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

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On behalf of the NA48/1 Collaboration:
Cambridge, Chicago, CERN, Dubna, Edinburgh
Ferrara, Firenze, Mainz, Northwestern, Perugia, Pisa, Saclay,
Siegen, Torino, Warsaw, Wien.

OUTLINE

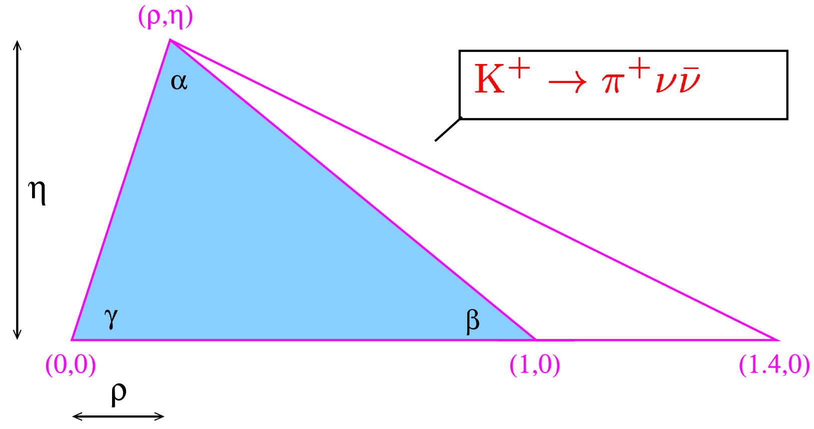
- Motivation for the measurements.
- NA48/1 beamline and detector.
- Background and event selcetion for $K_S \to \pi^0 e^+ e^-$.
- Background and event selection for $K_S \to \pi^0 \mu^+ \mu^-$.
- Results.
- Interpretation.

MOTIVATION.

In SM CPV is embeded as phase in CKM matrix.
Wolfestein parametrization: A,λ,η,ρ;
Kaon decays sensitive to ρ and η $\longrightarrow$ Direct CPV

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

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



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

- $\mathrm{K_L} \to \pi^0\nu\bar{\nu}$ and $\mathrm{K^+} \to \pi^+\nu\bar{\nu}$:
  Theoretically very clean.
  Determine the triangle.
  Experimentally very challenging.

- $K_L \to \pi^0 l^+ l^-$
  Not so clean theoretically.
  More accessible experimentally.

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

Theoretical predictions:

$$BR(K_L \to \pi^0 l^+ l^-) \simeq 10^{-12}$$

Three amplitudes contribute to the decays:

- CP conserving

  NA48 measurement $BR(K_L \to \pi^0 \gamma\gamma)$:

  $\to BR(K_L \to \pi^0 e^+ e^-)_{CP\,cons} = 0.47^{+0.22}_{-0.18} \times 10^{-12}$

  Negligible for $K_L \to \pi^0 e^+ e^-$, not for $\mathrm{K_L} \to \pi^0 \mu^+ \mu^-$

- direct CP violating

  Proportional to η or $\mathcal{I}m(\lambda_t)$

  $\mathcal{I}m(\lambda_t) = \eta A^2 \lambda^5 \qquad \lambda_t = V_{ts}^* V_{td}$

- indirect CP violating

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

$K_L \rightarrow \pi^0 l^+ l^-$

The CPV part of the $BR(K_L \rightarrow \pi^0 l^+ l^-)$ can be written as:

$$BR(K_L \rightarrow \pi^0 l^+ l^-)_{CPV} = C_{IND} \pm C_{INT}(Im(\lambda t)) + C_{DIR}(Im(\lambda t)^2)$$

Sign ambiguity in the interference term.

Measurement of $BR(K_S \rightarrow \pi^0 l^+ l^-)$ and $BR(K_L \rightarrow \pi^0 l^+ l^-)$ allow to extract information about the η parameter.

Alternatively, knowing $BR(K_S \rightarrow \pi^0 l^+ l^-)$ and taking the world average for Im(λt) we can predict $BR(K_L \rightarrow \pi^0 l^+ l^-)$

Theoretical prediction for $BR(K_S \rightarrow \pi^0 l^+ l^-) \simeq 10^{-9} - 10^{-10}$

Only very few events expected!!!!

Blind analysis strategy.

BLIND ANALYSIS METHOD FOR $K_S \to \pi^0 l^+ l^-$

Demands big understanding of possible background
Robust against potential human biases.

- Working plane: $m_{\gamma\gamma l^+ l^-} .vs. m_{\gamma\gamma}$
- Define signal and control regions that will be masked.
- Study potential background sources using both MC and data.
- Define a set of cuts to minimize backgrounds.
- ONLY ONCE CUTS ARE FIXED:

  Unmask control region: Gives final background estimate.

  Unmask signal region.

BEAMLINE

CERN SPS. NA48 beamline modified: K_S target only.

5×10^{10} protons per cycle (4.8 s/16 s)

400 GeV/c protons on 40 cm Beryllium target

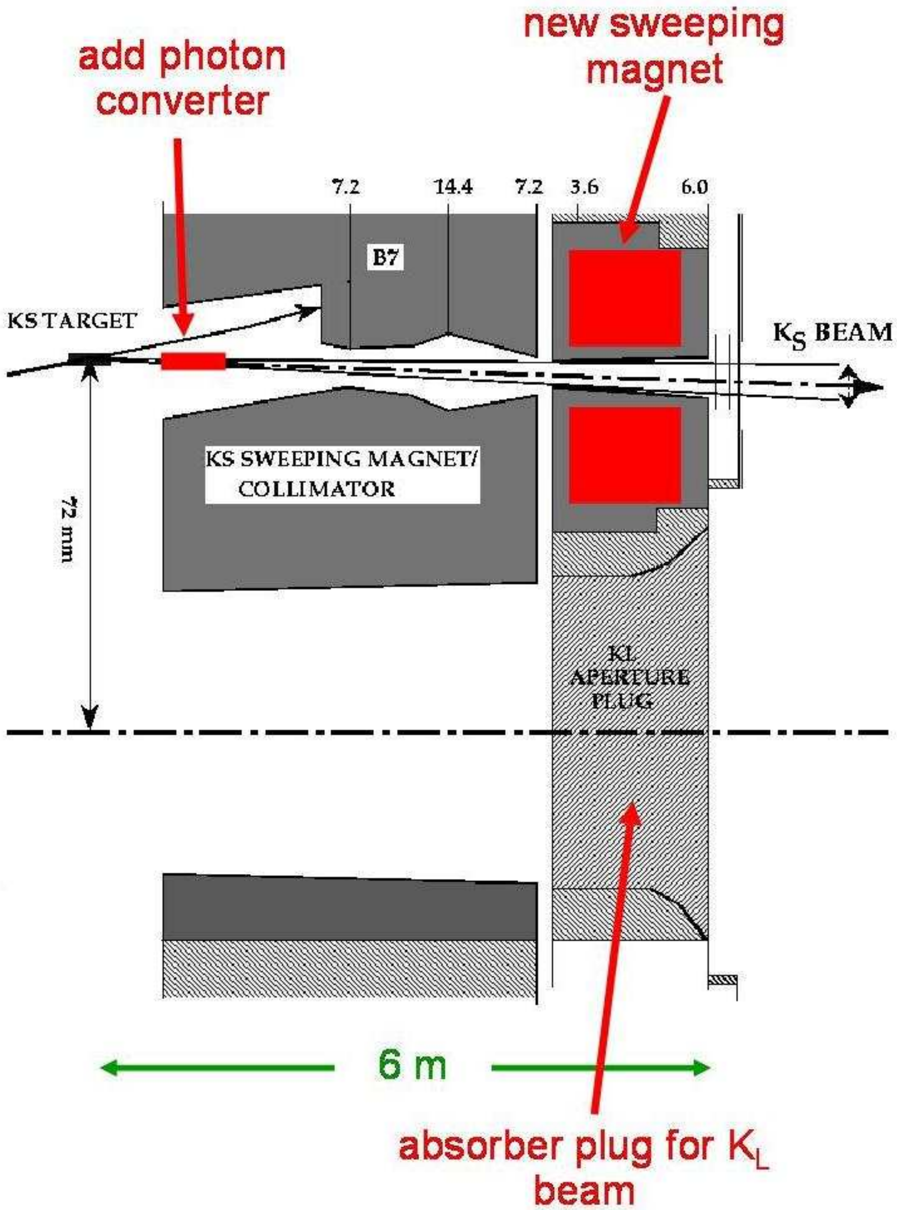
4.2 mrad production angle

Pt photon converter followed by sweeping magnet

90m vacuum tank.

$\sim 2.5 \times 10^5$ K_S / burst

Integrated: $\sim 4{\times}10^{10}$ K_S decays in fiducial volume.

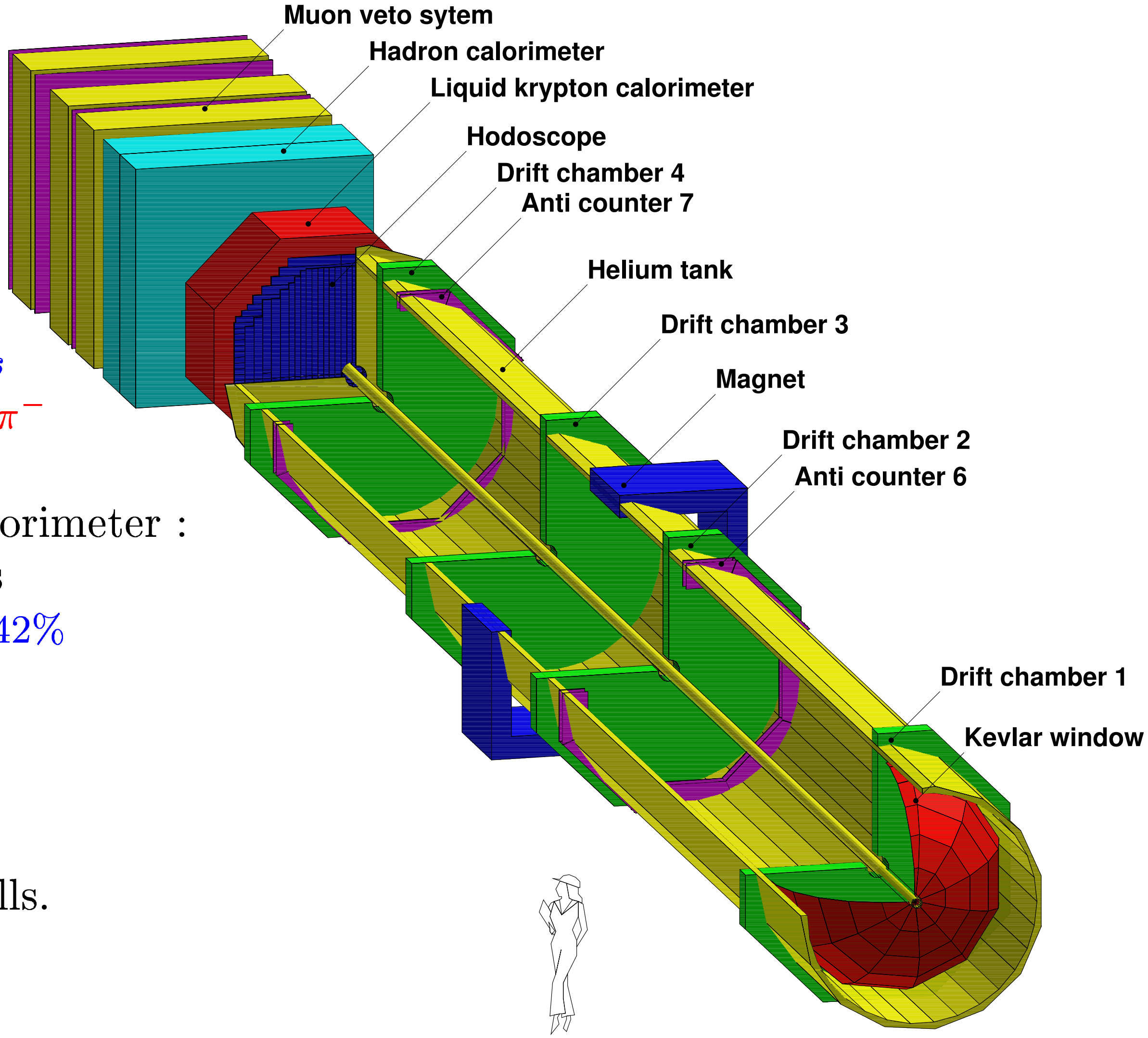


NA48 DETECTOR

- Magnetic spectrometer :
  3 DCH, 4 views, 2 planes/view
  $\sigma(p)/p \simeq 0.5\ \% \oplus 0.009\ p[GeV/c]\ \%$
  $(\mathrm{P}_{\perp}{}^{kick} \sim 265\mathrm{MeV}/c)$
  $\sigma(t) \simeq 1.4ns.$
  Charged hodoscope: $\sigma(t) \simeq 200ps$
  $\sigma(M_{\pi^+\pi^-}) \simeq 3MeV$ from $K_S \rightarrow \pi^+\pi^-$

- Liquid Krypton electromagnetic calorimeter :
  27 X_0 with 13212 2×2 cm^2 cells
  $\sigma(E)/E = 3.2\%/\sqrt{E} \oplus (9\%)/E \oplus 0.42\%$
  $\sigma(t) \simeq 265ps$
  $\sigma(M_{\gamma\gamma}) \simeq 1MeV$ from $K_S \rightarrow \pi^0\pi^0$

- Muon counters:
  2+1 planes (X,Y) 25cm×25cm cells.
  $\sigma(t) \simeq 350ps$



- Upgraded R/O for DCH and LKR allows 50K evts/burst.
  Active Level 3: reduct fact $\simeq 3$, 50 TB recorded.

SELECTION FOR $K_S \to \pi^0 e^+ e^-$.

- Trigger: Two tracks and energy deposit on Lkr. Eff: 99.0%, using $\pi^0\pi^0_D$
- Events with 2 tracks ($E/p \simeq 1$) and 4 clusters within 3ns.
- No additional in-time tracks or clusters. No hits in MUV. No energy on HAC.
- 4 compatible verteces:

  CDA-vertex and π^0-vertex.

  Neutral vertex: imposing $m_{ee\gamma\gamma} = m_k$
  $\longrightarrow$ determine $m_{\gamma\gamma}$

  Charged vertex: intersection point of tracks and kaon line of flight
  $\longrightarrow$ determine $m_{ee\gamma\gamma}$

- Control region:

$$3.0 \times \sigma_{m_{ee\gamma\gamma}} < |M_k - m_{ee\gamma\gamma}| < 6.0 \times \sigma_{m_{ee\gamma\gamma}}$$
$$3.0 \times \sigma_{m_{\gamma\gamma}} < |M_{\pi^0} - m_{\gamma\gamma}| < 6.0 \times \sigma_{m_{\gamma\gamma}}$$

- Signal region:

$$|M_k - m_{ee\gamma\gamma}| < 2.5 \times \sigma_{m_{ee\gamma\gamma}}$$
$$|M_{\pi^0} - m_{\gamma\gamma}| < 2.5 \times \sigma_{m_{\gamma\gamma}}$$

  Where $\sigma_{m_{ee\gamma\gamma}} = 4.6\ MeV/c^2$ $\sigma_{m_{\gamma\gamma}} = 1.0$, from MC verified with $\pi^0\pi^0_D$ data.

- Fid volume: $40\ GeV < E_{kaon} < 240\ GeV$ and $0 < c\tau_{K_S} < 2.5$

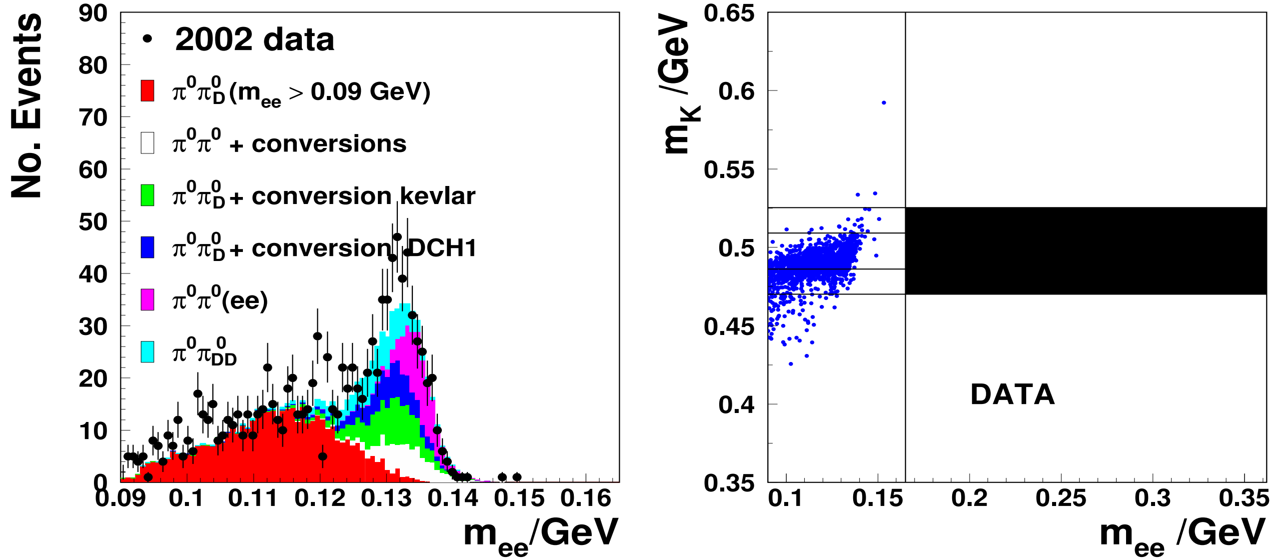
BACKGROUND SOURCES FOR $K_S \to \pi^0 e^+ e^-$: Physical background.

1. $K_S \to \pi^0 \pi^0$ with Dalitz decays and conversions.

- $K_S \to \pi^0 \pi^0_{Dalitz} \to \ \gamma\gamma \ \gamma e^+ e^-$ with lost γ
- $K_S \to \pi^0_{Dalitz} \pi^0_{Dalitz} \to \ \gamma e^+ e^- \ \gamma e^+ e^-$ with lost $e^+ e^-$
- Event rejected if:

  $m_{e^+e^-} > 165 MeV/c^2 = m_{\pi^0} + 30 MeV (\simeq 8\sigma(m_{ee}))$

  Both combinations $m_{e\gamma 1}$ and $m_{e\gamma 2}$ are less than $165 MeV/c^2$

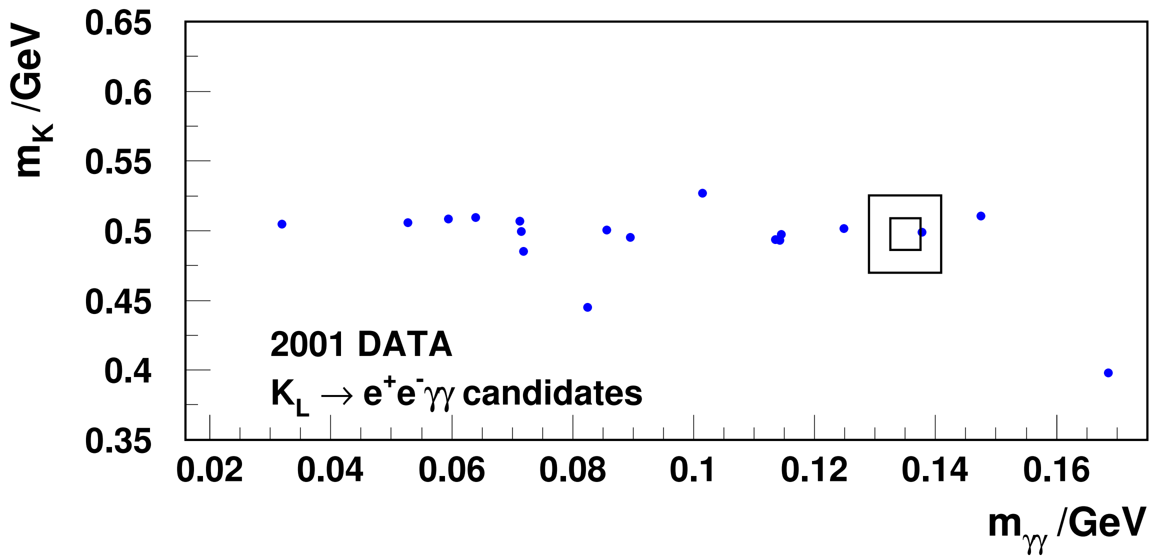


- Limit given by MC $\longrightarrow$ < 0.01 events expect. on signal region.
- Good check possible with same sign events.

BACKGROUND SOURCES FOR $K_S \to \pi^0 e^+ e^-$: Physical background.

2. $K_L \to e^+ e^- \gamma\gamma$ Greenlee

- Irreducible background: $(BR = 6 \times 10^{-7})$
- $\simeq$ 300 events expected in 2002 in allowed fid volume.
- Supressed by m_{ee} cut and by $m_{\gamma\gamma} = m_{\pi^0}$ condition.
- NA48 2001 data used,$\simeq$ 10 times 2002 statistics for K_L.



- Extrapolation from low $m_{\gamma\gamma}$ region $\longrightarrow$ $0.08^{+0.03}_{-0.02}$ events expected on signal region.

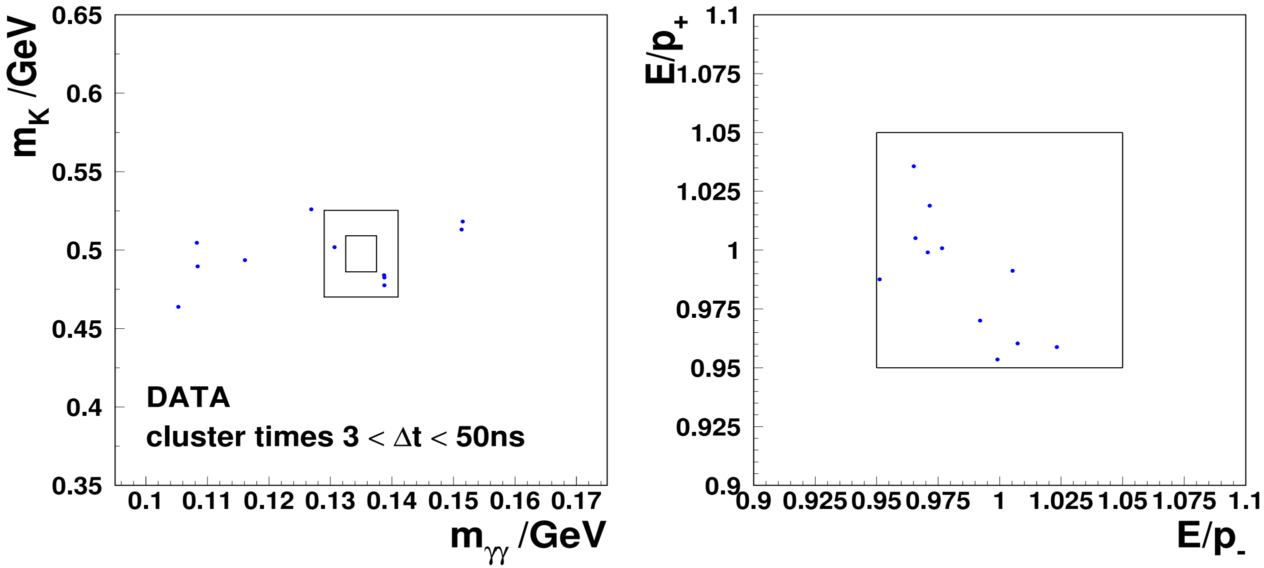
BACKGROUND SOURCES FOR $K_S \to \pi^0 e^+ e^-$: Accidental background.

3. Accidentals: Fragments of 2 different decays overlapping in time.

$$p_1 + Be \to K_S + X \text{ and } p_2 + Be \to K_L + X$$
$$K_S \to \pi^0\pi^0 \text{ and } K_L \to \pi^\pm e^\pm \nu$$

where one π^0 is lost and the π deposits all energy.

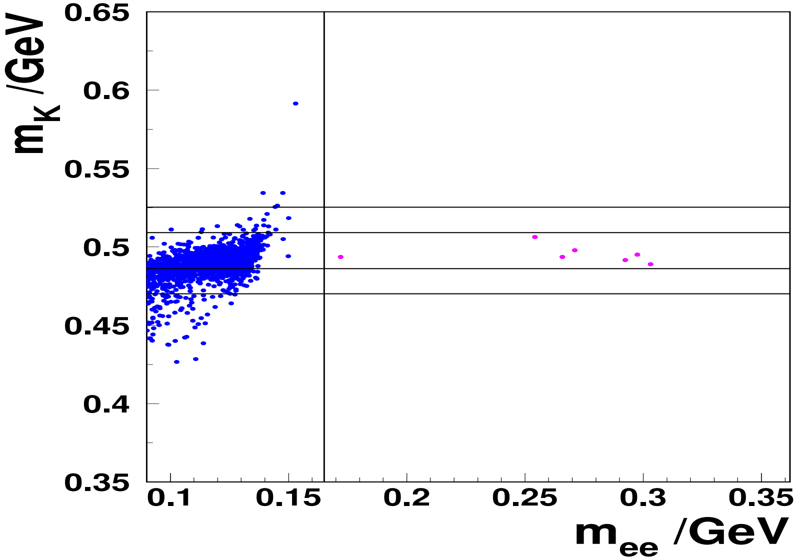
Control region: $3 < |$ LKR time of $\gamma\gamma -$track time$| < 50$ ns
Signal region: $|$ LKR time of $\gamma\gamma -$track time$| <3$ ns

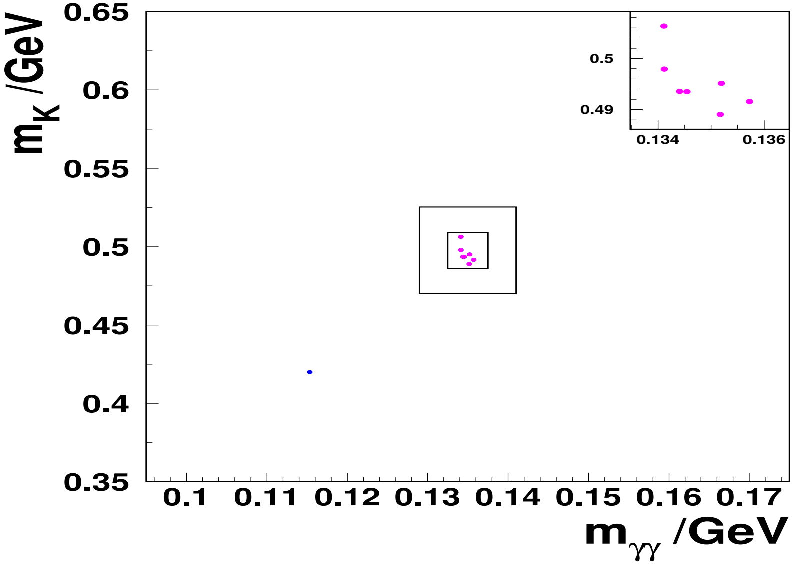


Extrapolate from out-of-time control region to out-time signal region with Toy MC.
Linear extrapolation to in-time signal region$\longrightarrow$ $0.07^{+0.07}_{-0.03}$ events expected.

RESULT

- Total background in signal region $0.15^{+0.10}_{-0.04}$. From Greenlee and accidentals.
- Unmask control region. No new events found.
- Unmask signal region $\longrightarrow$ 7 events found.





- Using flux from $K_S \to \pi^0\pi^0_D$ and computing model independent acceptance:
  $BR(K_S \to \pi^0 e^+e^-)_{(m_{ee}>0.165\ \mathrm{GeV})} = (3.0^{+1.5}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$
- Using unity form factor to extrapolate to all m_{ee}

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

SELECTION FOR $K_S \to \pi^0\mu^+\mu^-$

Trigger:

- For 40% of the data at least 2 hits in each of the first two MUC planes.
- For 60% of the data second component in parallel, requiring:
  Energy in HAC < 10 GeV, energy in LKr > 15 GeV.
  Allows one of the first two muon planes to contain only 1 hit.

Selection:

- Control region:

$$3.0 \times \sigma_{m_{\mu\mu\gamma\gamma}} < |M_k - m_{\mu\mu\gamma\gamma}| < 6.0 \times \sigma_{m_{\mu\mu\gamma\gamma}}$$
$$3.0 \times \sigma_{m_{\gamma\gamma}} < |M_{\pi^0} - m_{\gamma\gamma}| < 6.0 \times \sigma_{m_{\gamma\gamma}}$$

- Signal region:

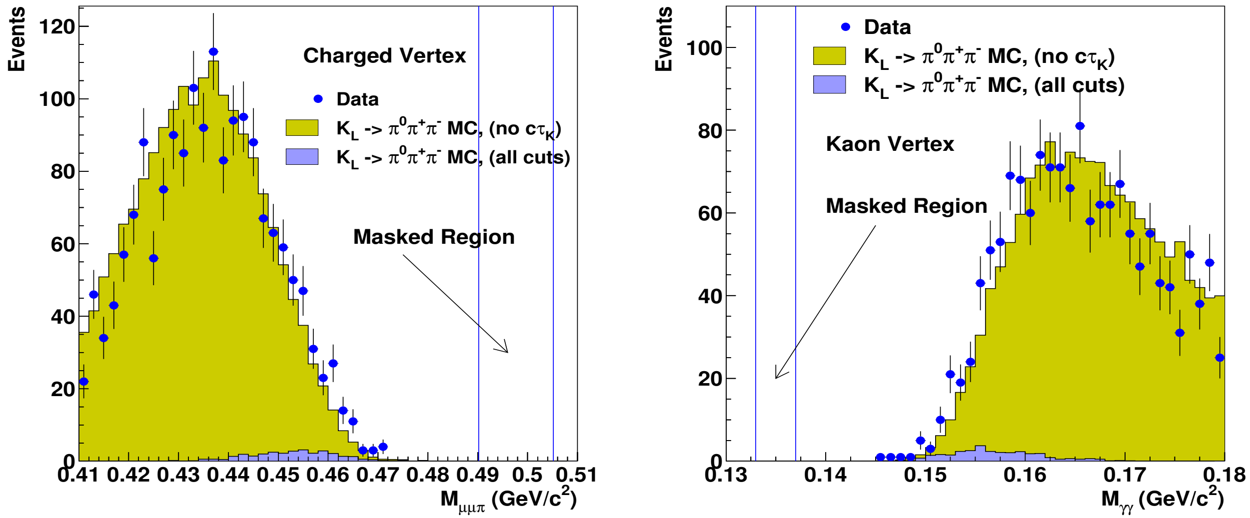
$$|M_k - m_{\mu\mu\gamma\gamma}| < 2.5 \times \sigma_{m_{\mu\mu\gamma\gamma}}$$
$$|M_{\pi^0} - m_{\gamma\gamma}| < 2.5 \times \sigma_{m_{\gamma\gamma}}$$

Where $\sigma_{m_{\mu\mu\gamma\gamma}} = 3\ MeV/c^2$ $\sigma_{m_{\gamma\gamma}} = 0.8 MeV/c^2$, from $K_L \to \pi^0\pi^+\pi^-$ data, in agreement with MC.

- Fid volume: $60\ GeV < E_{kaon} < 200\ GeV$ and $0 < c\tau_{K_S} < 3.0$

BACKGROUND SOURCES FOR $K_S \rightarrow \pi^0\mu^+\mu^-$: Physical background

- 1. $K_L \rightarrow \pi^0\pi^+\pi^-$ with decay in flight.
  Rejected by $c\tau$ cut (misreconstructed vertex)
  Expectation given by MC $\longrightarrow$ <0.018 events expected on signal region.



- Greenlee $K_L \rightarrow \mu^+\mu^-\gamma\gamma$
  Expectation given by MC $\longrightarrow$ $0.04^{+0.04}_{-0.03}$ events expected.

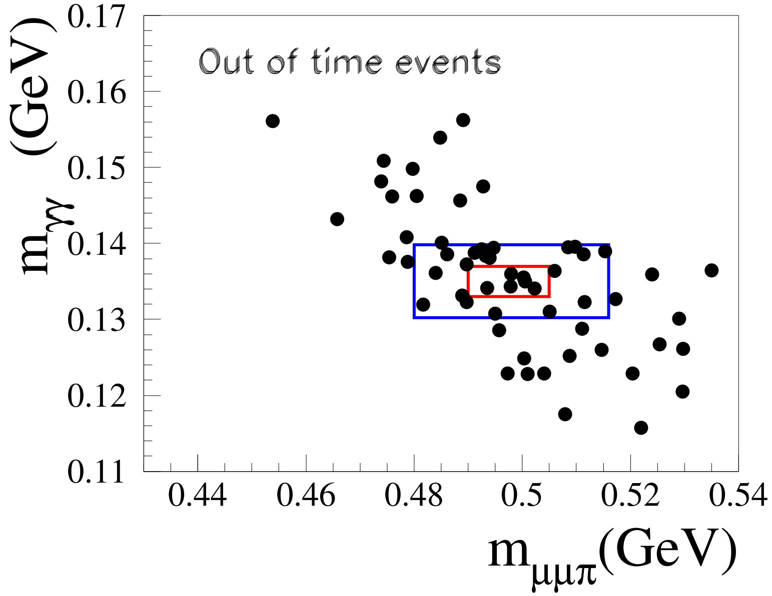
BACKGROUND SOURCES FOR $K_S \to \pi^0\mu^+\mu^-$: Accidental background

- 3. Two significant sources:

$$K_S \to \pi^0\pi^0 \text{ and } K_S \to \pi^+\pi^-$$
$$K_S \to \pi^0\pi^0 \text{ and } K_L \to \pi^\pm\mu^\pm\nu$$

whith π DIF or mis-identified.

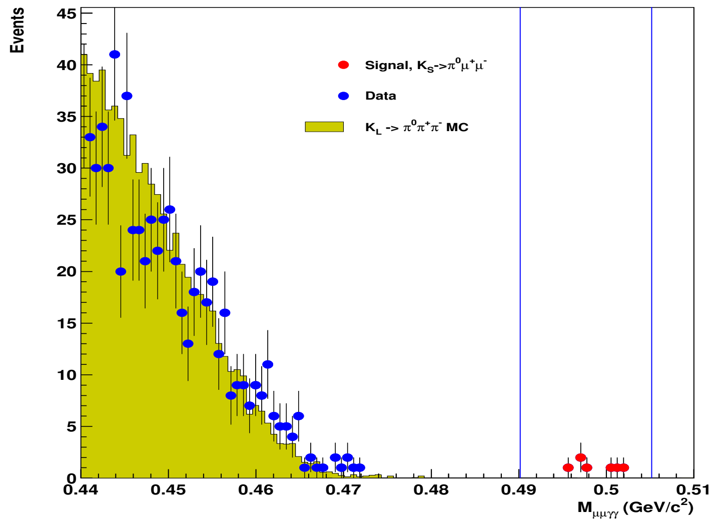
Control region: $-115ns < \Delta t < -$ 3ns and 3ns $< \Delta t <$ 60 ns
Signal region: -1.5ns $< \Delta t <$1.5 ns

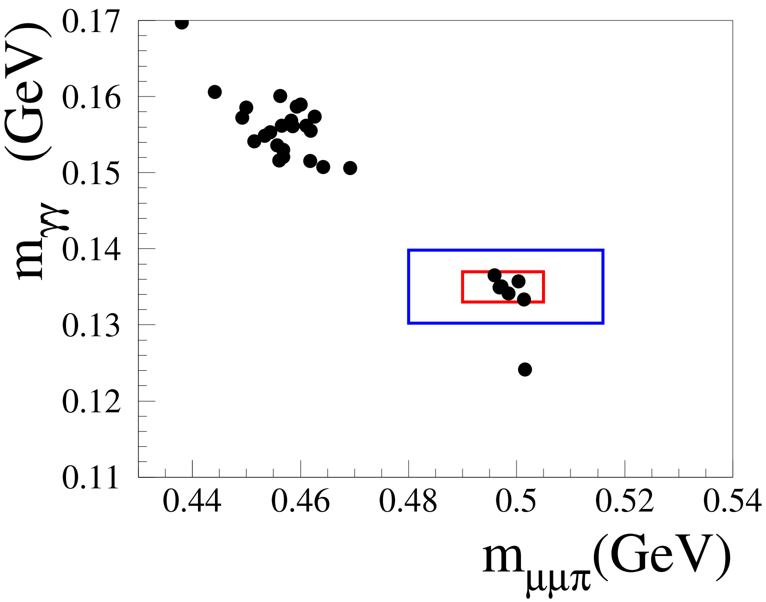


- 6 events found on out-time signal region.
- Extrapolation to in-time signal region$\longrightarrow$ $0.18^{+0.18}_{-0.11}$ events expected.

RESULT

- Total background in signal region $0.22^{+0.18}_{-0.11}$. Dominated by accidentals.
- Unmask signal region $\longrightarrow$ 6 events found.





- Using flux from $K_S \to \pi^+\pi^-$ corrected by acceptance and trigger efficiency:

$$BR(K_S \to \pi^0\mu^+\mu^-) = (2.8^{+1.5}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$$

SUMMARY OF THE RESULTS.

$K_S \to \pi^0 e^+ e^-$

- 7 events found in signal region.
- Background:

$K_S \to \pi^0_{Dalitz} \pi^0_{Dalitz}$	< 0.01
$K_L \to e^+ e^- \gamma\gamma$	$0.08^{+0.03}_{-0.02}$
Accidentals	$0.07^{+0.07}_{-0.03}$

- Total background $0.15^{+0.10}_{-0.04}$

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

- Using unity form factor to extrapolate to all m_{ee}

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

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

- 6 events found in signal region.
- Background:

$K_L \to \pi^0 \pi^+ \pi^-$	$0^{+0.02}_{-0.00}$
$K_L \to \mu^+ \mu^- \gamma\gamma$	$0.04^{+0.04}_{-0.03}$
Accidentals:	$0.18^{+0.18}_{-0.11}$

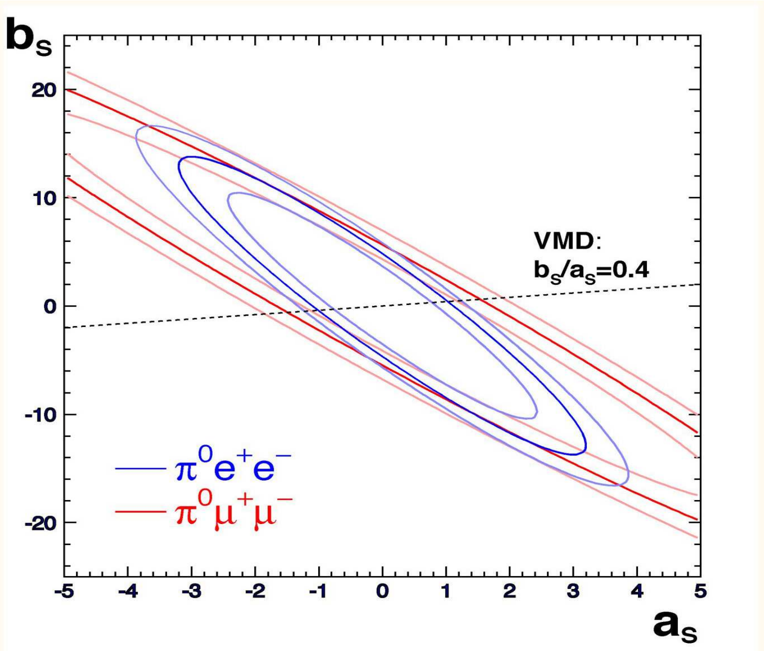
- Total background: $0.22^{+0.18}_{-0.11}$

$$BR(K_S \to \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$$

INTERPRETATION.

- Branching ratio predictions from χPT.
  $BR(K_S \to \pi^0 e^+ e^-) = [0.01 - 0.76 a_s - 0.21 b_s + 46.5 a_s^2 + 12.9 a_s b_s + 1.44 b_s^2] \times 10^{-10}$
  $BR(K_S \to \pi^0 \mu^+ \mu^-) = [0.07 - 4.52 a_s - 1.50 b_s + 98.7 a_s^2 + 57.7 a_s b_s + 8.95 b_s^2] \times 10^{-11}$

- Assuming VMD $|a_s|$ can be extracted from both channels independently.
  $BR(K_S \to \pi^0 e^+ e^-) \simeq 5.2 \times 10^{-9} a_s^2 \longrightarrow |a_s|_{\pi^0 ee} = 1.06^{+0.26}_{-0.21} \pm 0.07$
  $BR(K_S \to \pi^0 \mu^+ \mu^-) \simeq 1.2 \times 10^{-9} a_s^2 \longrightarrow |a_s|_{\pi^0 \mu\mu} = 1.53^{+0.38}_{-0.32} \pm 0.05$
  Compatible within errors.



- Allowed region of a_s and b_s
  (From number of events in each channel separately).
- Compatible with each other and with VDM.

- Both results combined in log-likelihood fit:

$$a_s = -1.6^{+2.1}_{-1.8} \; b_s = 10.7^{+5.4}_{-7.7}$$
$$a_s = 1.8^{+1.6}_{-2.4} \; b_s = -11.2^{+8.8}_{-4.5}$$

IMPLICATIONS FOR $K_L \to \pi^0 l^+ l^-$.

From the measurement of $K_S \to \pi^0 l^+ l^-$, taking Im(λt) world average

$$\mathrm{Im}(\lambda t) = (1.36 \pm 0.12) \times 10^{-4}$$

We can obtain a prediction for the CPV part of $K_L \to \pi^0 l^+ l^-$

$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} \simeq (17.2_{IND} \pm 9.4_{INT} + 4.7_{DIR}) \times 10^{-12}$$