

KTeV Results on Rare Kaon Decays

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Outline

- Introduction
- The KTeV experiment
- $K_L \rightarrow \mu^+ \mu^- \gamma$
- $K_L \rightarrow e^+ e^- \gamma$
- $K_L \rightarrow e^+ e^- \mu^+ \mu^-$
- Conclusions

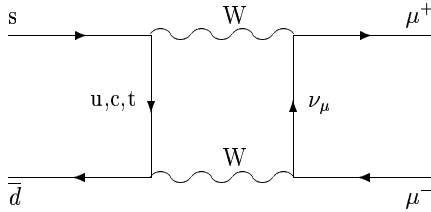
KTeV Rare Kaon Physics Program

Decay Mode	Publ.	# Events	BR
Direct CP Violation			
$K_L \rightarrow \pi^0 e^+ e^-$	✓	2	$< 5.1 \times 10^{-10}$
$K_L \rightarrow \pi^0 \mu^+ \mu^-$	✓	2	$< 3.8 \times 10^{-10}$
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	✓	0	$< 5.9 \times 10^{-7}$
Indirect CP violation			
$K_L \rightarrow \pi^+ \pi^- \gamma$	✓	8,669	$(2.08 \pm 0.03) \times 10^{-2}$ $\times B(K_L \rightarrow \pi^+ \pi^-)$
$K_L \rightarrow \pi^+ \pi^- e^+ e^-$		1,558	$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$
χ PT and VMD			
$K_L \rightarrow \pi^0 \gamma \gamma$	✓	884	$(1.68 \pm 0.07 \pm 0.08) \times 10^{-6}$
$K_L \rightarrow \pi^0 e^+ e^- \gamma$	✓	48	$(2.34 \pm 0.35 \pm 0.13) \times 10^{-8}$
$K_L \rightarrow \pi^0 \pi^0 e^+ e^-$		1	$< 5.4 \times 10^{-9}$
$K\gamma\gamma^*$ Vertex			
$K_L \rightarrow e^+ e^- \gamma$		127K	
$K_L \rightarrow \mu^+ \mu^- \gamma$	✓	9,327	$(3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$
$K_L \rightarrow e^+ e^- \gamma \gamma$	✓	1,543	$(5.84 \pm 0.15 \pm 0.32) \times 10^{-7}$
$K_L \rightarrow \mu^+ \mu^- \gamma \gamma$	✓	4	$(1.04^{+0.75}_{-0.59} \pm 0.07) \times 10^{-8}$
$K\gamma^*\gamma^*$ Vertex			
$K_L \rightarrow e^+ e^- e^+ e^-$	✓	441	$(3.72 \pm 0.18 \pm 0.23) \times 10^{-8}$
$K_L \rightarrow e^+ e^- \mu^+ \mu^-$	✓	43	$(2.62 \pm 0.40 \pm 0.17) \times 10^{-9}$
Lepton Flavor Violation			
$K_L \rightarrow \pi^0 \mu^\pm e^\mp$		0	$< 4.4 \times 10^{-10}$

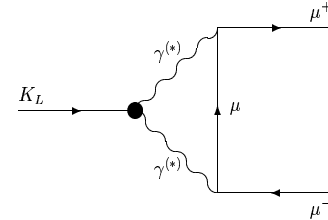
- Red $\rightarrow$ most precise or largest sample.
- Concentrate today on $K\gamma\gamma^*$ and $K\gamma^*\gamma^*$ vertex.

The Decay $K_L \rightarrow \mu^+ \mu^-$

Short Distance



Long Distance



- Short Distance contributions
 - Dominated by top quark.
 - Sensitive to V_{td} .
- Long Distance contributions
 - Large theoretical uncertainties.
 - Measure $K\gamma^*\gamma^*$ vertex $\rightarrow$ extract short distance contributions.
- Measurements
 - $K_L \rightarrow l^+ l^- \gamma$: $e^+ e^- \gamma$ and $\mu^+ \mu^- \gamma$
 - * Extrapolate to $K\gamma^*\gamma^*$ (model dependent).
 - $K_L \rightarrow e^+ e^- \mu^+ \mu^-$
 - * Best method for measuring $K\gamma^*\gamma^*$.
 - * Low statistics.

The KTeV Collaboration

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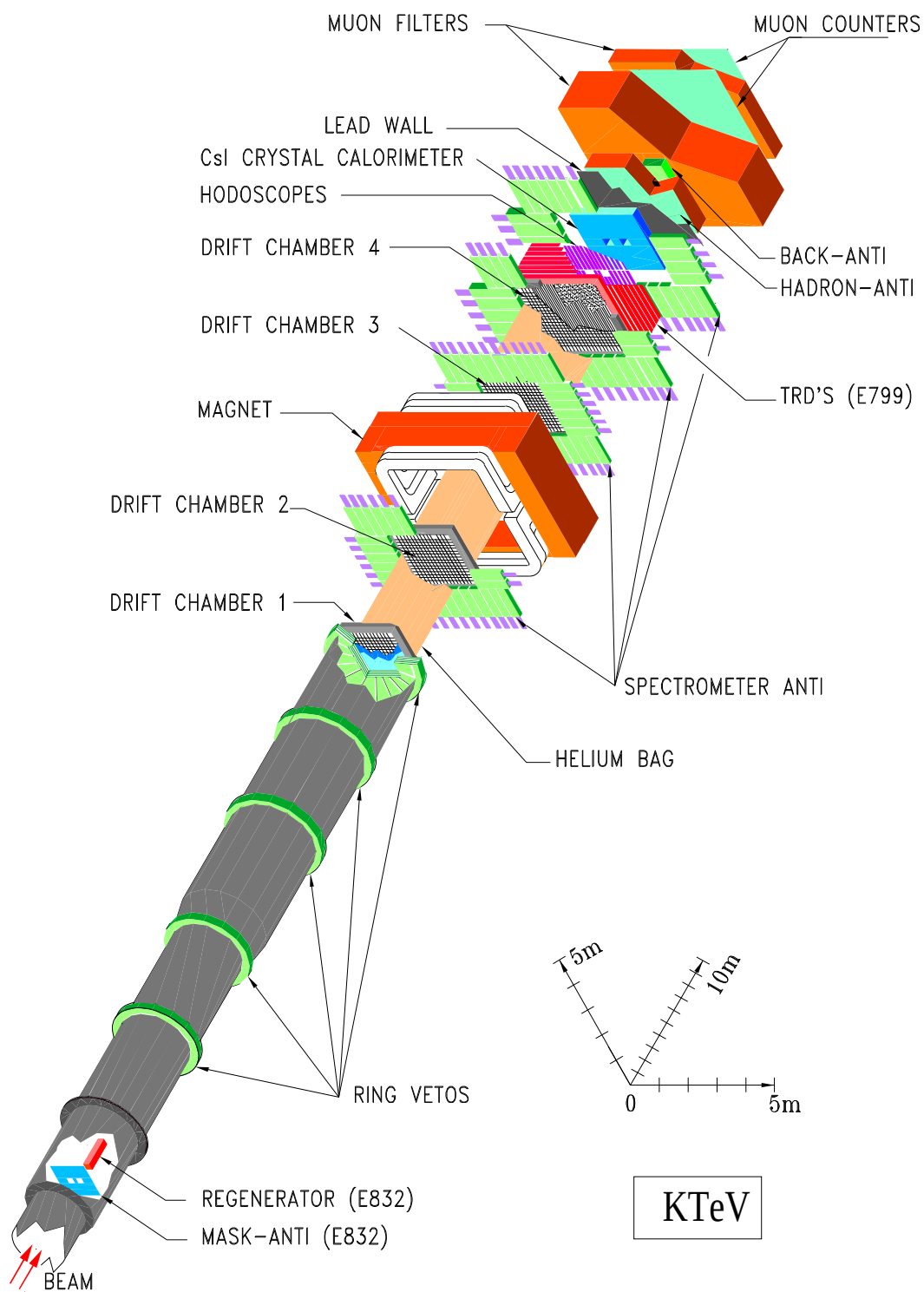
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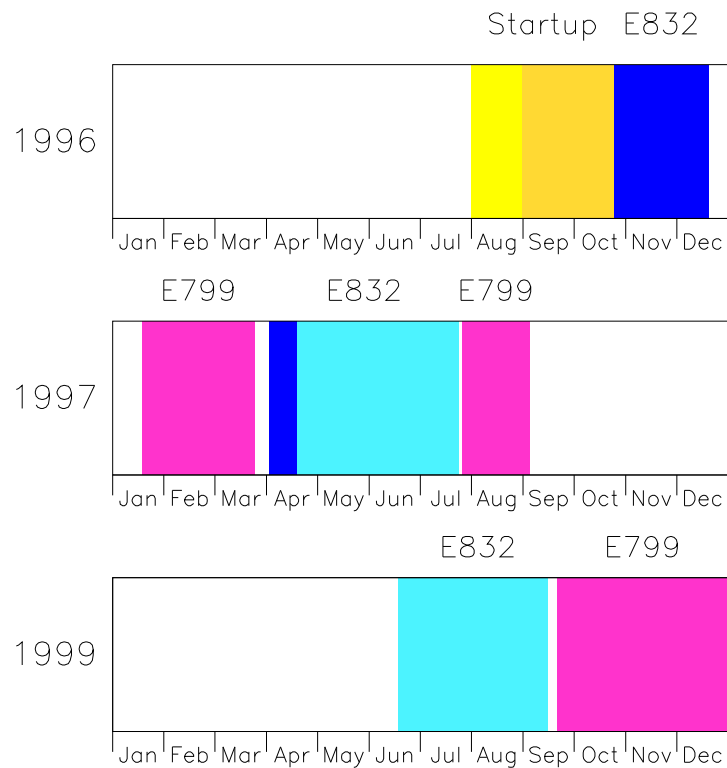
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The KTeV Detector



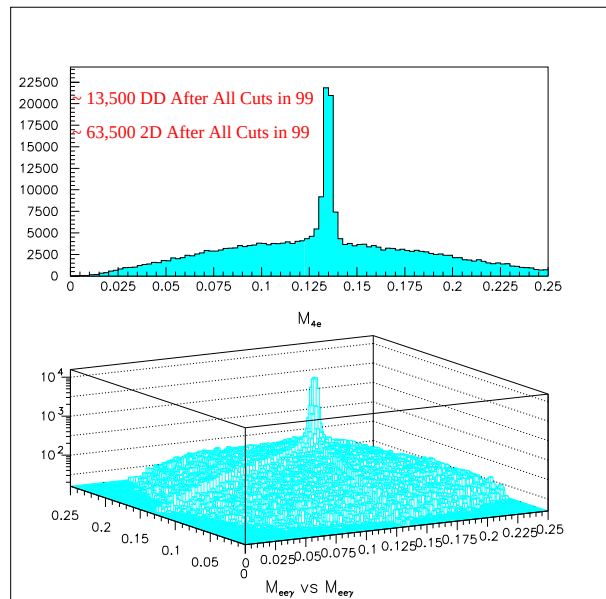
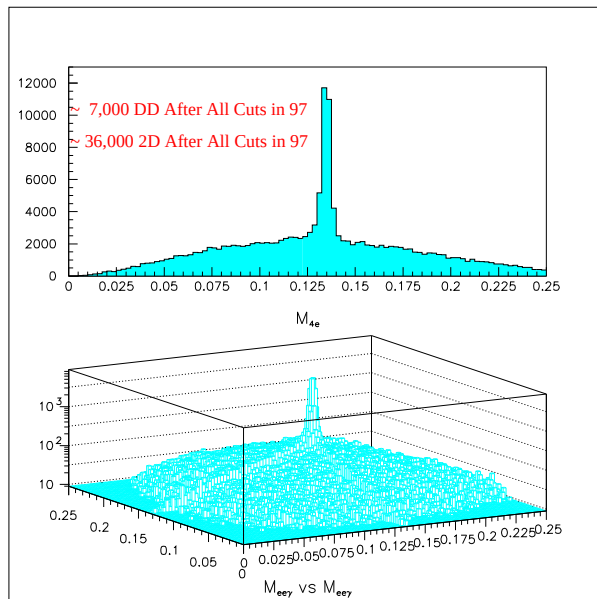
KTeV

The KTeV Data Set

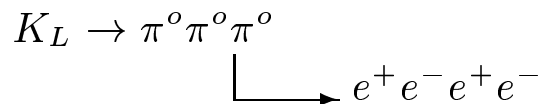


- Rare decay data (E799)
 - $K_L \rightarrow \pi^0 e^+ e^-$ and $K_L \rightarrow \pi^0 \mu^+ \mu^-$.
- Three running periods
 - 1997: Winter and Summer.
 - * Most results published from this data.
 - 1999: Doubled 1997 data.
 - * Many improvements to detector.

1997 and 1999 Data

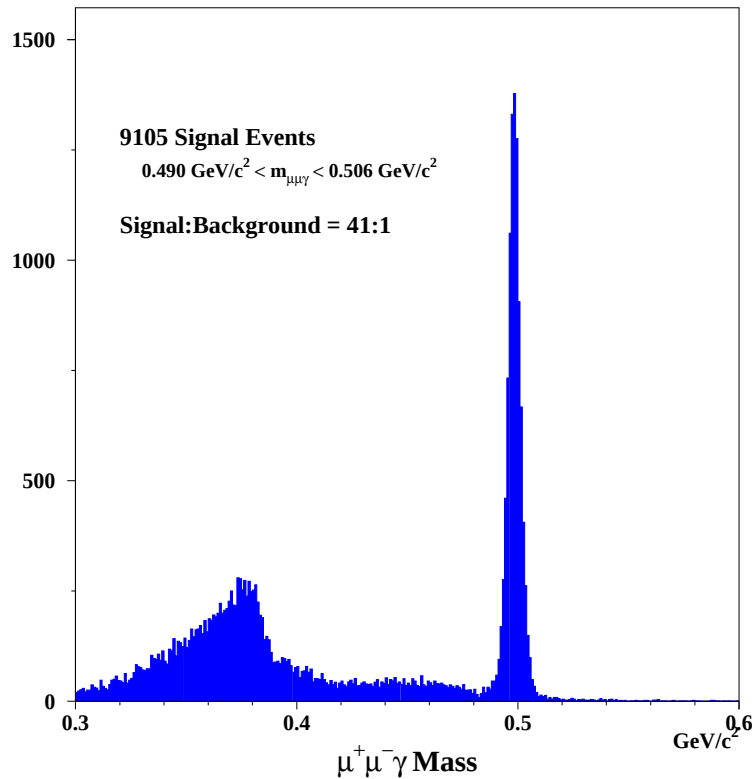


- All published KTeV results from 1997 data.
 - Combined analyses will have $\times 2.5 - 3.0$ more events.
 - Example



- New combined results soon.
 - $K_L \rightarrow \pi^0 \mu^\pm e^\mp$
 - $\pi^0 \rightarrow e^+ e^- e^+ e^-$
 - $K_L \rightarrow \pi^+ \pi^- e^+ e^-$
 - $K_L \rightarrow e^+ e^- \mu^+ \mu^-$

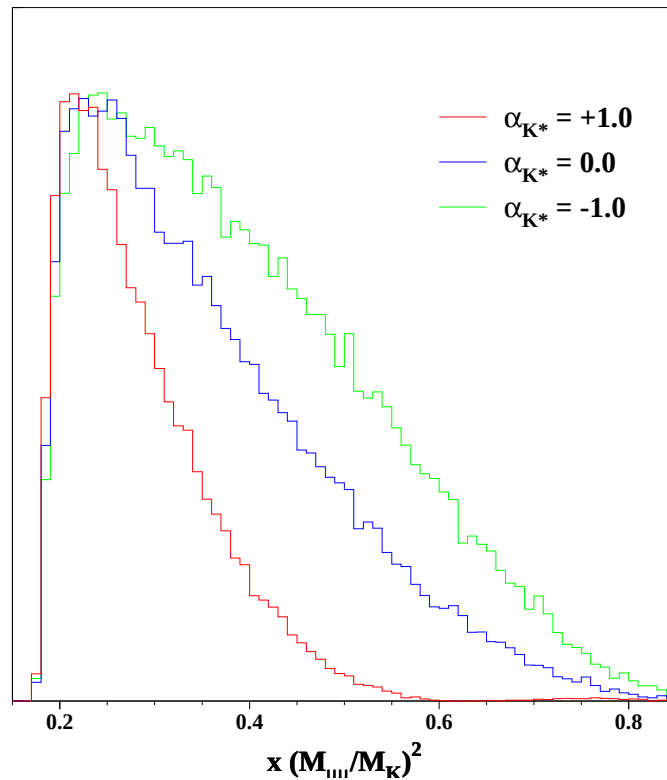
$\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma)$ Measurement



- Normalized to $K_L \rightarrow \pi^+ \pi^- \pi^0$.
 - 210K events.
- Backgrounds
 - Dominated by $K_L \rightarrow \pi^\pm \mu^\mp \nu$.
- Systematics
 - Largest internal: Muon system cracks.

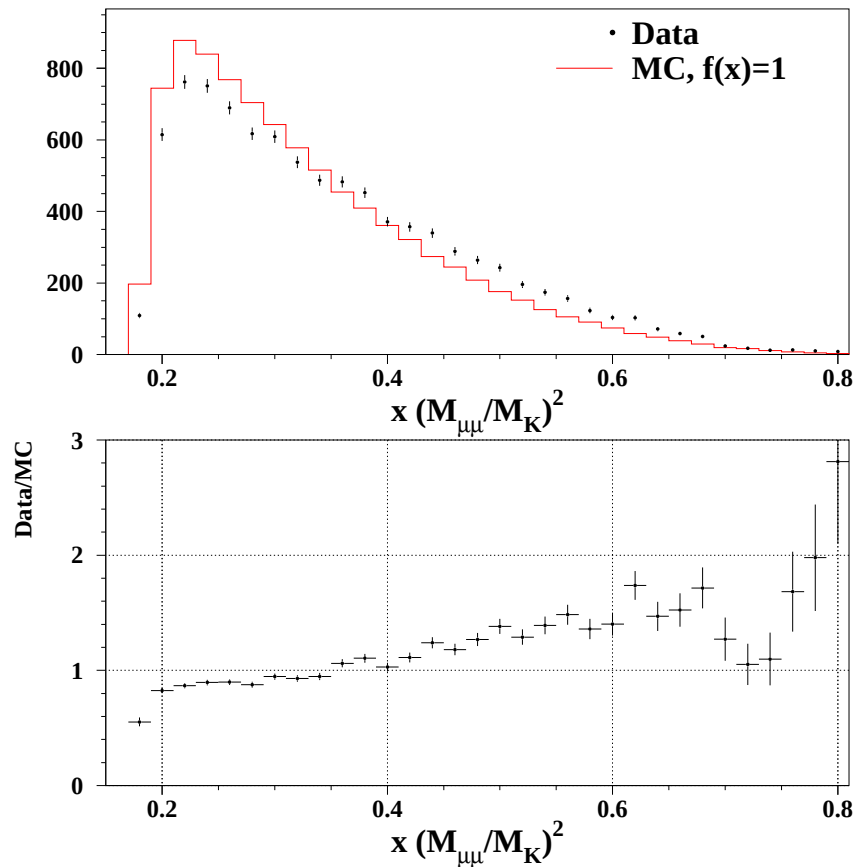
$$\text{BR}(K_L \rightarrow \mu^+ \mu^- \gamma) = (3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$$

$$K_L \rightarrow \mu^+ \mu^- \gamma$$



- Model for long distance $\gamma\gamma^*$ form factor depends upon single parameter.
 - Bergström, Massó & Singer: α_{K^*} .
 - * VMD + strangeness changing vector-vector.
 - D'Ambrosio, Isadori, Portolés: α
 - * ChPT expansion of $K_L \rightarrow \gamma^*\gamma^*$ form factor.
- Both Branching Ratio and $m_{\mu^+\mu^-}$ are sensitive to α and α_{K^*} .

Dimuon Mass Distribution



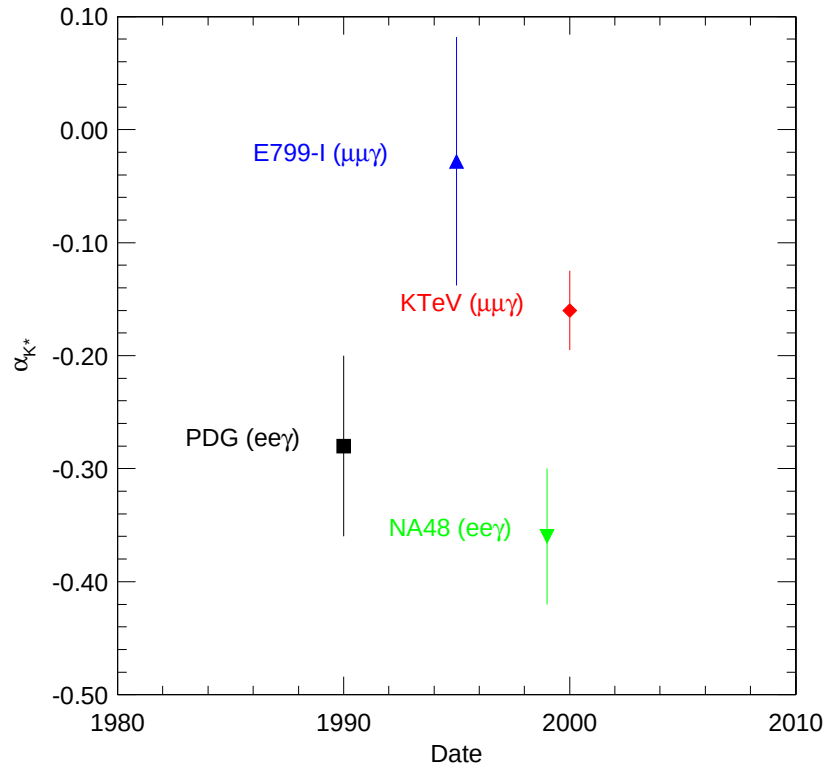
- $\mu^+\mu^-$ mass distribution.
 - Varies considerably as a function of α_{K^*} and α .
- Data/MC ratio is determination of form factor.
 - Monte Carlo with form factor = 1.
 - Sizeable effect.
 - Model independent.

KTeV Measurement of α_{K^*} and α

- Dimuon shape.
 - Unbinned maximum likelihood comparison to Monte Carlo.
 - Thousands of MC sets generated with various α_{K^*} and α values.
 - Largest systematic from cut on track momenta.
- Branching Ratio.
 - Integrate differential decay rate with either BMS or DIP form factor.
 - Use PDG $BR(K_L \rightarrow \gamma\gamma) = (5.92 \pm 0.15) \times 10^{-4}$
 - Acceptance dependence on form factor $\sim 0.04\%$.
- First measurement of α

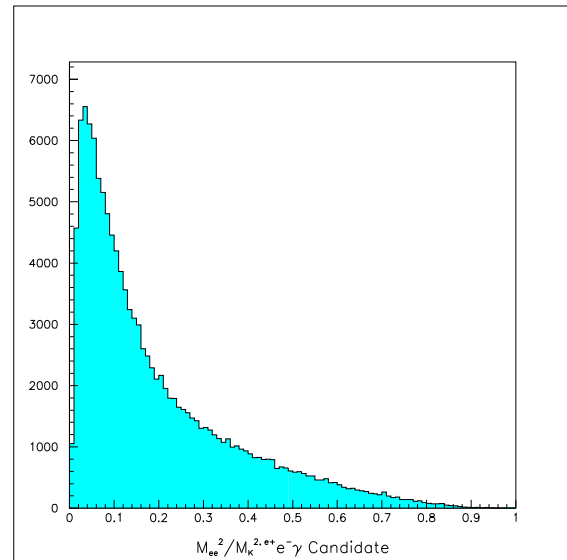
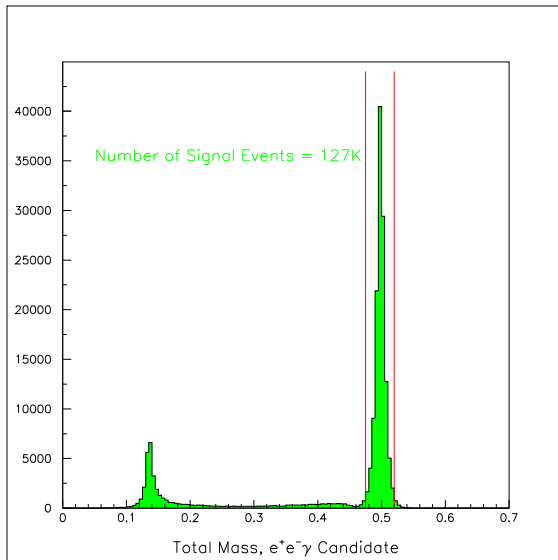
Method	α_{K^*}	α
Branching Ratio	-0.177 ± 0.040	-1.38 ± 0.13
Dimuon Shape	$-0.193^{+0.035}_{-0.049}$	$-1.73^{+0.14}_{-0.18}$
Combined	$-0.160^{+0.026}_{-0.028}$	-1.54 ± 0.10

Measurements of α_{K^*}



- Most precise measurement of α_{K^*}
 - $\alpha(\alpha_{K^*} = -0.161) = -1.50 \pm 0.11$
- Approximately 3σ discrepancy between $\mu^+\mu^-\gamma$ and $e^+e^-\gamma$ measurements.
 - $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ sample different k^2 regions.
 - * Possible problem with form factor models.
 - Await results from large KTeV $K_L \rightarrow e^+e^-\gamma$ sample and NA48 $K_L \rightarrow \mu^+\mu^-\gamma$ sample.

$$K_L \rightarrow e^+ e^- \gamma$$

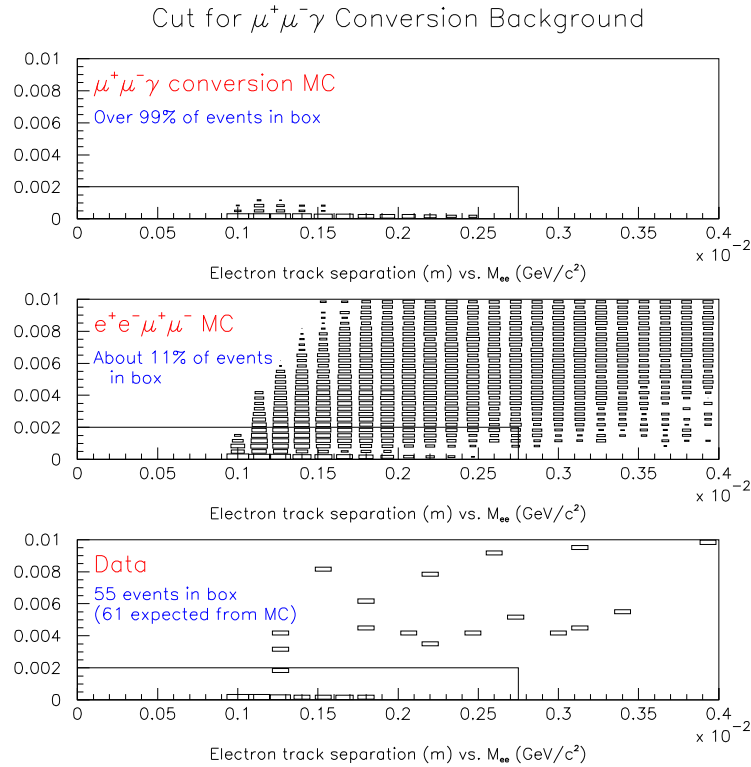


- Current best measurement: NA48
 - ~ 7000 events
- KTeV 1997 sample.
 - 127,000 events.
- Form Factor measurement.
 - Complicated by significant radiative corrections.
 - Not present in $K_L \rightarrow \mu^+ \mu^- \gamma$ measurement.

$K_L \rightarrow e^+ e^- \mu^+ \mu^-$ Analysis

- Measurement of $K\gamma^*\gamma^*$ Vertex.
- Previous Measurement
 - KTeV: 43 events.
 - $\text{BR}(K_L \rightarrow e^+ e^- \mu^+ \mu^-) = (2.62 \pm 0.40 \pm 0.17) \times 10^{-9}$.
- New Measurement
 - Combined 1997 and 1999 analysis.
- Form Factor Measurement
 - DIP model.
 - * $f(q_1^2, q_2^2) = 1 + \alpha \left(\frac{q_1^2}{q_1^2 - m_\rho^2} + \frac{q_2^2}{q_2^2 - m_\rho^2} \right) + \beta \frac{q_1^2 q_2^2}{(q_1^2 - m_\rho^2)(q_2^2 - m_\rho^2)}$
 - * α measured in $K_L \rightarrow \mu^+ \mu^- \gamma$.
 - * $K_L \rightarrow e^+ e^- \mu^+ \mu^-$ sensitive to β .
 - Simultaneous fit to $m_{e^+e^-}$ and $m_{\mu^+\mu^-}$.
 - Statistics limited.

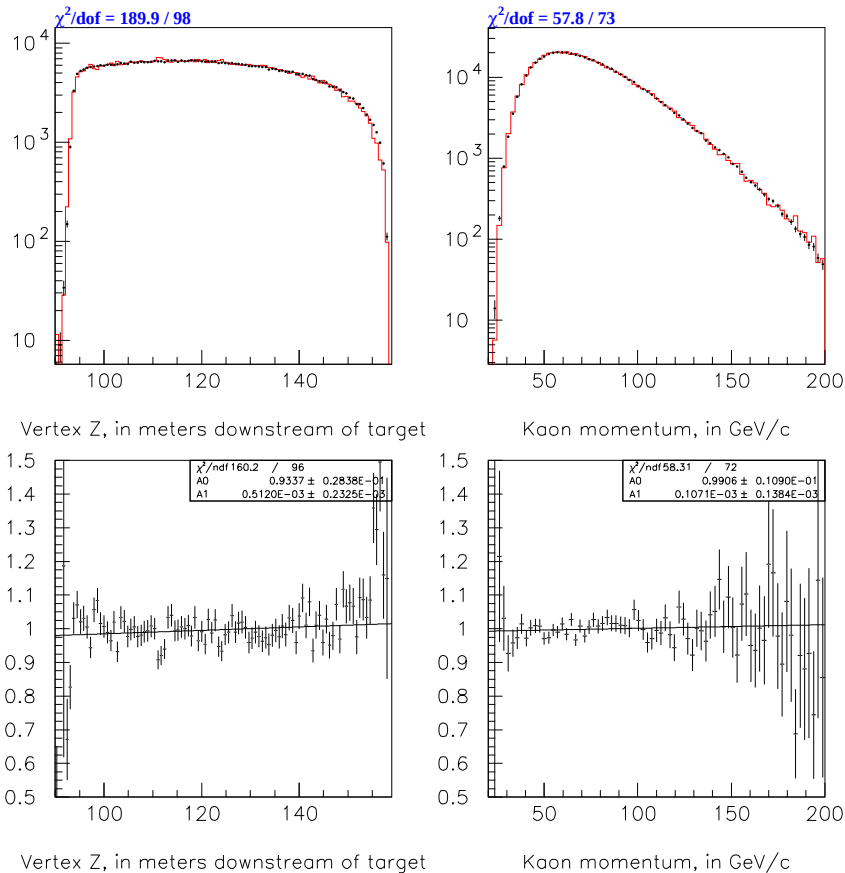
Backgrounds to $K_L \rightarrow e^+e^-\mu^+\mu^-$



- Largest source from $K_L \rightarrow \mu^+\mu^-\gamma$
 - Removed by cutting on $m_{e^+e^-}$ and track separation.
- Other sources of background.
 - $K_L \rightarrow \pi^+\pi^-\pi^0$
 - $K_L \rightarrow \pi^\pm e^\mp \nu + K_L \rightarrow \pi^\pm \mu^\mp \nu$
 - $K_L \rightarrow \pi^+\pi^-e^+e^-$

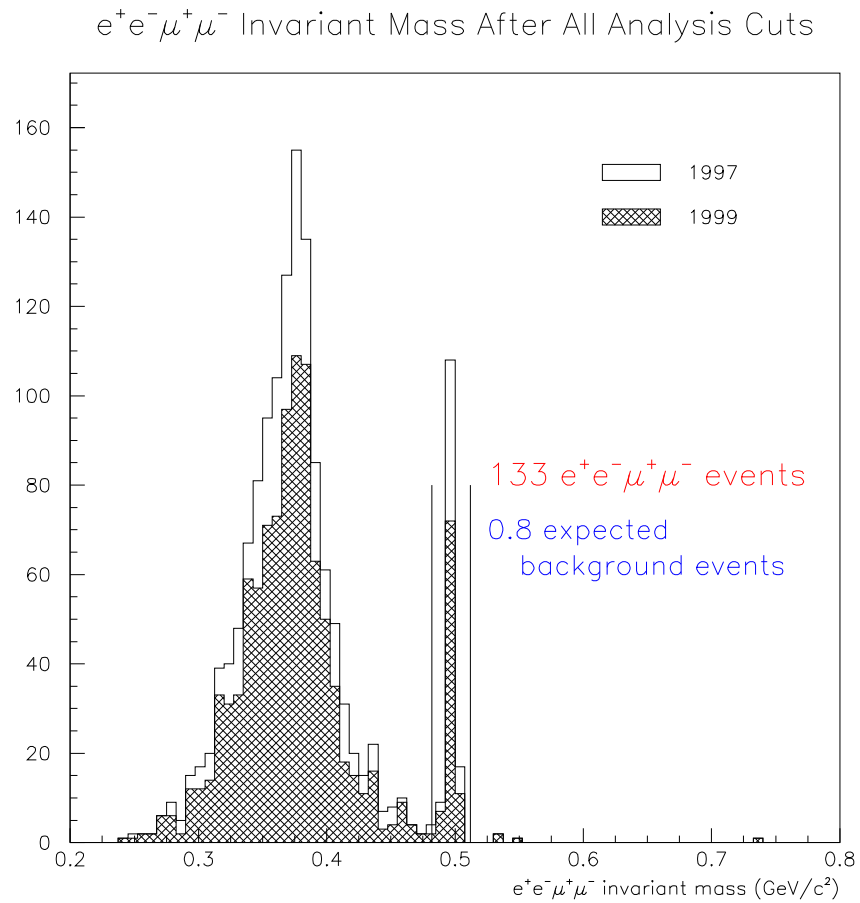
$K_L \rightarrow e^+ e^- \mu^+ \mu^-$ Normalization

Data/MC Overlays for 1999 $\pi^+ \pi^- \pi^0$ Normalization Events



- Normalization: $K_L \rightarrow \pi^+ \pi^- \pi^0$.
 - 490K Events.
 - Well understood with low background.
 - Similar kinematics but no muon requirements.

$$\text{BR}(K_L \rightarrow e^+ e^- \mu^+ \mu^-)$$

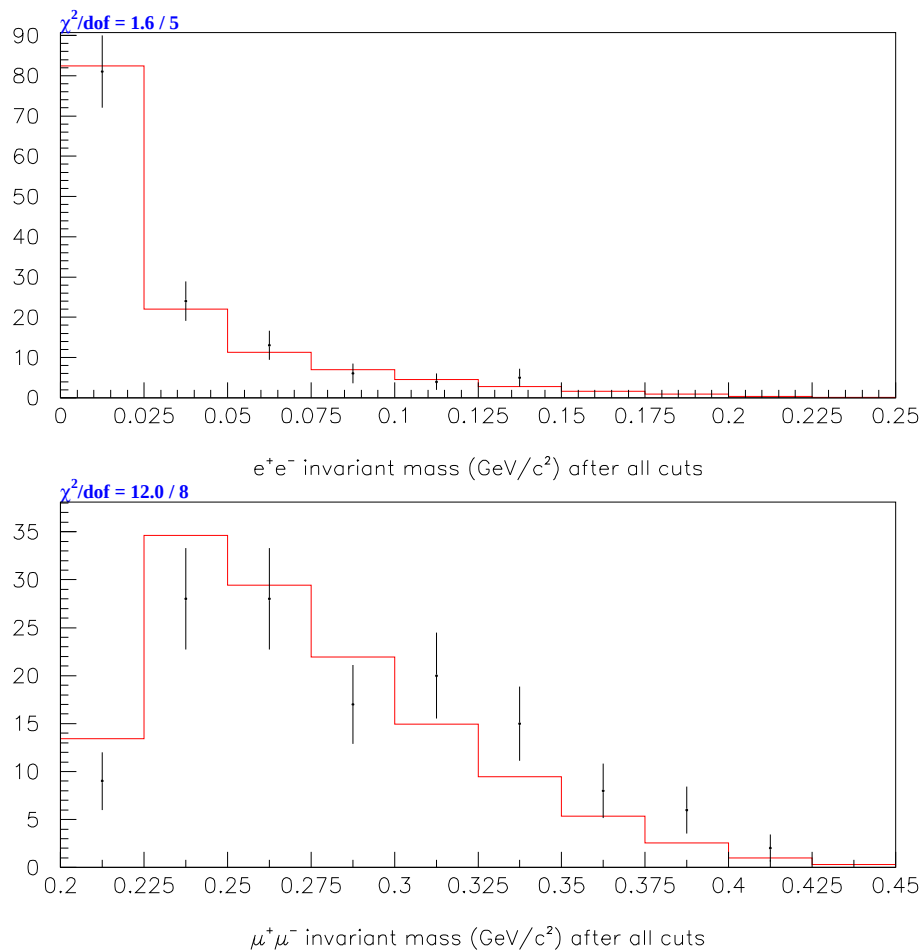


- Combined 1997 and 1999 samples.
 - Nearly triple previous measurement.
 - Low background.

$$\text{BR}(K_L \rightarrow e^+ e^- \mu^+ \mu^-) = (2.61 \pm 0.23 \pm 0.18) \times 10^{-9}$$

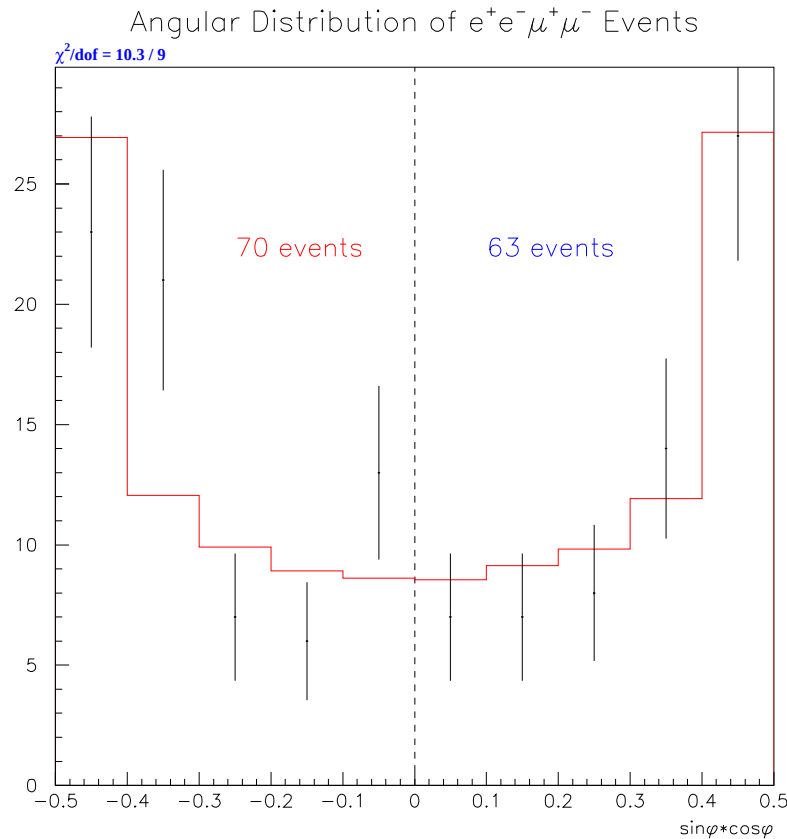
Preliminary

$K_L \rightarrow e^+ e^- \mu^+ \mu^-$ Form Factors



- $m_{e^+e^-}$ and $m_{\mu^+\mu^-}$ mass distributions.
 - MC shown with constant form factors.

CP Violation in $K_L \rightarrow e^+e^-\mu^+\mu^-$



- In $K_L \rightarrow e^+e^-\mu^+\mu^-$ asymmetry about $\sin 2\phi = 0$ indicates CP violation.
 - Similar to $K_L \rightarrow \pi^+\pi^-e^+e^-$.
 - Large effect in $K_L \rightarrow \pi^+\pi^-e^+e^-$.
 - Small effect expected in $K_L \rightarrow e^+e^-\mu^+\mu^-$.
- MC shown has no CP violation.

Conclusions

- KTeV has made many contributions to rare decay physics.
- Addition of 1999 data will triple statistics.
- New result on $K_L \rightarrow e^+e^-\mu^+\mu^-$
 - 1997 + 1999 combined statistics.
- Perhaps resolution to α_{K^*} discrepancy soon.