First observation of $K_S \to \pi^0\mu^+\mu^-$ and $K_S \to \pi^0 e^+ e^-$ at NA48/1

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On behalf of the NA48/1 collaboration: Cambridge, Chicago, CERN, Dubna,

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Siegen, Torino, Warsaw, Wien

Outline

- Introduction.

- First observation of:

$K_S \to \pi^0\mu^+\mu^-$ (NEW!!!) and

$K_S \to \pi^0 e^+ e^-$ (Phys.Lett.B 576:43-54,2003)

◇ Background.

◇ Signal.

◇ Branching ratio.

  - Chiral perturbation theory.

  - $K_L \to \pi^0\mu^+\mu^-$ and $K_L \to \pi^0 e^+ e^-$ CP violating branching ratio predictions.

- Summary.

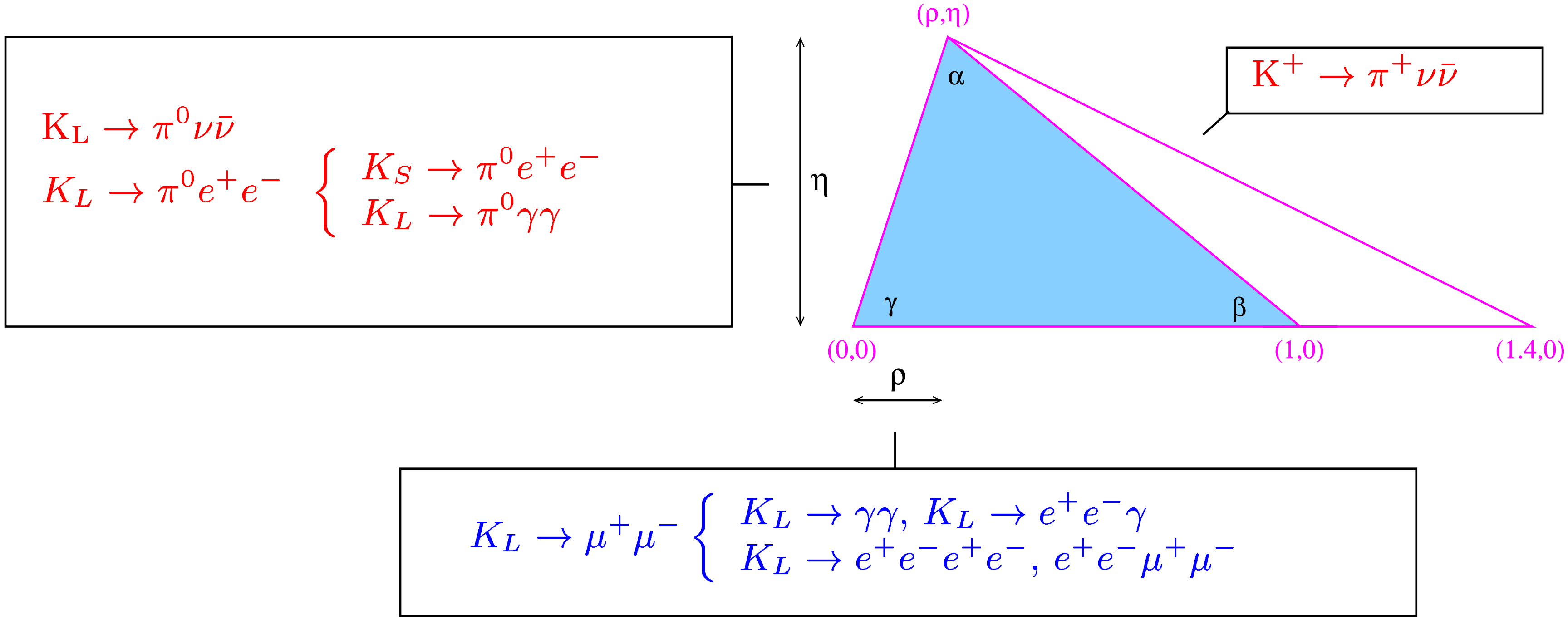
Why $K_S \rightarrow \pi^0\mu^+\mu^-$ and $K_S \rightarrow \pi^0 e^+ e^-$?

Motivation to search for $K_S \rightarrow \pi^0\mu^+\mu^-$ and $K_S \rightarrow \pi^0 e^+ e^-$:

- Kaon physics could be sensitive to physics beyond the Standard Model.

- Direct CP violation has been measured by NA48 and KTeV, ϵ'/ϵ. The next goal in kaon physics is to test the Standard Model predictions on CP, this can be achieved testing quantitatively the CKM paradigm (Unitarity triangle) by means of rare kaon decays.

Unitarity triangle



$\mathrm{K_L} \to \pi^0 \nu\bar{\nu}$

$K_L \to \pi^0 e^+ e^- \left\{ \begin{array}{l} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \end{array} \right.$

$\mathrm{K}^+ \to \pi^+ \nu\bar{\nu}$

$K_L \to \mu^+\mu^- \left\{ \begin{array}{l} K_L \to \gamma\gamma,\ K_L \to e^+e^-\gamma \\ K_L \to e^+e^-e^+e^-,\ e^+e^-\mu^+\mu^- \end{array} \right.$

Note: Analogous picture for $K_L \to \pi^0 \mu^+ \mu^-$ you just need to substitute e^+e^- by $\mu^+\mu^-$.

$\mathrm{K_L} \to \pi^0 \nu\bar{\nu}$ and $\mathrm{K}^+ \to \pi^+ \nu\bar{\nu}$ are:

- ◇ Very clean theoretically.
- ◇ Very difficult experimentally.

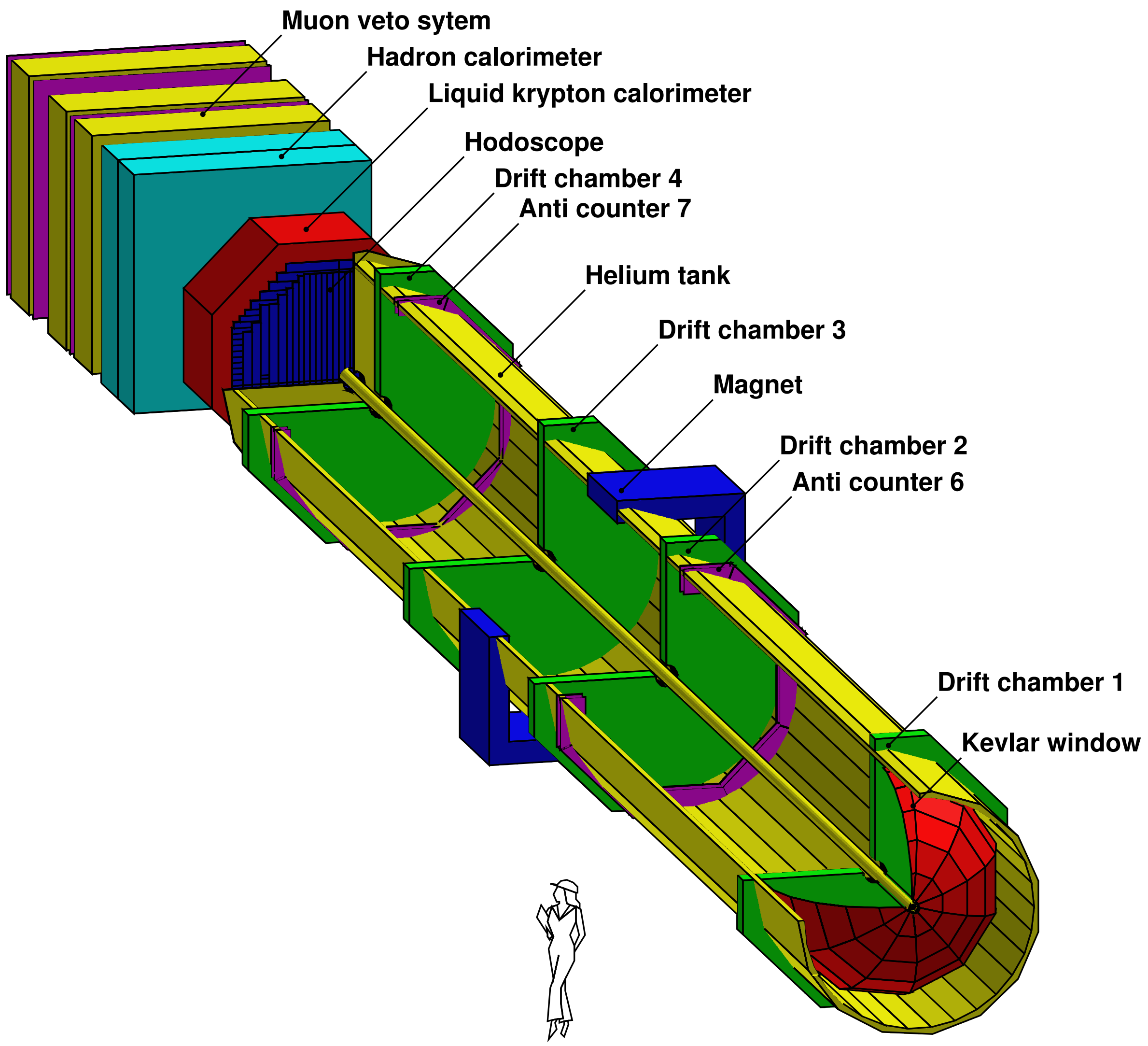
$K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ are:

- ◇ Not so clean theoretically
- ◇ But more accesible experimentally.

NA48/1 High intensity K_S beam (2002)

- 400 GeV protons
- SPS flat top 4.8 s/16.8 s
- $\sim 5 \times 10^{10}$ protons per pulse
- impinging on a 40 cm long Be target at 4.2 mrad production angle.
- 24 mm pt absorber between target and sweeping magnet.
- 5.1 m thick collimator.
- 120 m vacuum decay volume.
- $\sim 2 \times 10^{5}$ K_S decays per spill in the fiducial volume with a mean energy of 120 GeV.

Na48 detector



About the Analysis

- Predicted $\mathrm{BR}(K_S \to \pi^0 l^+ l^-) \sim 10^{-10} - 10^{-9}$ $l^+l^- = \mu^+\mu^-$ or e^+e^-
- K_S flux expected $\sim few\ 10^{10}$

- This required tight cuts to control the background, but not so tight that they will kill the signal.

Blind analysis

- Signal and control regions masked.

Signal defined in the $m_{\pi^0 l^+ l^-}$ vs $m_{\gamma\gamma}$ plane.

- ◇ Cuts tuned with a fraction of the data, while the signal region was masked.
- ◇ Unmask control region.
- ◇ Unmask signal region.

Background Summary

$K_S \to \pi^0\mu^+\mu^-$	
Background source	Event in signal region
$K_L \to \pi^+\pi^-\pi^0$	$0^{+0.02}_{-0.00}$
$K_L \to \mu^+\mu^-\gamma\gamma$	0.04 ± 0.04
Accidentals	$0.18^{+0.18}_{-0.11}$
Total background	$0.22^{+0.19}_{-0.12}$

Dominated by accidental background.

$K_S \to \pi^0 e^+ e^-$	
Background source	Event in signal region
$K_S \to \pi^0_D\pi^0_D$	< 0.01
$K_L \to e^+e^-\gamma\gamma$	$0.08^{+0.03}_{-0.02}$
Accidentals	$0.07^{+0.07}_{-0.03}$
Total background	$0.15^{+0.10}_{-0.04}$

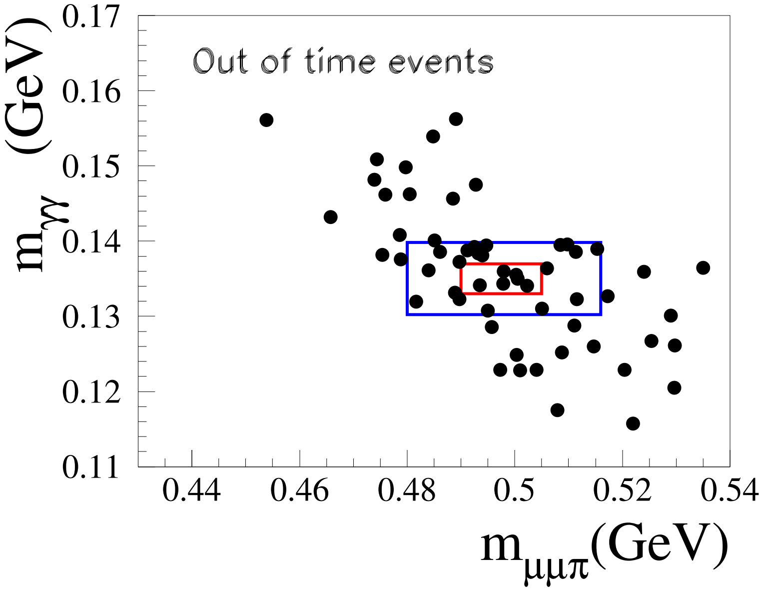
Dominated by $K_L \to e^+e^-\gamma\gamma$ and accidental background.

Many backgrounds were studied using both data and MC, here only the non negligible ones are presented.

Accidental Background

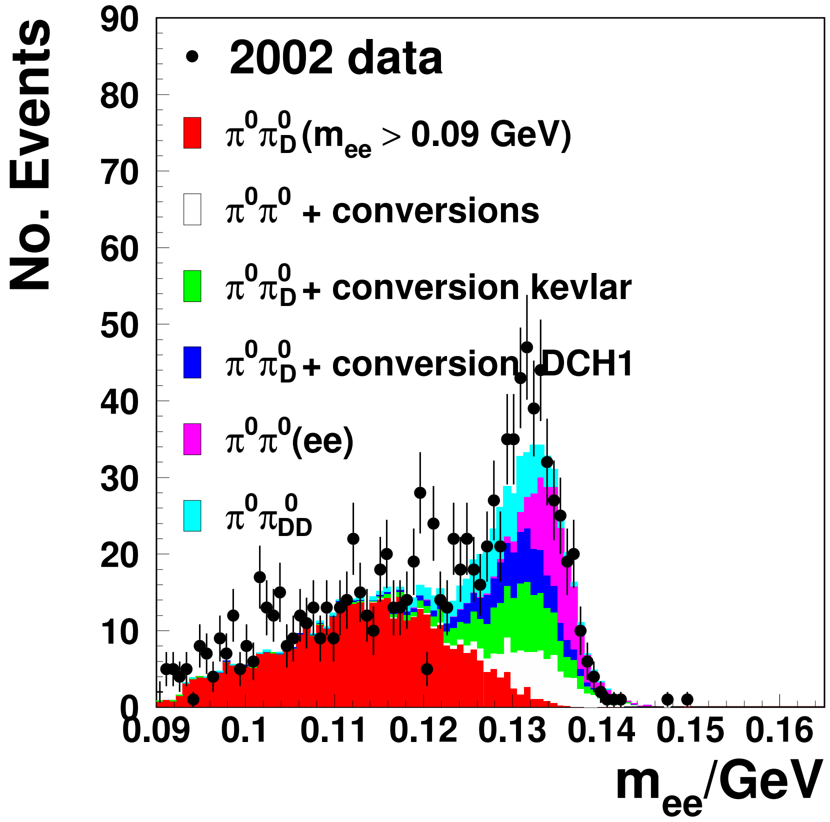
- Accidental background: accidental overlap of particles from two decays that happen to be in-time and fake the signal.
- Accidental background can be determined from data extrapolating from the *out of time* side bands.

(note: *out of time* window $\sim 125ns$, intime window $\pm 1.5ns$)



- Tight cuts imposed to veto on accidental activity.
- Major accidental for $K_S \to \pi^0\mu^+\mu^-$: $K_S \to \pi^+\pi^- + K_S \to \pi^0\pi^0$ (main), $K_L \to \pi^\pm\mu^\mp\nu + K_S(K_L) \to \pi^0\pi^0(\pi^0)$ (significant)
- Major accidental for $K_S \to \pi^0 e^+e^-$: $K_L \to \pi^\pm e^\mp\nu + K_S(K_L) \to \pi^0\pi^0(\pi^0)$
- Accidental background $K_S \to \pi^0\mu^+\mu^-$: $0.18^{+0.18}_{-0.11}$
- Accidental background $K_S \to \pi^0 e^+e^-$: $0.07^{+0.07}_{-0.03}$

$K_S \to \pi^0\pi^0_D$ background in $K_S \to \pi^0 e^+e^-$



A cut on the m_{ee} distribution

is required to reject $K_S \to \pi^0\pi^0_D$

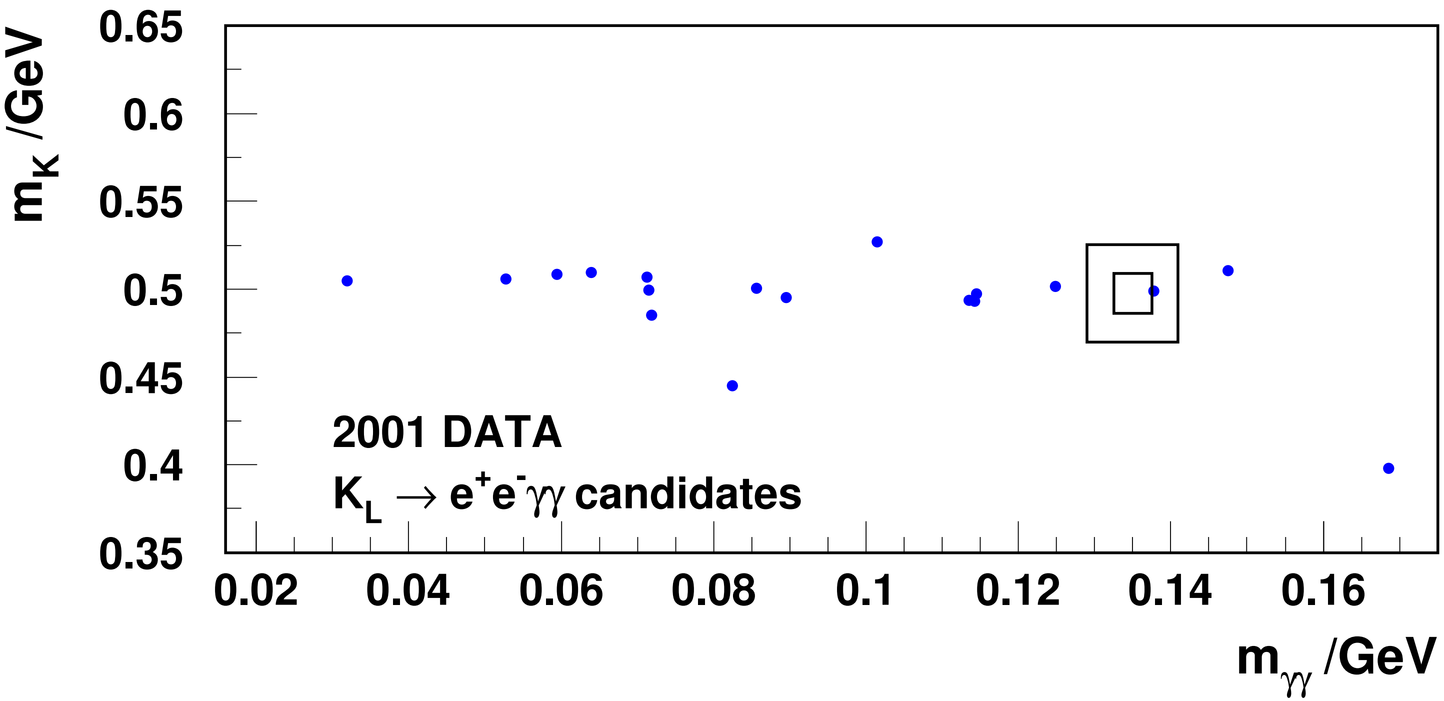
$(\pi^0_D \longrightarrow e^+e^-\gamma)$ background.

A conservative cut is applied

$m_{ee} > 0.165\,\text{GeV}$

$K_S \to \pi^0\pi^0_D$ background above $0.165\,\text{GeV}$ is negligible.

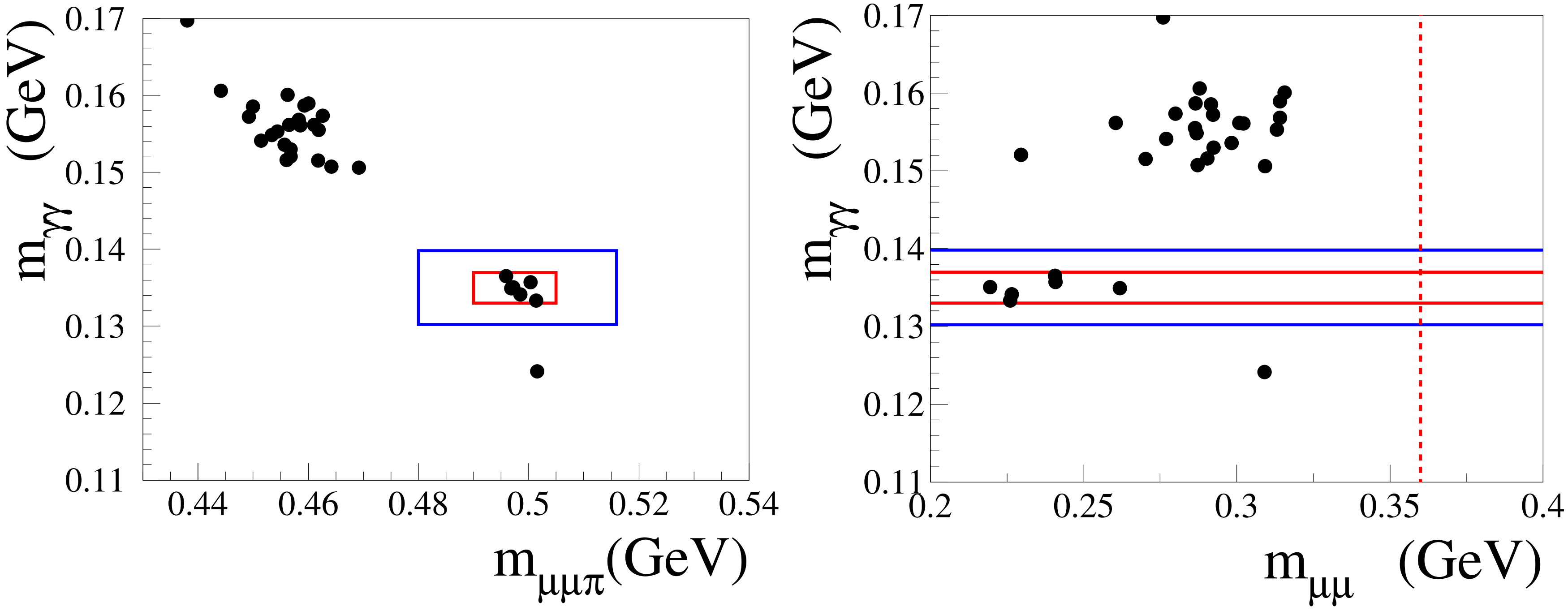
$K_L \to e^+e^-\gamma\gamma$ background in $K_S \to \pi^0 e^+e^-$



$K_L \to e^+e^-\gamma\gamma$ background is estimated using 2001 K_L data (10 × 2002 *statistics*).

→ $K_L \to e^+e^-\gamma\gamma$ background $= 0.08^{+0.03}_{-0.02}$

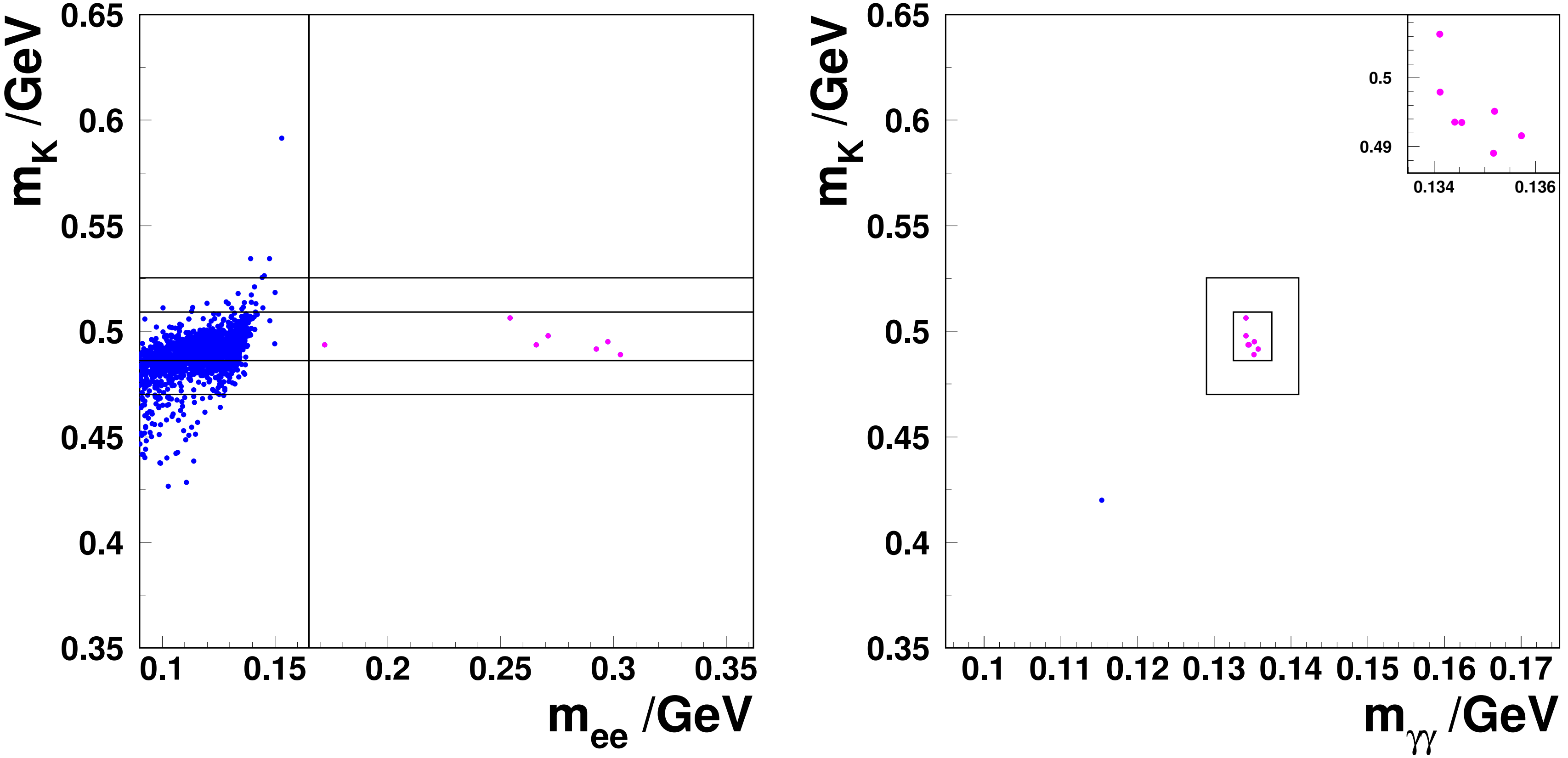
First observation of $K_S \to \pi^0\mu^+\mu^-$



6 events found in signal region

- No events found in equivalent same sign distributions
- No accumulation of background close to the signal region by relaxing the cuts.

First observation of $K_S \to \pi^0 e^+ e^-$



7 events found in signal region

- No events found in equivalent same sign distributions
- No accumulation of background close to the signal region by relaxing the cuts.

Branching Ratio Summary Table

	$K_S \to \pi^0\mu^+\mu^-$	$K_S \to \pi^0 e^+ e^-$
K_S Flux	$(2.50 \pm 0.08) \times 10^{10}$	$(3.51 \pm 0.17) \times 10^{10}$
Acceptance × Trigger Efficiency	$0.081 \pm 0.002 \pm 0.004$	0.065 ± 0.004
Background	$0.22^{+0.19}_{-0.12}$	$0.15^{+0.10}_{-0.04}$
Events	6	7
Branching Ratio	$(2.9^{+1.4}_{-1.2} \pm 0.2) \times 10^{-9}$	$(m_{ee} > 0.165 GeV)$ $(3.0^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9}$ extrapolated ⋆ $(5.8^{+2.8}_{-2.3} \pm 0.8) \times 10^{-9}$

- The systematic error is one order of magnitude smaller than the statistical error.
- ⋆ A vector matrix element with no form factor dependence has been assumed to estimate acceptance and to extrapolate to the full m_{ee} spectrum. The uncertainty in the form factor dependence dominates the systematic error.
- Statistical error in flux measurement is completely negligible.

Systematics due to form factor dependences

- Main source of systematics to determine the Branching Ratio is the unknown form factor ($W(z)$).

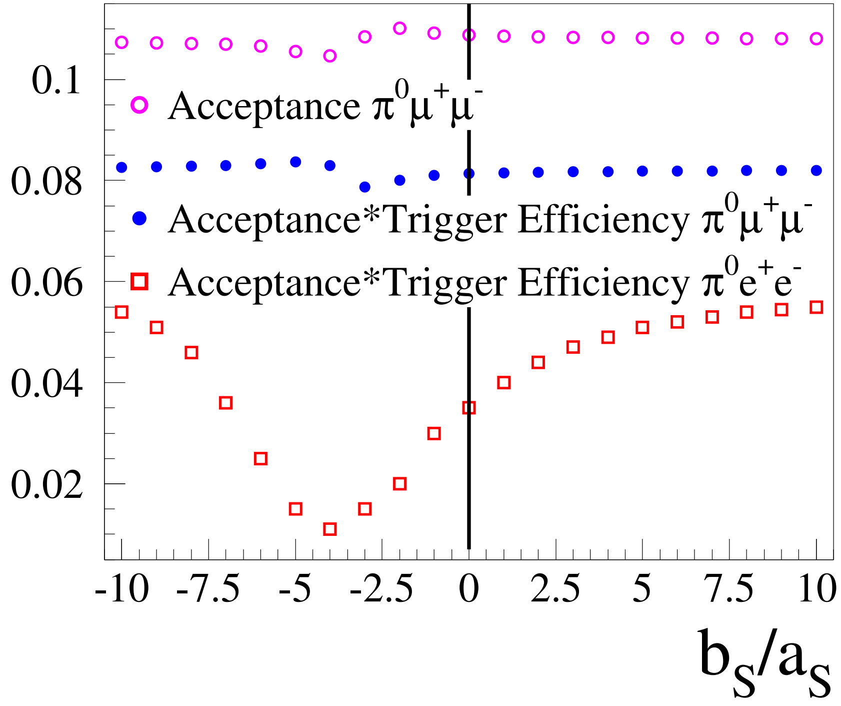
- $W(z) = a_S + b_S \cdot z$ where $z = \frac{m_{ll}^2}{m_K^2}$

- a_S and b_S parameters have to be determined experimentally (theory prediction only available for b_S/a_S).

- Event geometry depends on a_S and b_S :

- Geometrical acceptance depends on a_S and b_S .

- To determine BR($K_S \rightarrow \pi^0 e^+ e^-$) for the whole m_{ee} spectrum an extrapolation is needed.



a_S and b_S determination

$$Br(K_S \to \pi^0 e^+ e^-) = \left[0.01 - 0.76 a_S - 0.21 b_S + 46.5 a_S^2 + 12.9 a_S b_S + 1.44 b_S^2\right] \times 10^{-10}$$

$$Br(K_S \to \pi^0 \mu^+ \mu^-) = \left[0.07 - 4.52 a_S - 1.50 b_S + 98.7 a_S^2 + 57.7 a_S b_S + 8.95 b_S^2\right] \times 10^{-11}$$

hep-ph/9808289

Assuming VMD ($b_S\,/a_S = 0.4$) a_S can be extracted independently:

$Br(K_S \to \pi^0 e^+ e^-) \simeq 5.2 \times 10^{-9} a_S^2 \quad \Longrightarrow |a_S|_{\pi^0 ee} = 1.06^{+0.26}_{-0.21} \pm 0.07$

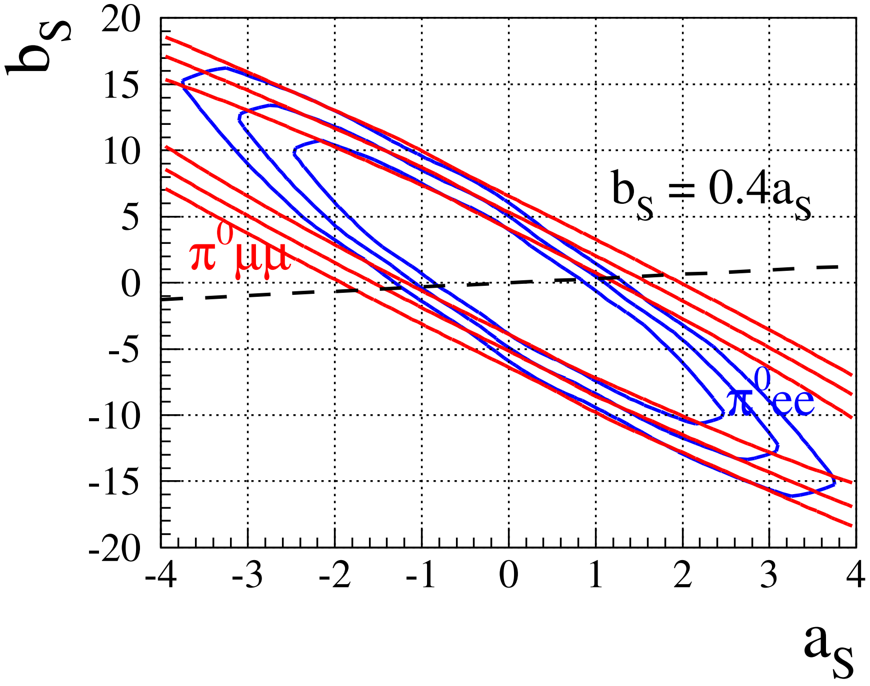
$Br(K_S \to \pi^0 \mu^+ \mu^-) \simeq 1.2 \times 10^{-9} a_S^2 \quad \Longrightarrow |a_S|_{\pi^0 \mu\mu} = 1.55^{+0.38}_{-0.32} \pm 0.05$

$K_S \to \pi^0 \mu^+ \mu^-$ and $K_S \to \pi^0 e^+ e^-$ combined (log-likelihood fit):

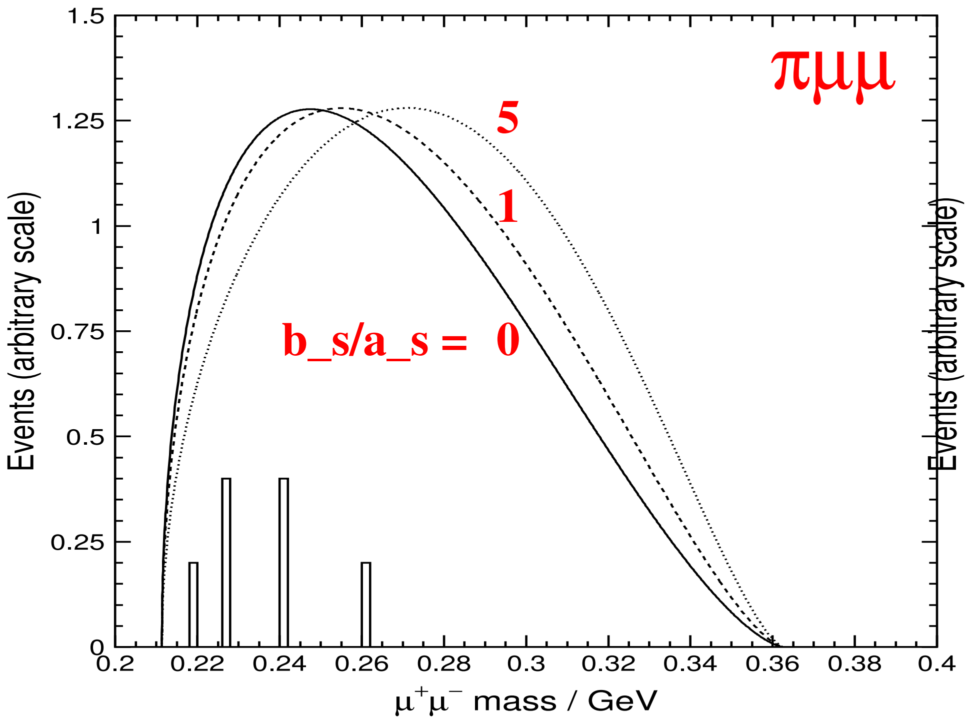
➡ $a_S = -1.4^{+3.6}_{-2.2}$ and $b_S = 9.8^{+5.8}_{-7.6}$

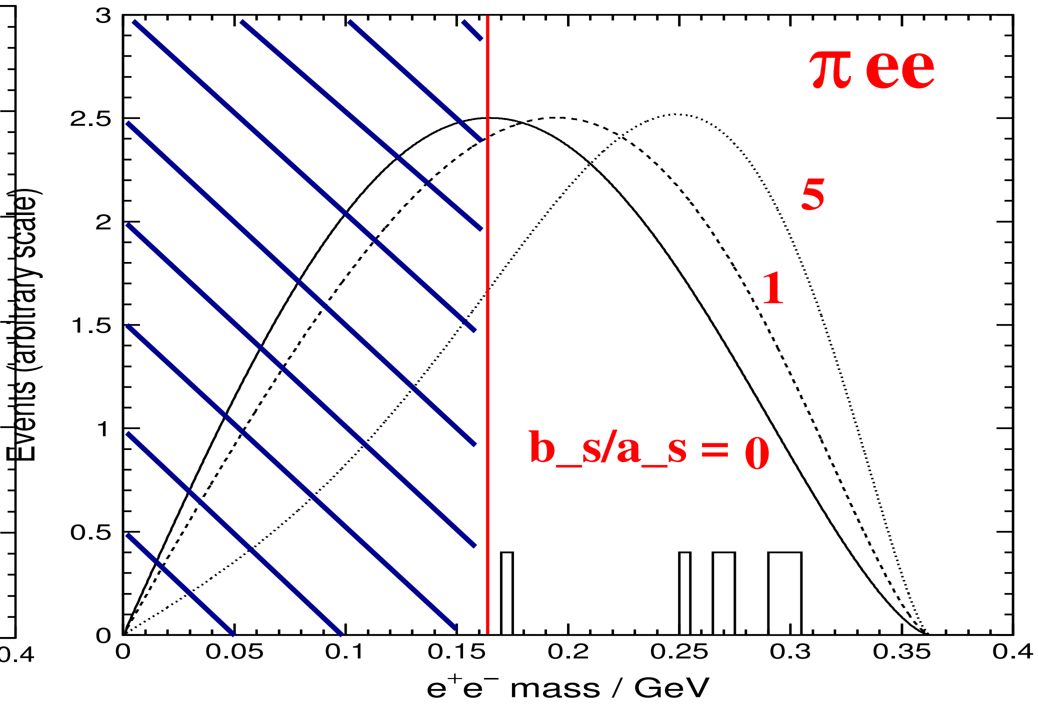
or

➡ $a_S = 1.2^{+2.2}_{-2.1}$ and $b_S = -9.2^{+7.9}_{-5.8}$



m_{ll} Invariant Mass Distribution





→ Our statistics are too low to determine the m_{ll} distribution.

Results on BR($K_S \to \pi^0\mu^+\mu^-$)/BR($K_S \to \pi^0 e^+e^-$)

BR($K_S \to \pi^0\mu^+\mu^-$)/BR($K_S \to \pi^0 e^+e^-$) is interesting because:

➡ There is a clean theoretical prediction.

$$\frac{BR(K_S\to\pi^0\mu^+\mu^-)}{BR(K_S\to\pi^0 e^+e^-)}_{NA48/1\ data} = 0.50^{+0.31}_{-0.32} \pm 0.08$$

$$\frac{BR(K_S\to\pi^0\mu^+\mu^-)}{BR(K_S\to\pi^0 e^+e^-)}_{\chi PT\ prediction} = 0.23$$ [hep-ph/9808289]

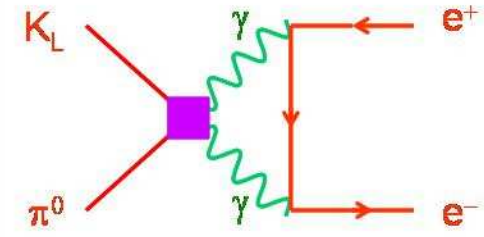
$$\frac{BR(K_S\to\pi^0\mu^+\mu^-)}{BR(K_S\to\pi^0 e^+e^-)}_{pure\ phase\ space} = 0.21$$

[Ecker,etall,NPBB291(1987)692–719]

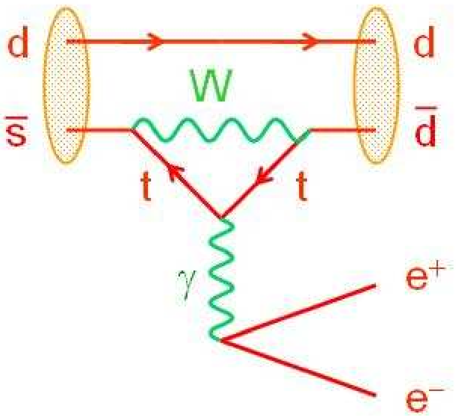
$K_L \to \pi^0 l^+ l^-$ components

The decay $K_L \to \pi^0 l^+ l^-$ $(l = e \; or \; \mu)$ has three components :

- CP conserving
  NA48 measurement $BR(K_L \to \pi^0 \gamma\gamma)$:
  $BR(K_L \to \pi^0 l^+ l^-)_{CP\,cons} \sim 10^{-12}$
  [Phys Rev D 47:4920-4938,1993]



- direct CP violating
  Proportional to η or $Im(\lambda_t)$
  $Im(\lambda_t) = \eta A^2 \lambda^5 \qquad \lambda_t = V_{ts}^* V_{td}$
  [Kettell, et al, hep-ph/0212321]



- indirect CP violating
  $\to BR(K_L \to \pi^0 l^+ l^-)_{ind} = |\epsilon|^2 (\frac{\tau_L}{\tau_S}) BR(K_S \to \pi^0 l^+ l^-)$

The measured BR($K_S \to \pi^0 \mu^+ \mu^-$) allows the prediction of CPV branching ratio of $K_L \to \pi^0 \mu^+ \mu^-$ as a function $Im(\lambda_t)$ to within a sign ambiguity

Branching Ratio Prediction for K_L

$$BR(K_L \to \pi^0 l^+ l^-)_{\rm CPV} \times 10^{12} = C_{\rm IND} \pm C_{\rm INT} \left(\frac{Im(\lambda_t)}{10^{-4}} \right) + C_{\rm DIR} \left(\frac{Im(\lambda_t)}{10^{-4}} \right)^2$$

where:

hep-ph/0308008

⇒ $C_{\rm DIR}$	Direct CPV component
⇒ $C_{\rm IND} \sim BR(K_S \to \pi^0 l^+ l^-)$	Indirect CPV component
⇒ $C_{\rm INT} \sim \sqrt{BR(K_S \to \pi^0 l^+ l^-)}$	Intereference DIR-IND

Taking $Im(\lambda_t)$ PDG world average $(1.36 \pm 0.12) \times 10^{-4}$:

$$BR(K_L \to \pi^0 \mu^+ \mu^-)_{CPV} \times 10^{12} \approx 9_{\rm indirect} \pm 6_{\rm interference} + 1_{\rm direct}.$$

$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} \times 10^{12} \approx 17_{\rm indirect} \pm 9_{\rm interference} + 5_{\rm direct}.$$

KTeV measurement: $BR(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10} (90\% CL)$

KTeV measurement: $BR(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10} (90\% CL)$

Summary (I)

- First observation of $K_S \rightarrow \pi^0\mu^+\mu^-$: 6 events. (NEW!!!)

- First observation of $K_S \rightarrow \pi^0 e^+e^-$: 7 events.

$$\mathrm{BR}(K_S \rightarrow \pi^0\mu^+\mu^-) = (2.9^{+1.4}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9} \text{(NEW!!!)}$$

$$BR(K_S \rightarrow \pi^0 e^+e^-)_{(m_{ee}>0.165GeV)} = (3.0^{+1.5}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$$

$$\mathrm{BR}(K_S \rightarrow \pi^0 e^+e^-) = (5.8^{+2.8}_{-2.3}(stat) \pm 0.8(syst)) \times 10^{-9}$$

Phys.Lett.B 576:43-54,2003
hep-ex/0309075

Summary (II)

- K_S BR results together with χ_{PT} predict:
- $B(K_L \to \pi^0 \mu^+ \mu^-)_{CPV} \approx (0.4 - 1.6) \times 10^{-11}$ (NEW!!!)
- $B(K_L \to \pi^0 e^+ e^-)_{CPV} \approx (1.3 - 3.1) \times 10^{-11}$
- Higher statistics are needed to have a precision χ_{PT} test.

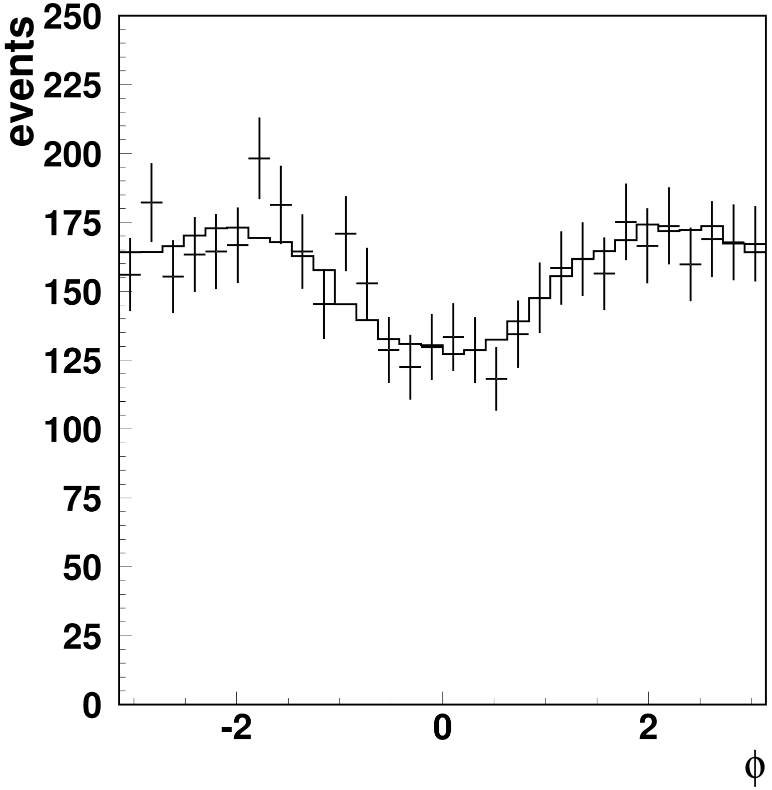
Other rare decays results from NA48

NEW!!!

$K_L \to \pi^\pm \pi^0 e^\pm \nu_e(\overline{\nu_e})$

$$BR(Ke4) = [5.21 \pm 0.07(stat) \pm 0.09(syst)] \times 10^{-5}$$

$Ke4$ form factors:



$$\overline{f}_s = 0.052 \pm 0.006 \pm 0.002$$

$$\overline{f}_p = -0.051 \pm 0.011 \pm 0.005$$

$$\lambda_g = 0.087 \pm 0.019 \pm 0.006$$

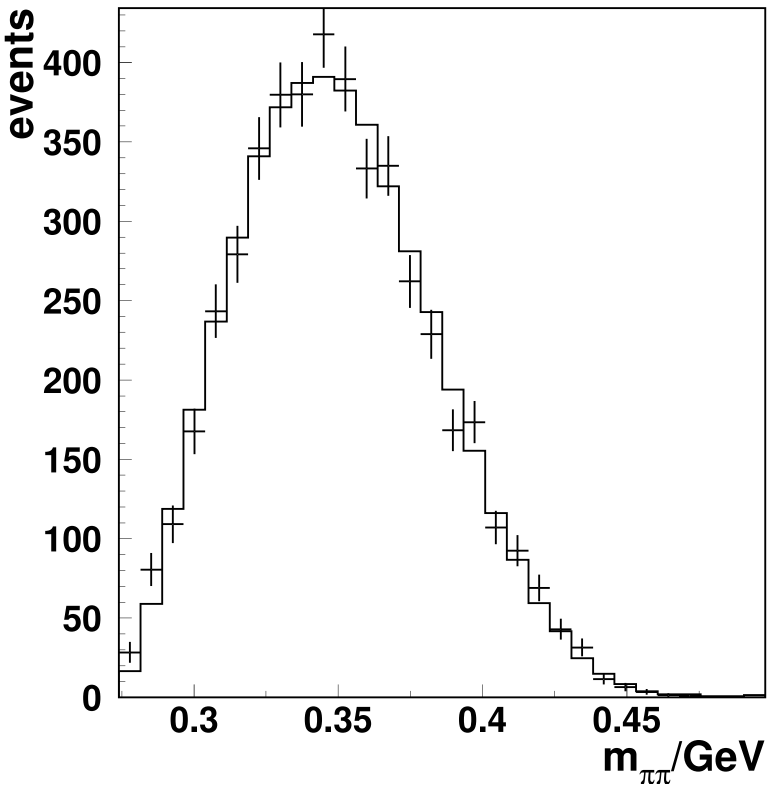
$$\overline{h} = -0.32 \pm 0.12 \pm 0.07$$

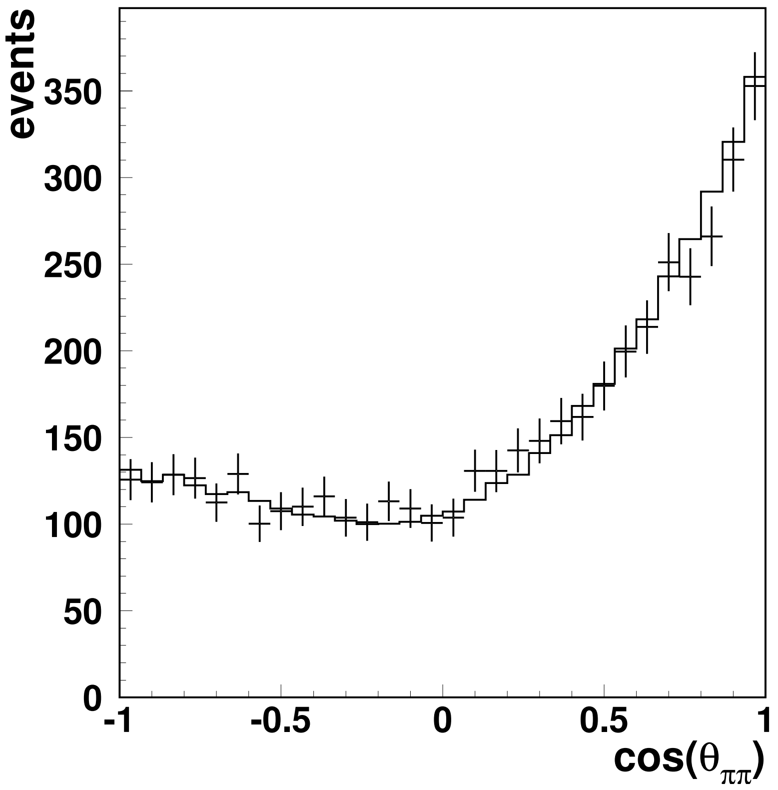
$Ke4$ sample: 5464 events with 62 background events.

Form factors agree with previous measurements with improved accuracy.

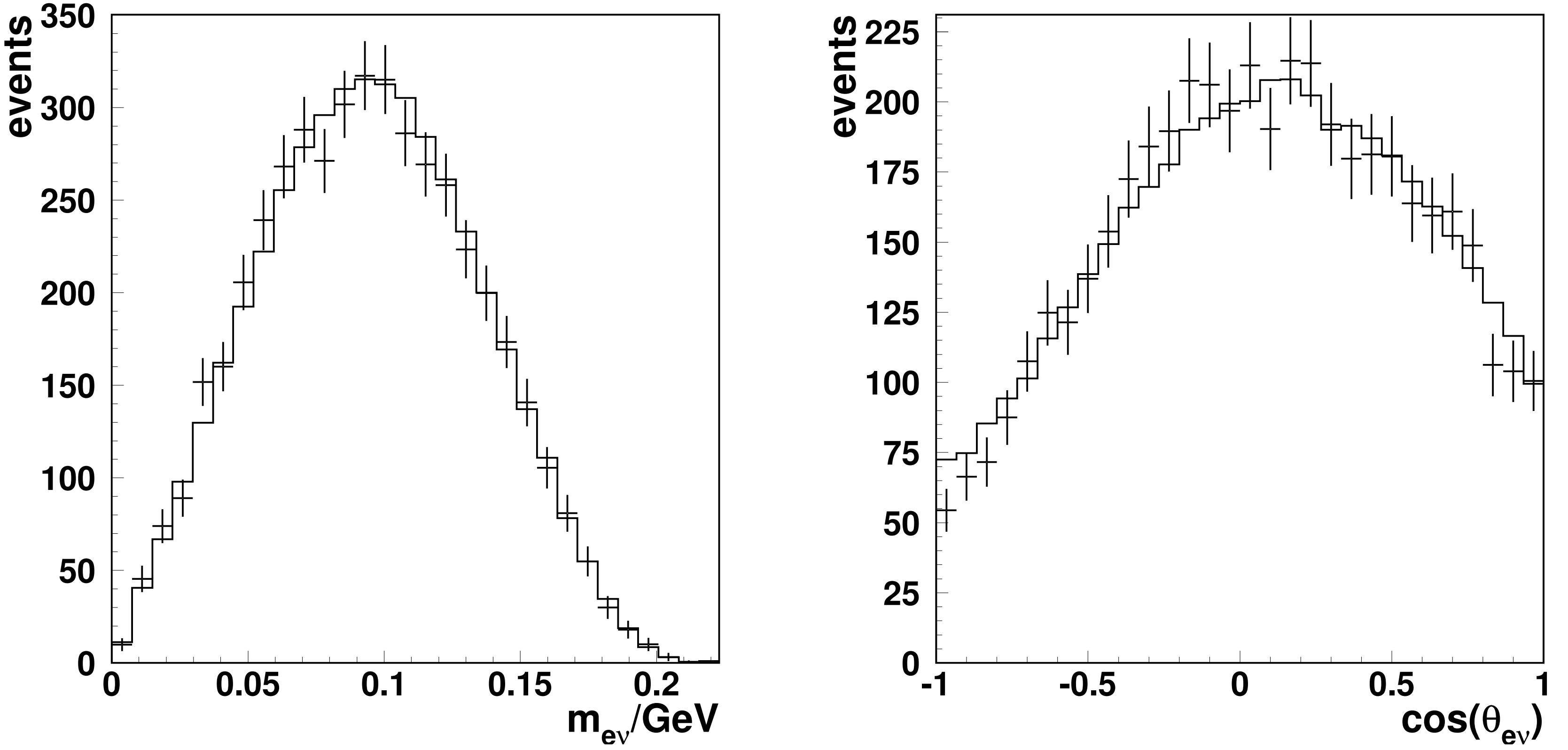
Coupling parameter of the chiral Lagrangian $L_3 = (-4.1 \pm 0.2) \times 10^{-3}$ evaluated from data.

$K_L \to \pi^{\pm}\pi^{0}e^{\pm}\nu_e(\overline{\nu_e})$





$K_L \to \pi^{\pm}\pi^0 e^{\pm}\nu_e(\overline{\nu_e})$



$\boxed{K_0 \rightarrow \pi^{\pm} e \mp \nu(\overline{\nu})\gamma}$

$$BR(Ke3\gamma, E^{\star}_{\gamma} > 30Mev, \theta^{\star}_{e\gamma} > 20deg) \;=$$
$$[0.962 \pm 0.007(stat)^{+0.012}_{-0.011}(syst)]\%$$

Data sample :

- More than 18000 $Ke3\gamma$ events.
- Normalization: $5 \times 10^6\ Ke3$

- Result compatible with theoretical predictions.
- Result disagrees with the previous high statistic experimental measurement.