KTeV Results on Chiral Perturbation Theory

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Outline

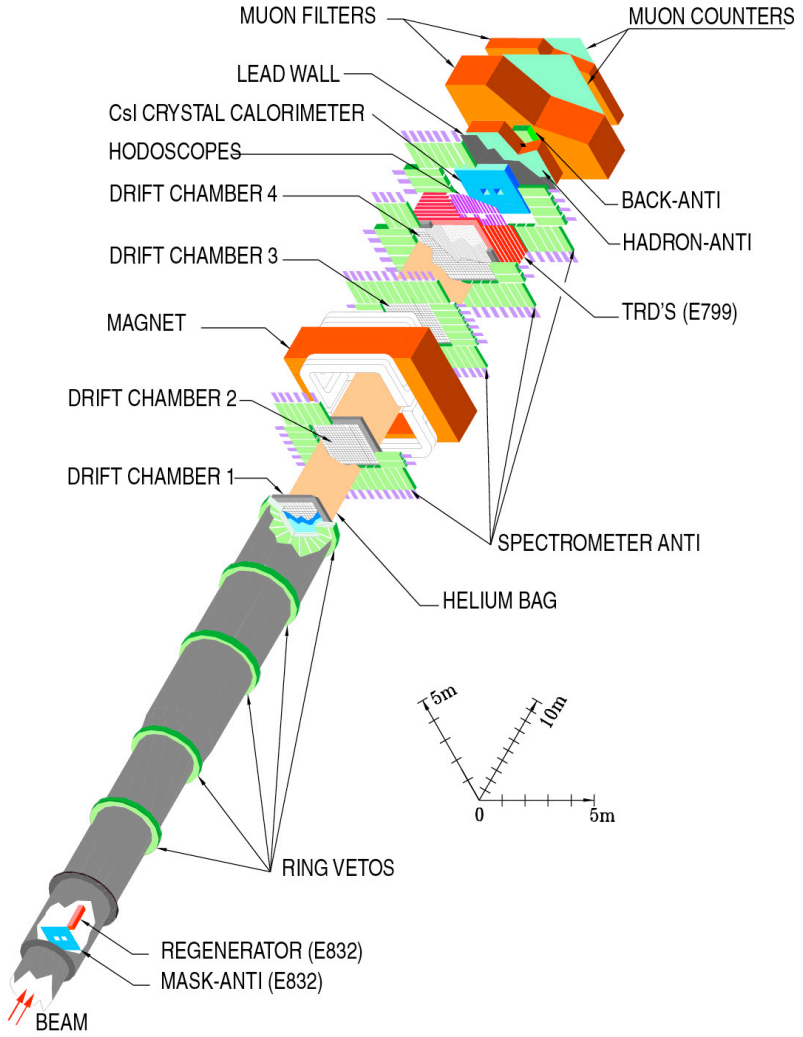
- **The KTeV experiment**
- **Probes of ChPT at $\mathcal{O}(p^6)$**
  - $K_L \rightarrow \pi^0\gamma\gamma$
  - $K_L \rightarrow \pi^0 e^+ e^- \gamma$
  - $K_L \rightarrow \pi^0\pi^0\gamma$
- **Summary**

- **Other KTeV results at this meeting: See talks by Bob Tschirhart, Ron Ray and Erin Abouzaid.**

The KTeV Detector (E799 configuration)

- Pure CsI Calorimeter:(Energy resolution < 1% at $\langle E_g \rangle$ = 10GeV; (π/e rejection of > 700)
- Four drift chambers: resolutions: ~100μm
- Transition radiation detectors: (π/e rejection of > 200) [E799]
- Intense beams: 5 x 10^{12} protons on target per spill → 5 x 10^9 kaons/spill

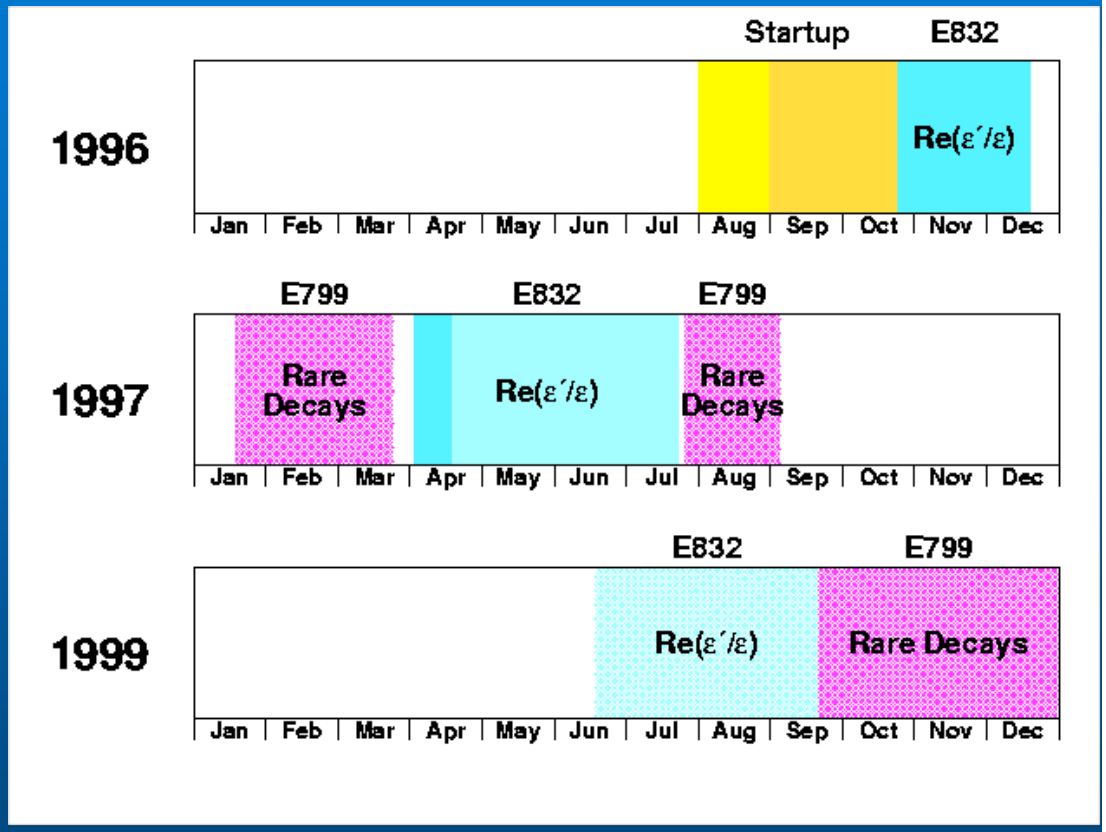
- For E_K ~ 70 GeV: K_S: $\gamma\beta c\tau$ ~ 3.5m
  K_L: $\gamma\beta c\tau$ ~ 2.2 km



The KTeV Experiment

The KTeV Collaboration:

Arizona, Campinas (Brazil), Chicago, Colorado, Elmhurst, Fermilab, Osaka (Japan), Rice, Rutgers, San Paulo (Brazil), UCLA, UCSD, Virginia, Wisconsin

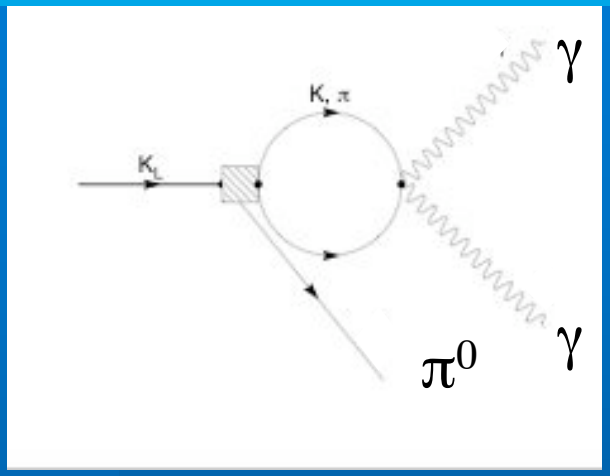


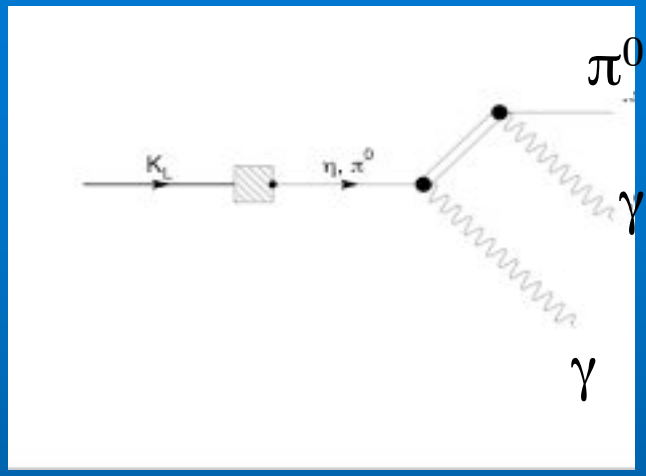
Two KTeV Goals:

E832: Measure ε'/ε

E799: Investigate rare decays of the kaon

$K_L \rightarrow \pi^0\gamma\gamma$





Chiral perturbation calculations of the branching ratio

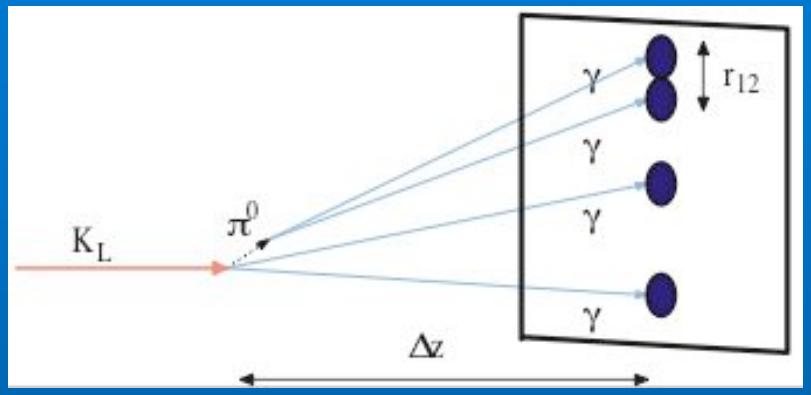
- $\mathcal{O}(p^4)$ calculations predict BR($K_L \rightarrow \pi^0\gamma\gamma$) = 0.6 x 10^{-6}
- Earlier measurements have shown that this prediction is low by a factor of 2-3
- $\mathcal{O}(p^6)$ calculations increase this rate.
- The variable a_v parameterizes the contribution of vector meson exchange to the decay amplitude.

Results can be used to predict the relative contributions of the CP conserving and direct CP violating components in the decay $K_L \rightarrow \pi^0 e^+ e^-$

$K_L \rightarrow \pi^0\gamma\gamma$ event selection

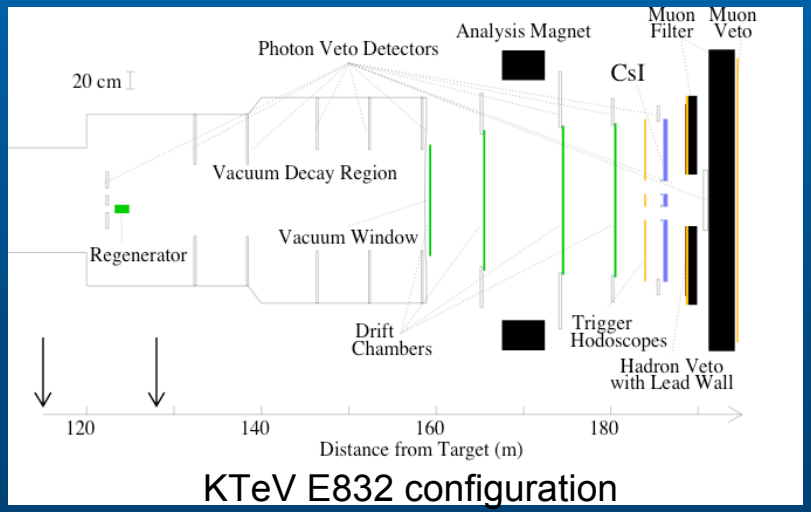
- Require 4 electromagnetic clusters in the calorimeter, and
- no charged tracks.
- Select best π^0 mass combination from the 4 photon candidates.

signal topology: $K_L \rightarrow \pi^0\gamma\gamma$



$$m_{\gamma\gamma} \times \Delta z = \sqrt{E_1 E_2} \times r_{12}$$

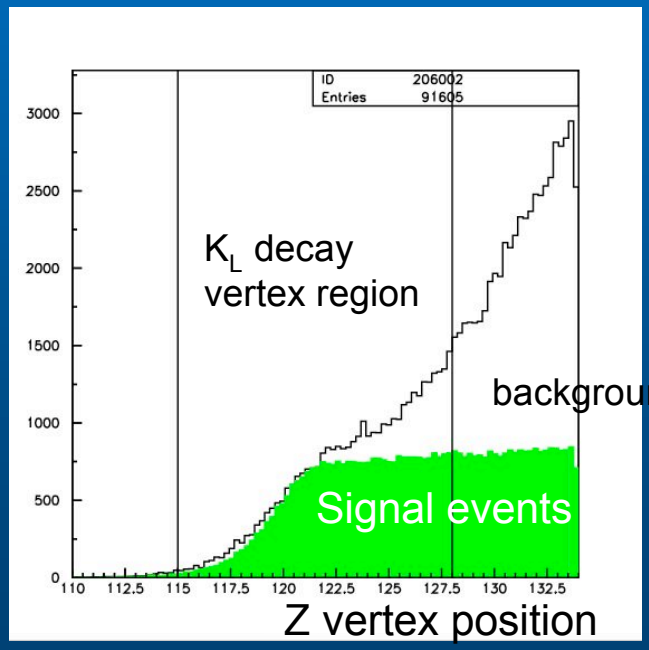
- The background comes from $K_L \rightarrow \pi^0\pi^0$ and $K_L \rightarrow \pi^0\pi^0\pi^0$. The largest and most troublesome background originates from $K_L \rightarrow \pi^0\pi^0\pi^0$ decays with missing/merged photon clusters.
- The normalization mode is $K_L \rightarrow \pi^0\pi^0$.

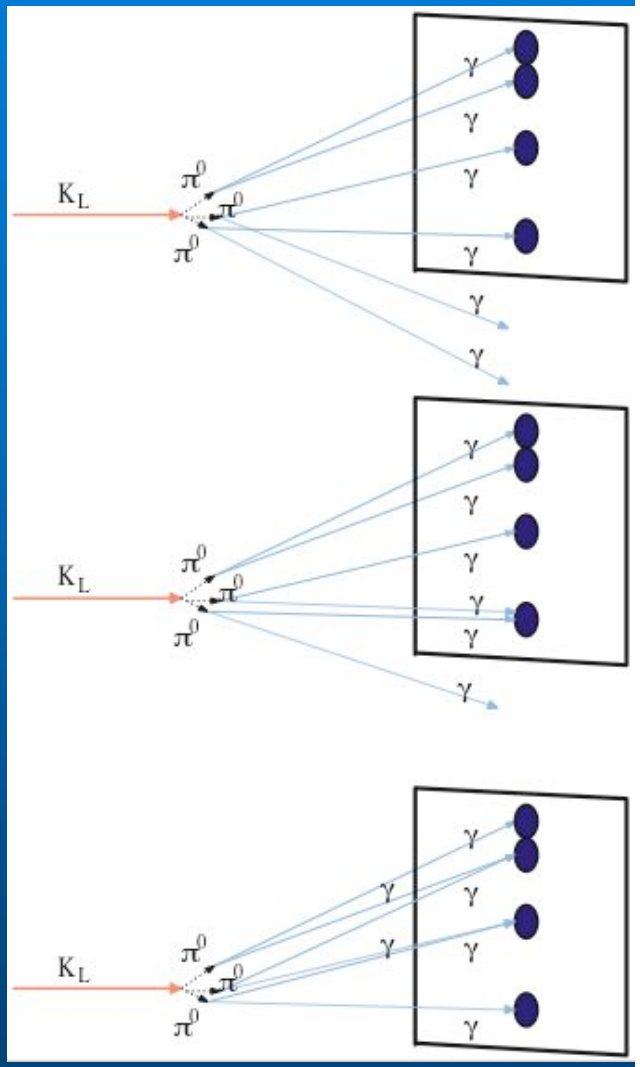


KTeV E832 configuration

$K_L \rightarrow \pi^0\gamma\gamma$ backgrounds

The major background to $\pi^0\gamma\gamma$ comes $3\pi^0$ decays where only 4 clusters are detected. These events form a vertex downstream of the true K_L vertex.



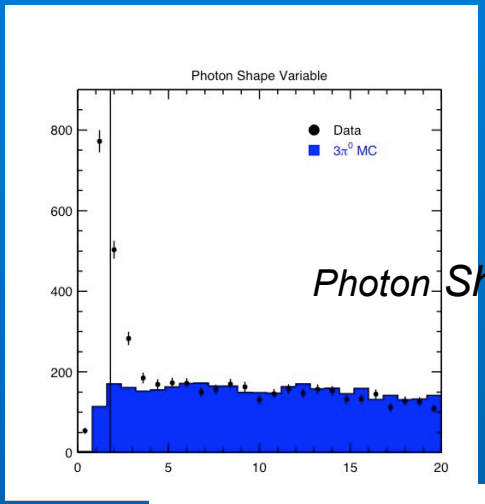


$K_L \rightarrow \pi^0\gamma\gamma$ – background in published result

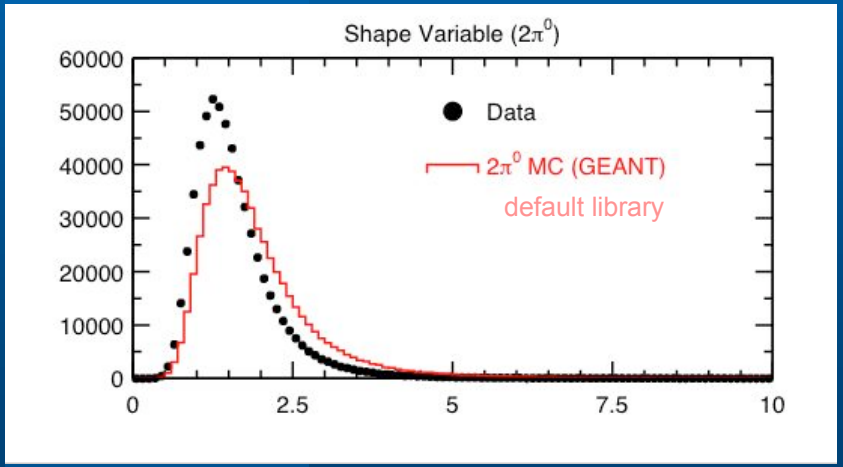
We remove overlapping showers with a photon shape variable.

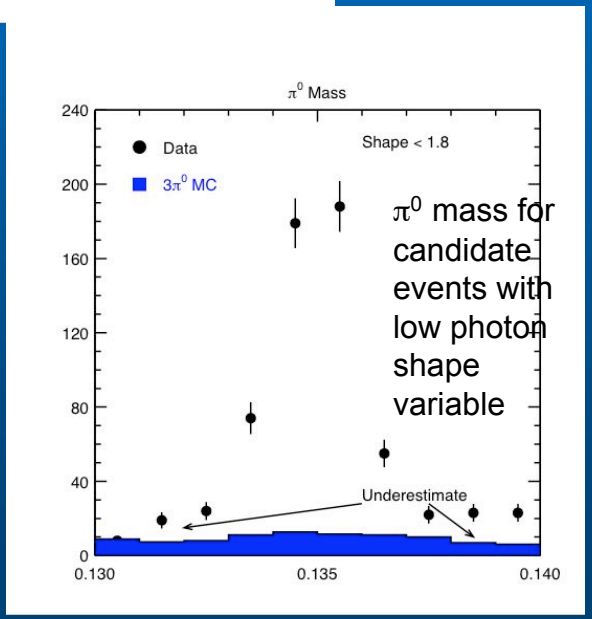
- Disagreement between data and $3\pi^0$ MC at low values of photon shape variable - the region where there should be no overlapping photons.

Result: underestimate of background from $3\pi^0$ events.



Photon Shape Variable

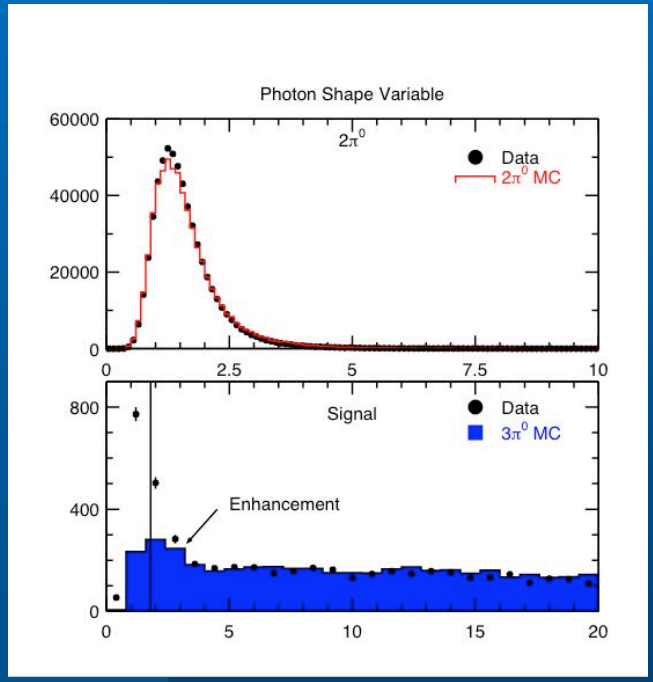


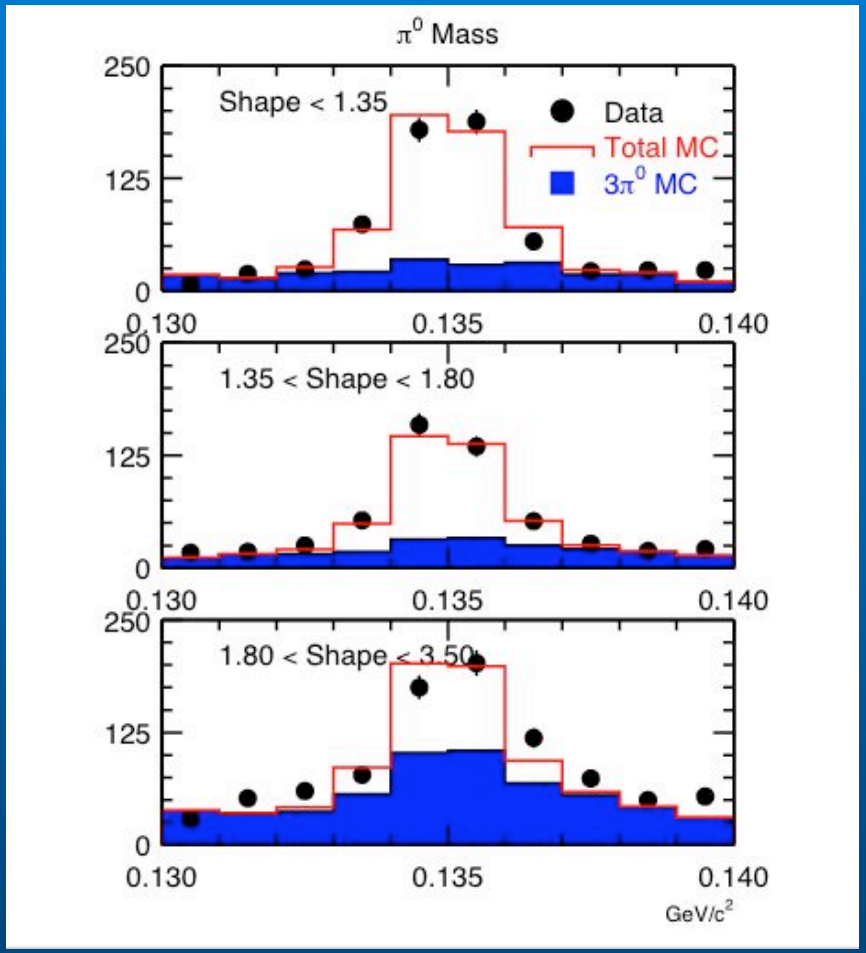


π^0 mass for candidate events with low photon shape variable

$K_L \rightarrow \pi^0\gamma\gamma$ – estimating the background

For this analysis we improved the simulation to get a better match for the photon shape variable.
The background levels increased.
Better agreement in $m_{\pi 0}$ tails.

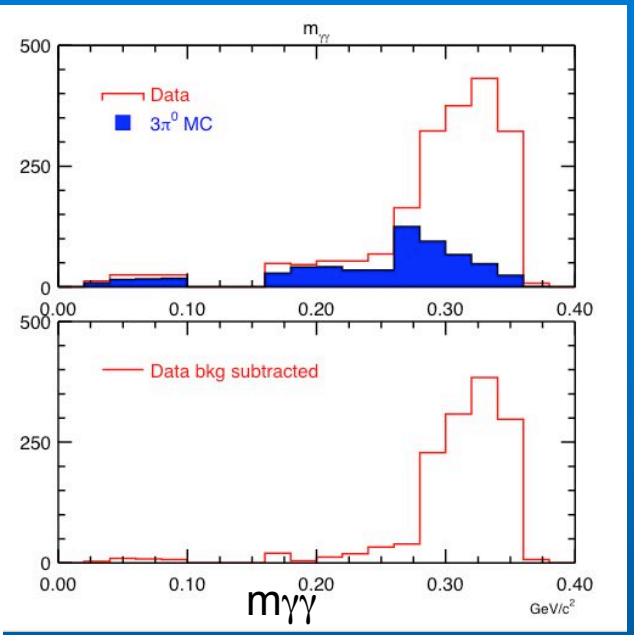


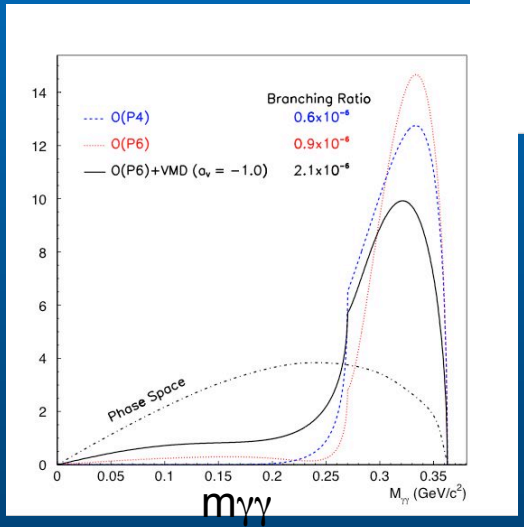


Final results: $K_L \rightarrow \pi^0\gamma\gamma$ decays

- From the full combined 1997-1999 data sample, 1982 $K_L \rightarrow \pi^0\gamma\gamma$ candidate events are observed.

- The background is estimated to be 601 events coming from primarily from $K_L \rightarrow \pi^0\pi^0\pi^0$ events.





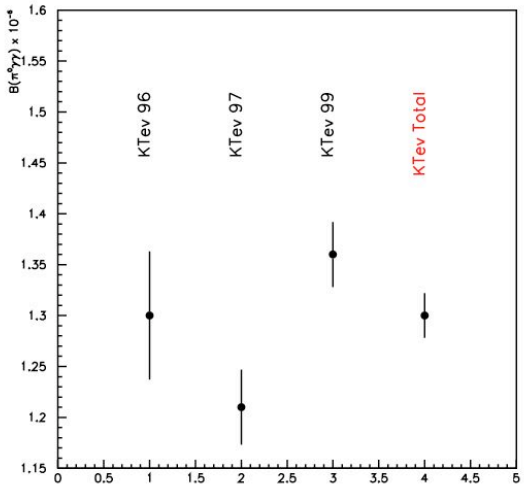
The normalization mode is $K_L \rightarrow \pi^0\pi^0$.

$BR(K_L \rightarrow \pi^0\gamma\gamma) = 1.30 \pm 0.03(stat) \times 10^{-6}$ Preliminary result

$K_L \rightarrow \pi^0\gamma\gamma$: systematic error on BR

Source of Uncertainty	Uncertainty
a_v dependence	1.5 %
$3\pi^0$ background	1.3 %
MC statistics	1.0 %
Normalization	0.9 %
Photon Shape	1.1 %
Tracking Chamber	0.9 %
$2\pi^0$ branching ratio	0.9 %
Photon vetoes	0.9 %
Kaon Energy	0.7 %
Decay Vertex	0.4 %
Total	2.9 %

$\pi^0\gamma\gamma$ branching ratio



BR vs Run period

Preliminary $BR(K_L \rightarrow \pi^0\gamma\gamma) = (1.30 \pm 0.03(stat) \pm 0.04(sys)) \times 10^{-6}$

Updated BR for $K_L \rightarrow \pi^0\gamma\gamma$ decays

$BR(K_L \rightarrow \pi^0\gamma\gamma) = (1.30 \pm 0.03(stat) \pm 0.04(sys)) \times 10^{-6}$

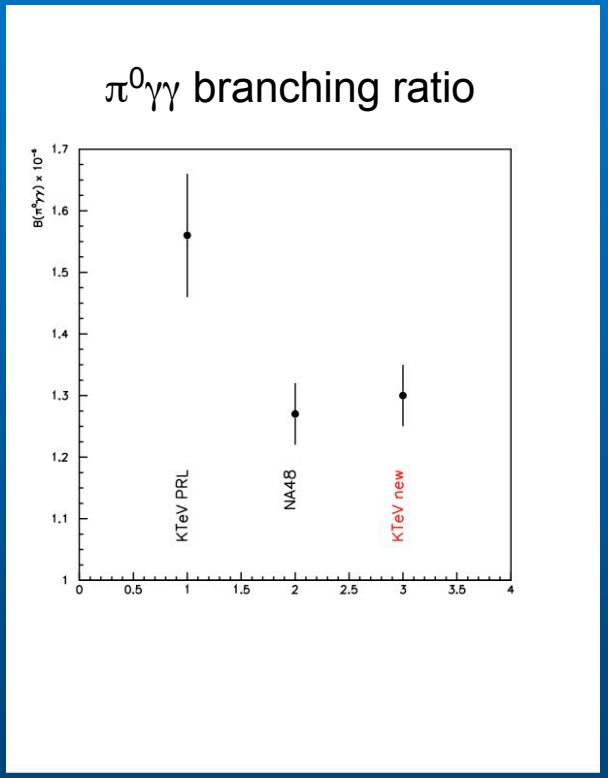
KTeV Preliminary

- This measurement is consistent with chiral perturbation theory with the addition of vector meson exchange through the parameter a_V.
- The extraction of a_V should be available soon.

Previous results:

KTeV: PRL 83, 917 (1999)

NA48: PL B536, 229 (2002)



A related decay: $K_L \rightarrow \pi^0 e^+ e^- \gamma$

The rare decay $K_L \rightarrow \pi^0 e^+ e^- \gamma$ is related to the decay $K_L \rightarrow \pi^0 \gamma\gamma$ via the internal conversion of one of the photons.

$K_L \rightarrow \pi^0 e^+ e^- \gamma$ provides another handle for untangling the CP conserving amplitude in the decay $K_L \rightarrow \pi^0 e^+ e^-$.
The rate for $K_L \rightarrow \pi^0 e^+ e^- \gamma$ is expected to be several orders of magnitude higher than $K_L \rightarrow \pi^0 e^+ e^-$.

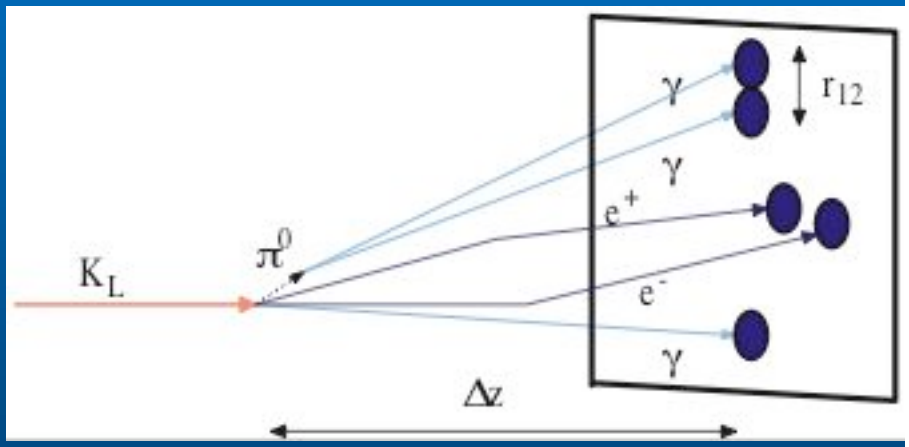
First observation of this decay was made by KTeV and published in PRL. A.Alavi-Harati et al.,PRL 87, 021801 (2001)

This new analysis uses the full KTeV (E799) data set.

$K_L \rightarrow \pi^0 e^+ e^- \gamma$ event selection

- Require 2 charged tracks and 5 clusters in the calorimeter.
- Require each charged track to point to a cluster and form a good vertex.
- Select best π^0 mass combination from photon candidates.

signal topology: $K_L \rightarrow \pi^0 e^+ e^- \gamma$

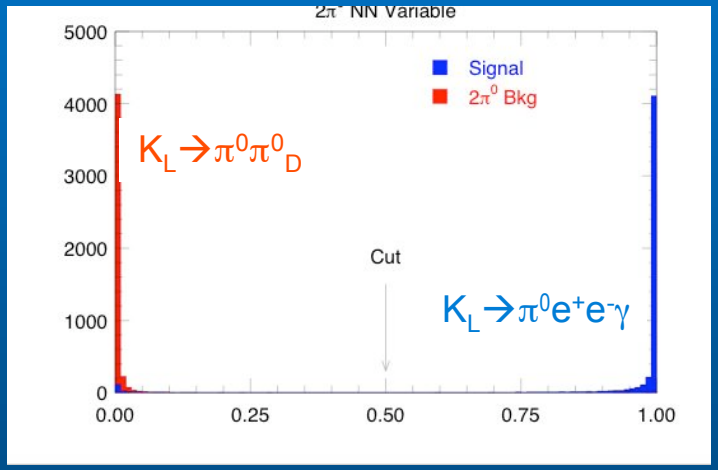


Background: $K_L \rightarrow \pi^0\pi^0, \pi^0 \rightarrow e^+e^-\gamma$

$2\pi^0$ **Dalitz decay**

- There are 3 ways to combine the photons to form a π^0 candidate.
- Most $K_L \rightarrow \pi^0\pi^0_D$ events can be removed through a π^0 mass cut on the best $e^+e^-\gamma$ combination.
- The remaining $2\pi^0$ background from wrong π^0 combinations is removed using a neural network analysis. (m_{π^0} and $m_{e^+e^-\gamma}$ for the 2nd and 3rd best combinations.)

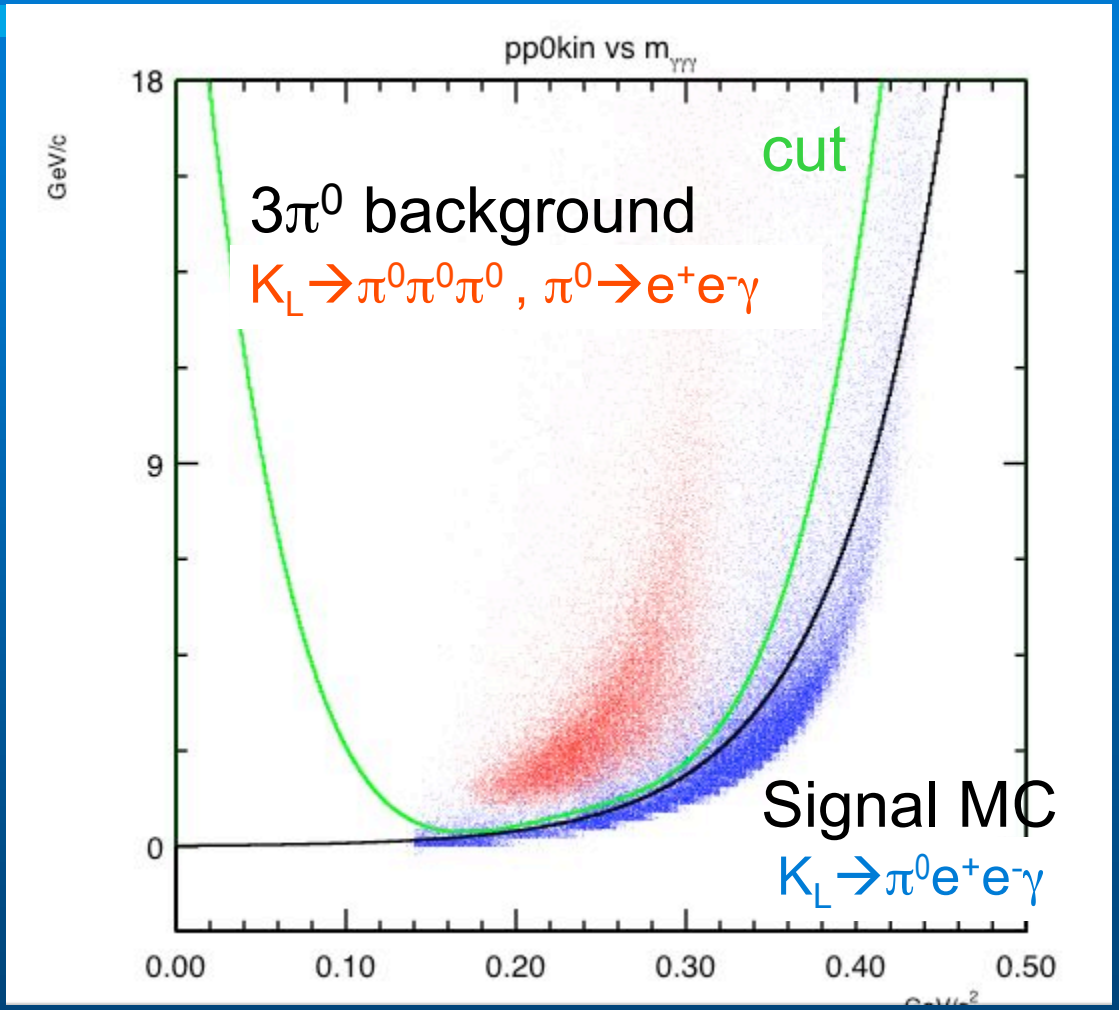
The NN variable for $2\pi^o$ and $\pi^o e^+e^-\gamma$ MC events. Events for which the best $e^+e^-\gamma$ combination has the π^o mass have been removed.



Neural Net Variable (NN)

Backgrounds from $3\pi^0$ Dalitz decays

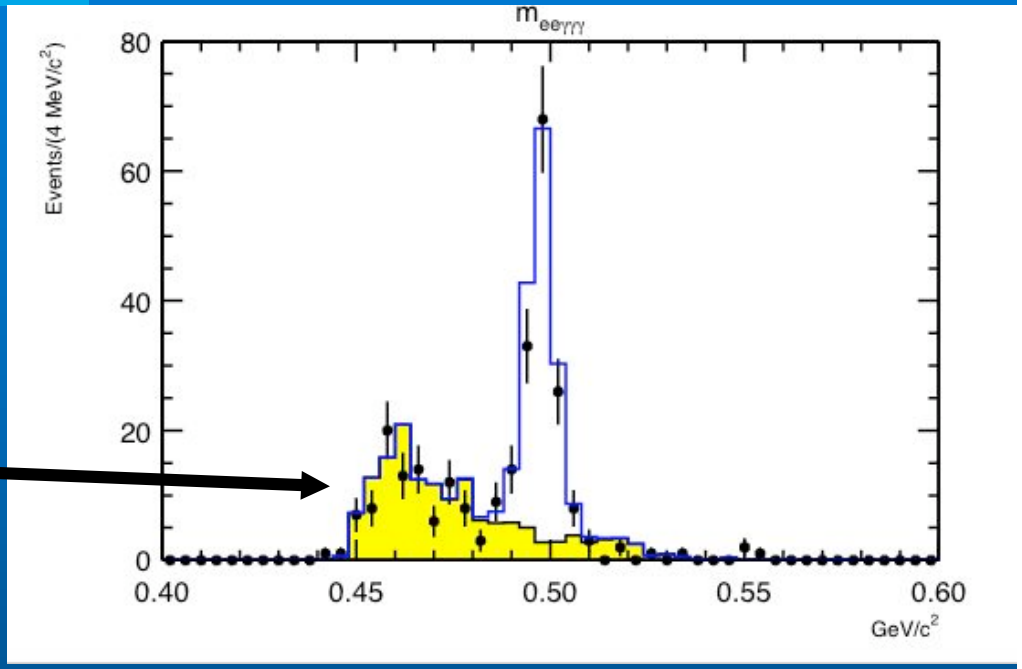
- These events have missing photons.
- We require that each photon candidate has a small value for the shape variable to eliminate events with overlapping photons.



Missing momentum versus the $m_{\gamma\gamma\gamma}$ for $3\pi^0$ events

$K_L \rightarrow \pi^0 e^+ e^- \gamma$ results

- From the combined 1997-1999 data sample, 139 $K_L \rightarrow \pi^0 e^+ e^- \gamma$ candidate events are observed.
- The background is estimated to be 14.4 events coming from $K_L \rightarrow \pi^0 \pi^0_D$ and $K_L \rightarrow \pi^0 \pi^0 \pi^0_D$.
- The normalization mode is $K_L \rightarrow \pi^0 \pi^0_D$. ($\gamma\gamma$ $e^+e^-\gamma$)



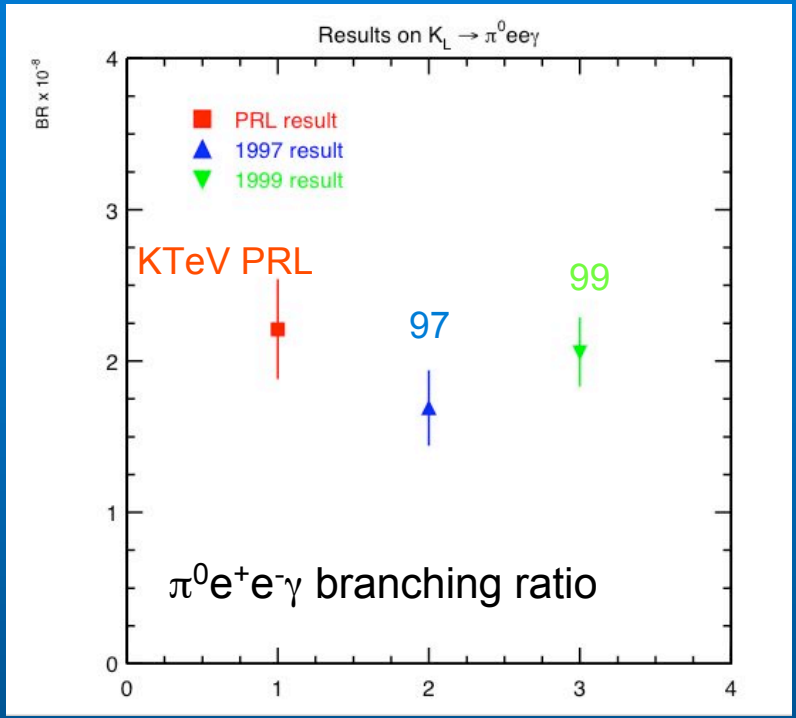
$m_{e+e-\gamma\gamma}$

$BR(K_L \rightarrow \pi^0 e^+ e^- \gamma) = (1.90 \pm 0.16(stat)) \times 10^{-8}$

preliminary

$K_L \rightarrow \pi^0 e^+ e^- \gamma$: preliminary result for BR

Source of Uncertainty	Uncertainty
MC statistics	4.2 %
a_v dependence	3.8 %
K_L and π^0 BR	2.8 %
3 π0 background	0.8 %
acceptance	0.4 %
$2\pi^0$ background	0.1 %
Total	6.4 %



$BR(K_L \rightarrow \pi^0 e^+ e^- \gamma) = (1.90 \pm 0.16(stat) \pm 0.12(sys)) \times 10^{-8}$

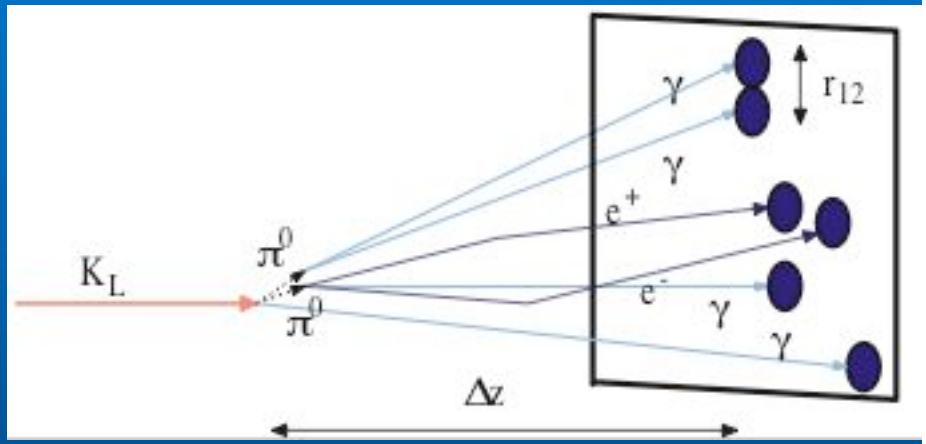
Preliminary result

$K_L \rightarrow \pi^0\pi^0\gamma$

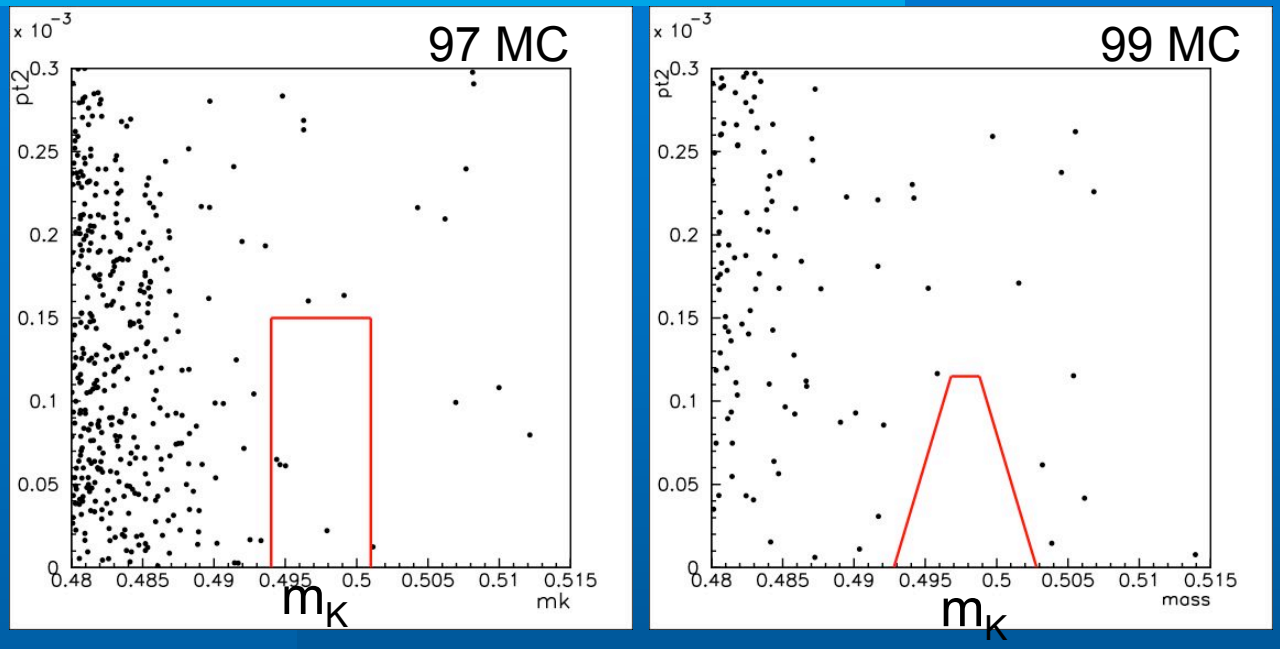
- Select events with a Dalitz decay of one of the π^0.
- Choose the best π^0 mass combinations.
- Main background is from $K_L \rightarrow \pi^0\pi^0\pi^0_D$.

The normalization is made with $K_L \rightarrow \pi^0\pi^0\pi^0_D$ decays that are not fully reconstructed. One photon passes through one of the beam holes in the calorimeter.

signal topology: $K_L \rightarrow \pi^0\pi^0\gamma$



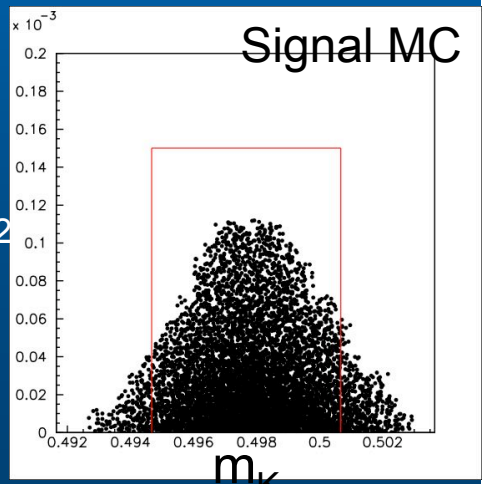
$K_L \rightarrow \pi^0\pi^0\gamma$ Monte Carlo



p_t^2

m_K

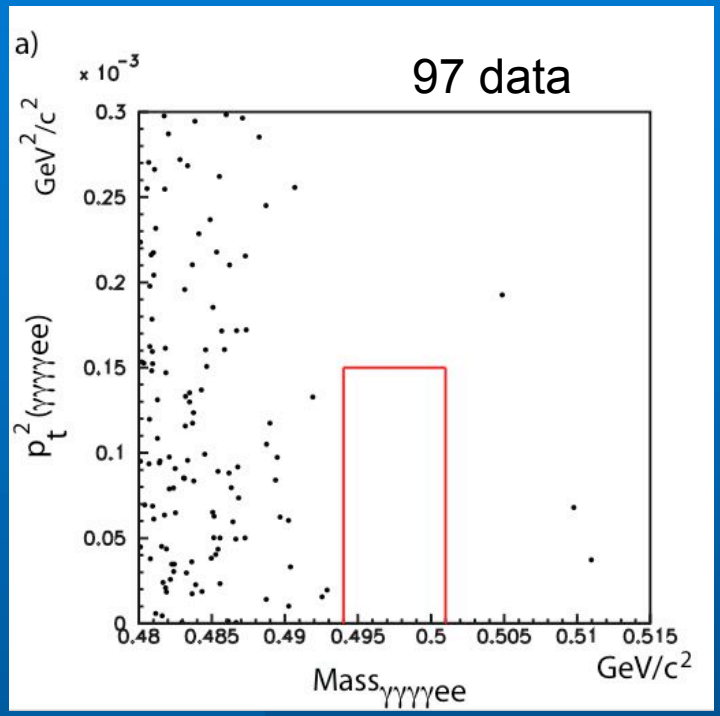
Background MC:
Generated $K_L \rightarrow \pi^0\pi^0\pi^0_D$ MC with statistics 4x data

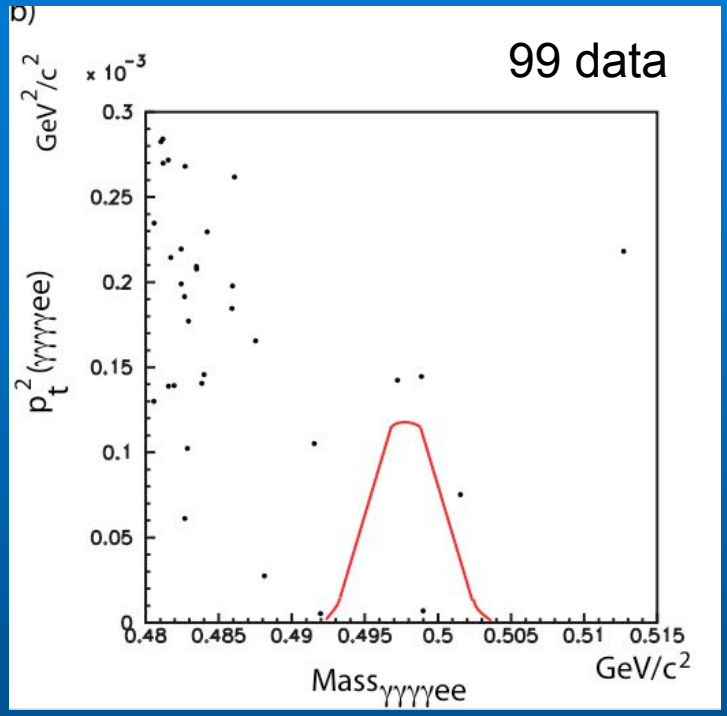


p_t^2

m_K

$K_L \rightarrow \pi^0\pi^0\gamma$ Results





Blind analysis: One event seen 99 data, none in 97
Probability that event comes from background is 10%

Limit: BR($K_L \rightarrow \pi^0\pi^0\gamma$) < 2.32 X 10^{-7} KTeV prelimiinary

KTeV tests of Chiral Perturbation Theory

The measured branching ratio results for $K_L \rightarrow \pi^0\gamma\gamma$ and $K_L \rightarrow \pi^0 e^+ e^- \gamma$ are *inconsistent* with $\mathcal{O}(p^4)$ predictions of chiral perturbation theory, but are **consistent** with $\mathcal{O}(p^6)$ calculations.

Decay Mode	Publ.	# Events	Branching Ratio
$K_L \rightarrow \pi^0\gamma\gamma$	Prel 97+99	1982	$(1.30 \pm 0.03 \pm 0.04) \times 10^{-6}$
$K_L \rightarrow \pi^0 e^+ e^- \gamma$	Prel 97+99	139	$(1.90 \pm 0.16 \pm 0.12) \times 10^{-8}$
$K_L \rightarrow \pi^0\pi^0\gamma$	Prel 97+99	1	$< 2.32 \times 10^{-7}$

Summary and Conclusions

- **The branching ratio results are preliminary, but represent results from the full KTeV data sample.**
- **Fits for a_V from the 97-99 combined data sets should be available soon.**
- **KTeV results in these channels agree with $\mathcal{O}(p^6)$ calculations in chiral perturbation theory that include contributions from vector meson exchange through the parameter a_V.**

Additional slides

Search for $K_L \rightarrow \pi^0 e^+ e^-$

$$|K_L\rangle \cong |K_{ODD}\rangle + \varepsilon |K_{EVEN}\rangle$$

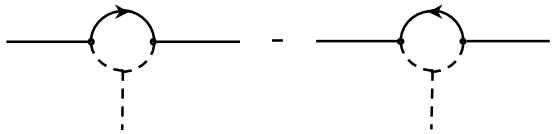
$\pi^0\gamma^* \rightarrow \pi^0 e^+ e^-$ **Indirect CP Violation**

$$Br(K_L \rightarrow \pi^0 e^+ e^-) = |\varepsilon|^2 \frac{\tau(K_L)}{\tau(K_S)} Br(K_S \rightarrow \pi^0 e^+ e^-)$$

The decay $K_L \rightarrow \pi^0 e^+ e^-$ decay is of interest because it is expected to have a large CP-violating component.

$\pi^0\gamma^*$
$\pi^0 Z^*$ $\rightarrow \pi^0 e^+ e^-$ **Direct CP Violation**
π^0 W+* W-*

$$|K_{ODD}\rangle \propto |K^0\rangle - |\overline{K}^0\rangle$$



$$V_{td}V_{ts}^* - V_{td}^*V_{ts}$$

$$\propto \Im(V_{td}V_{ts}^*) \propto A^2\lambda^5\eta$$

The Standard Model prediction for the Branching Ratio is (3-10 x 10^{-12}). The major background is from the radiative Dalitz decay of the kaon $K_L \rightarrow ee\gamma\gamma$.

$\pi^0\gamma^*\gamma^* \rightarrow \pi^0 e^+ e^-$ **CP conserving Helicity suppressed**

Backgrounds from $\pi^0\pi^0$ Dalitz decays

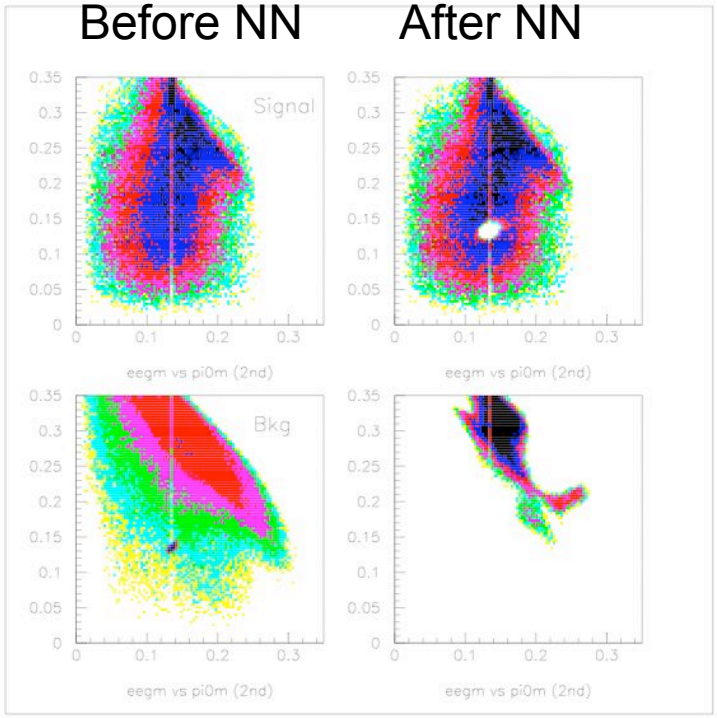
Signal

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

$m_{e^+e^-\gamma}$

$2\pi^0$ background

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



m_{π^0}

2nd best combination