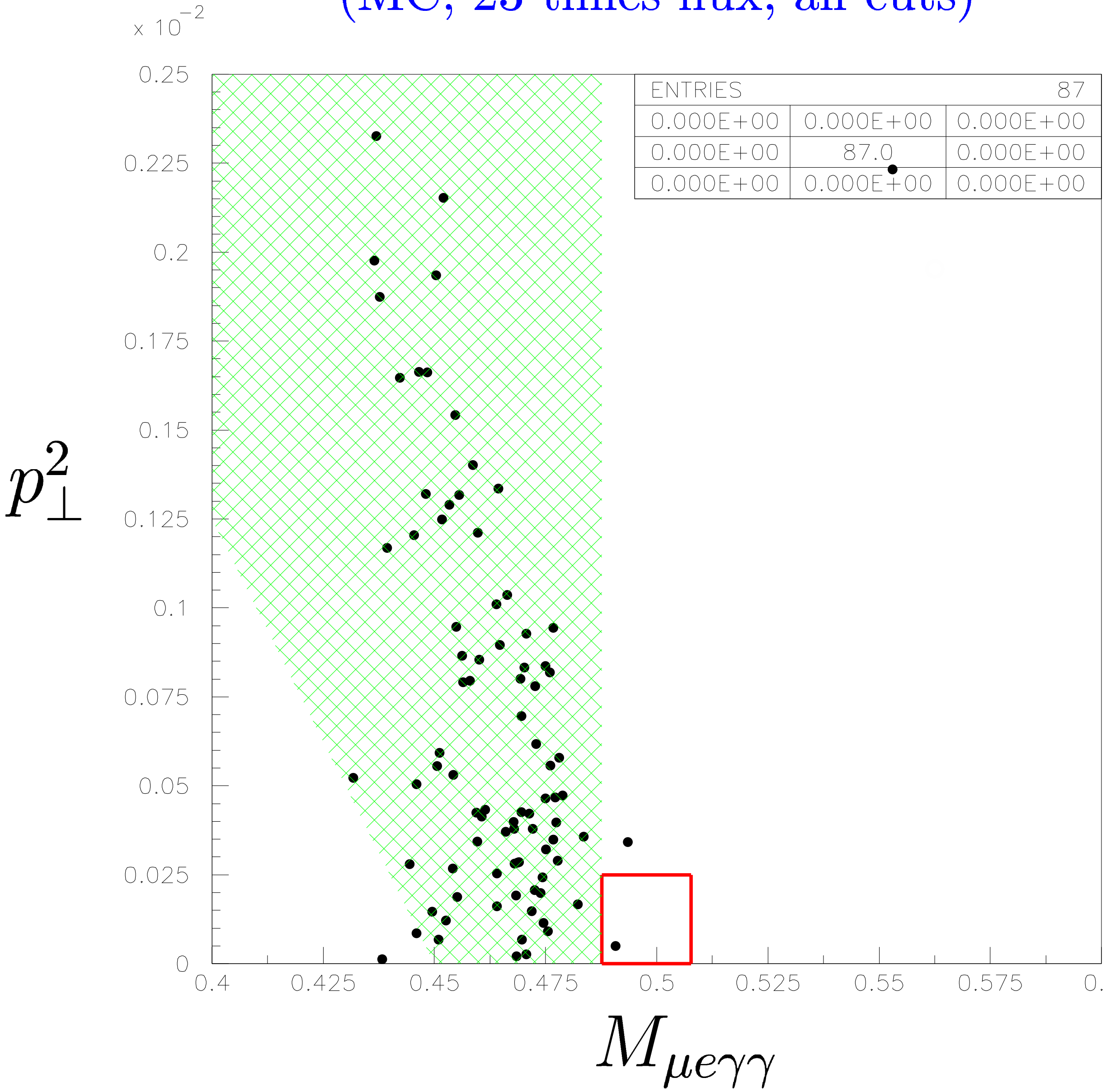


Expected events in 97 study plot : 2.5 ± 0.5

Expected events in 99 study plot : 8.0 ± 3.8

Ke4 Background

(MC, 23 times flux, all cuts)

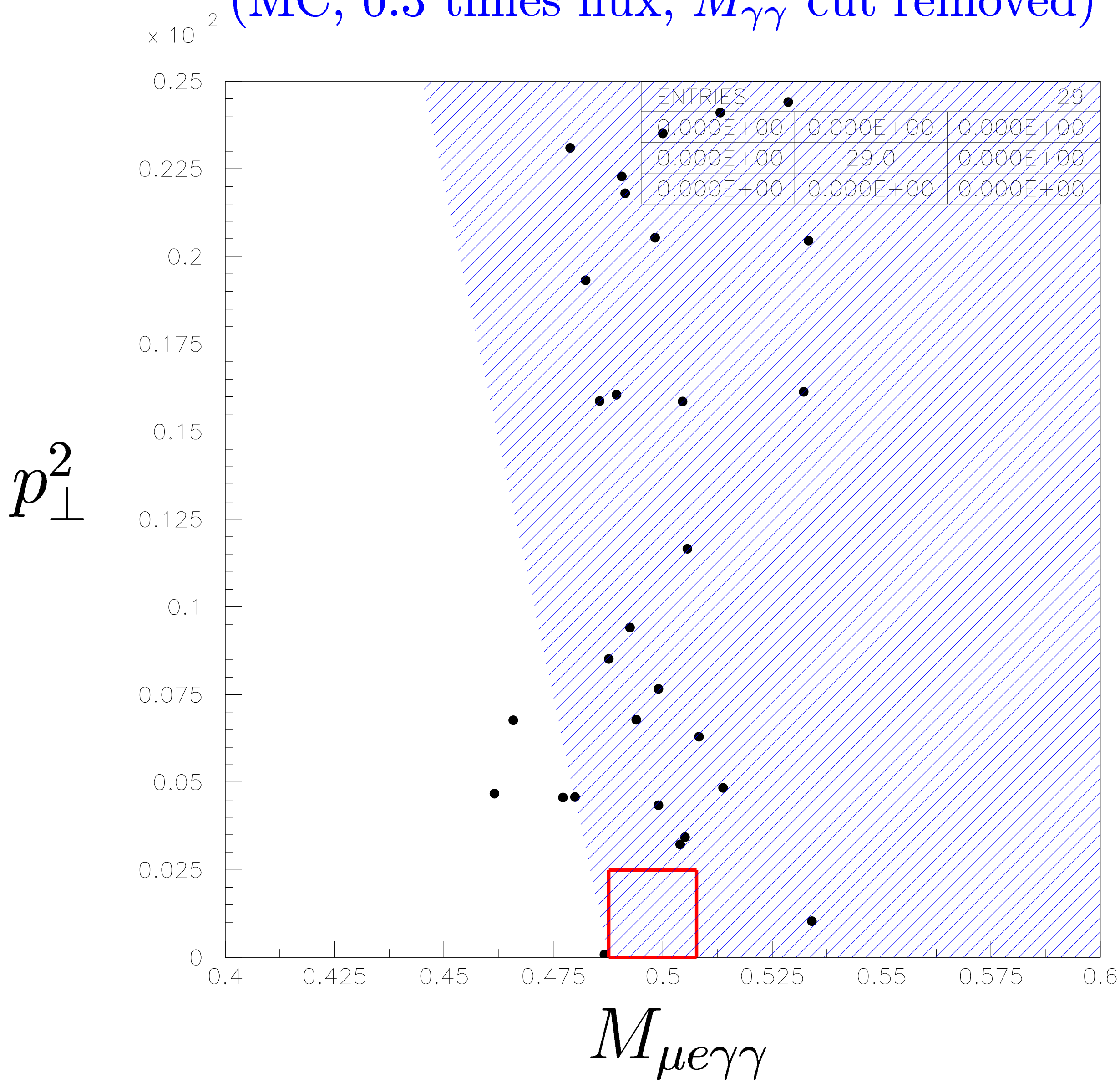


Expected events in 97 study plot : 9.4 ± 1.1

Expected events in 99 study plot : 4.8 ± 0.6

Ke3 Background

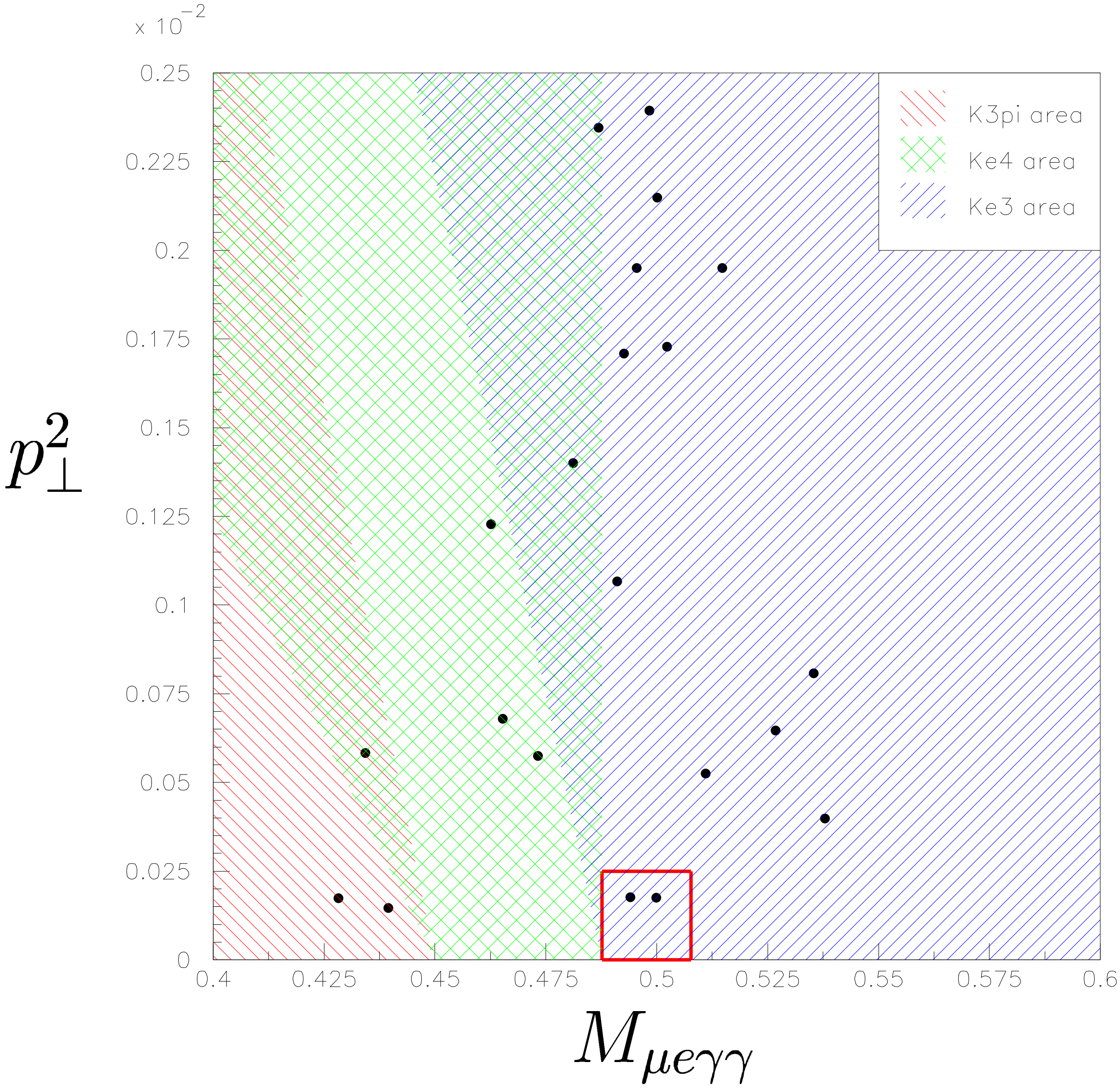
(MC, 0.3 times flux, $M_{\gamma\gamma}$ cut removed)



Expected events in 97 study plot : 10.1 ± 8.1

Expected events in 99 study plot : 9.3 ± 4.1

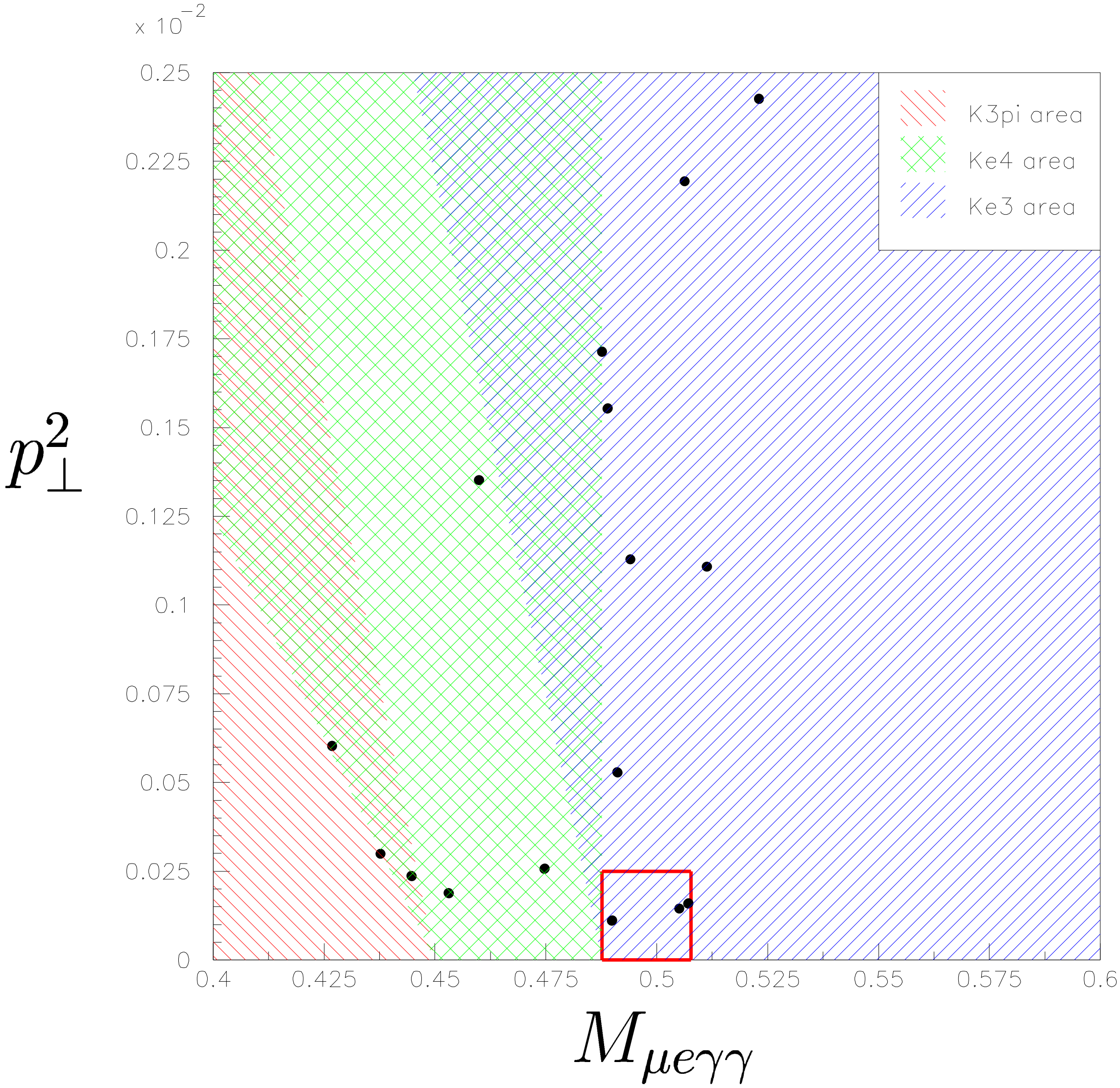
97 Search Data



19 events total	22.0±8.2 expected
3 "K3pi" events	2.5±0.5 expected
3 "Ke4" events	9.4±1.1 expected
13 "Ke3" events	10.1±8.1 expected

From MC: 0.61±0.56 evts. expected in box
From data: 0.53±0.14 evts. expected in box

99 Search Data



13 events total	22.3±5.7 expected
≈3 "K3pi" events	8.0±3.8 expected
≈3 "Ke4" events	4.8±0.6 expected
≈7 "Ke3" events	9.3±4.1 expected

MC(Ke3+Ke4): 0.49±0.22 expected in box

data(Ke3)+MC(Ke4): 0.48±0.14 exp. in box

...but distribution is *not* consistant with signal!

% of signal MC beyond data event:
(farther from M_K or larger $p_\perp^2$)

97 event #1 : 43.4% in M_K, 2.5% in $p_\perp^2$
97 event #2 : 23.8% in M_K, 2.4% in $p_\perp^2$

99 event #1 : 1.1% in M_K, 5.8% in $p_\perp^2$
99 event #2 : 1.8% in M_K, 3.8% in $p_\perp^2$
99 event #3 : 0.7% in M_K, 3.3% in $p_\perp^2$

- These data events are not currently explained by our background estimation techniques, but we believe them to be background.

- We are continuing to explore background scenarios within the signal box.

- To be conservative, we are currently quoting an upper limit which treats the data events as signal.

Branching Ratio Limits

- 97 data only

$$BR(K_L \rightarrow \pi^0 \mu^\pm e^\mp (97)) < 4.40 \times 10^{-10}$$
$$(90\% CL, Preliminary)$$

- 99 data only

$$BR(K_L \rightarrow \pi^0 \mu^\pm e^\mp (99)) < 5.33 \times 10^{-10}$$
$$(90\% CL, Preliminary)$$

- 97 and 99 data combined

Using Baysean Probability Density Functions (PDFs)

$$BR(K_L \rightarrow \pi^0 \mu^\pm e^\mp (97+99)) < 3.31 \times 10^{-10}$$
$$(90\% CL, Preliminary)$$

Summary

- $K_L \to \pi^+\pi^-e^+e^-$, 5056 events in full sample, CP violating asymmetry measured to be $(13.3 \pm 1.1 \pm 1.0)\%$.

- $K_L \to e^+e^-\gamma$, from 93,000 events branching fraction is $(10.13 \pm 0.04 \pm 0.06 \pm 0.29) \times 10^{-6}$. Form factor fit gives $\alpha_{K^*} = -0.192 \pm 0.011 \pm 0.009$.

- $K_L \to e^+e^-\mu^+\mu^-$ 133 events in full sample, yielding branching fraction of $(2.61 \pm 0.23 \pm 0.18) \times 10^{-9}$. Form factor fits in progress. Limit on $K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$ of 4.12×10^{-11}.

- $\pi^0 \to e^+e^-e^+e^-$ 28,000 events in full sample, yield branching fraction of $(3.274 \pm 0.022 \pm 0.197) \times 10^{-5}$ with respect to $\pi^0 \to \gamma\gamma$. Detailed angular analysis requres radiative corrections which are just now available.

- Search for $K_L \to \pi^0\mu^\pm e^\mp$. In total sample expect about 1.1 background in signal box, observe 5 events. However these are not distributed like data should be. Conservative upper limit for branching fraction is 3.31×10^{-10}.