Results on Rare Decays of

$$K_S \to \gamma\gamma$$

$$K_{S,L} \to \pi^+\pi^- e^+ e^-$$

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

On Behalf of NA48 Collaboration

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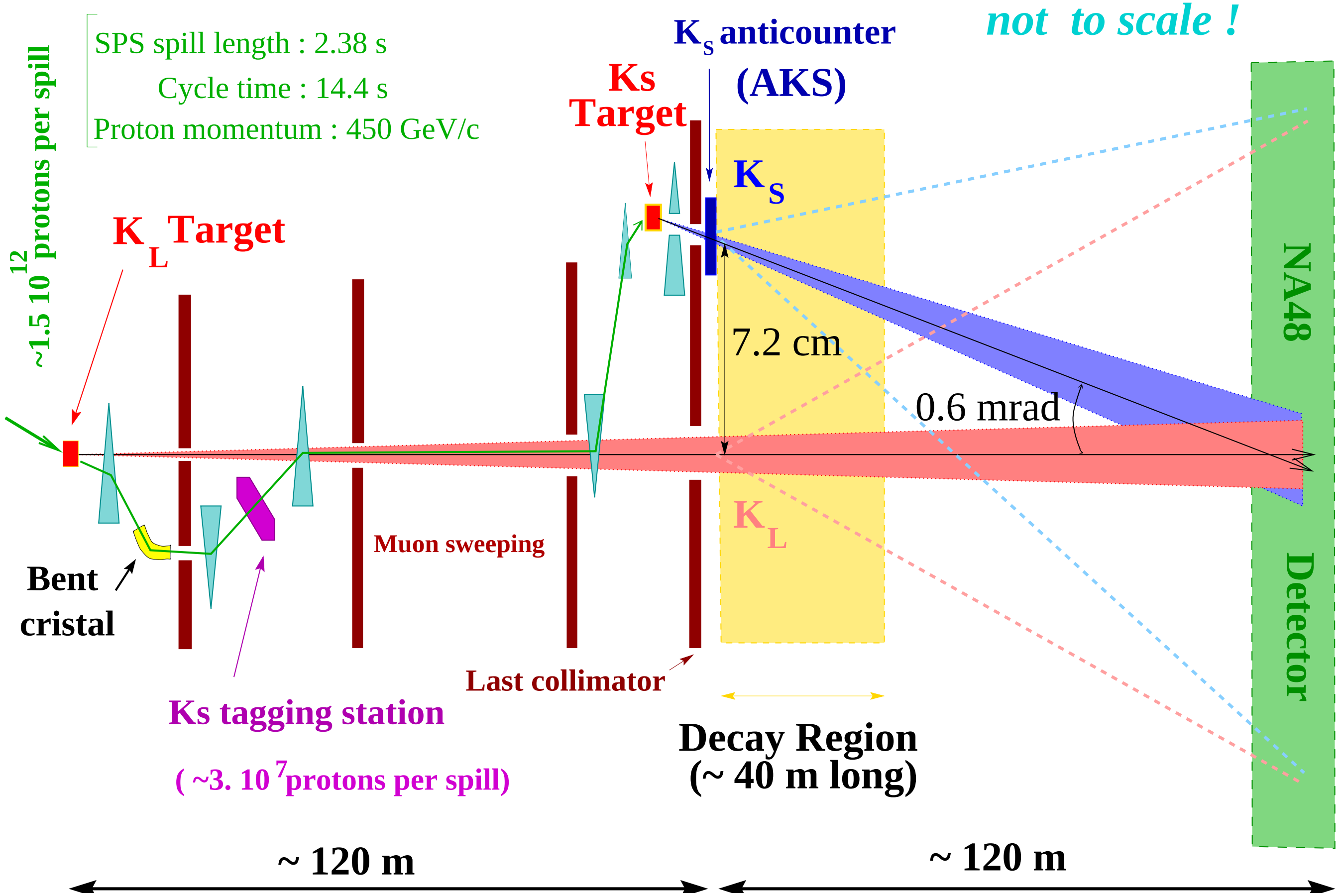
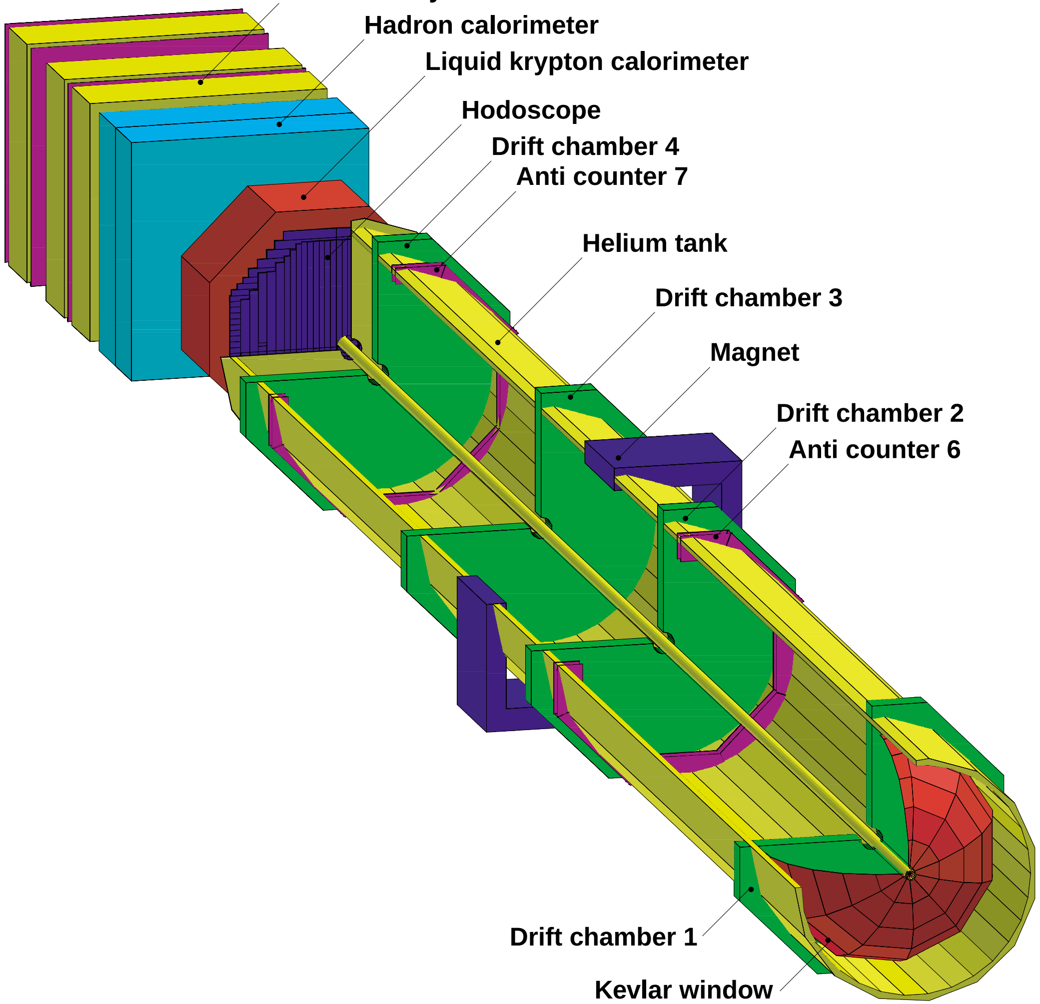
The Experiment - Simultaneous K_S and K_L beams



1997-1999 3.2×10^{10} K_L decays/year, 6.5×10^{7} K_S decays/year

1999 KSHI proton beam intensity increased by ~200, 2.3×10^{8} K_S, No KL beam

The Experiment - Detectors



Magnetic Spectrometer

$$\frac{\sigma_p}{p} = 0.5\% + 0.009\%\text{p}$$

$$\sigma_{x,y} \approx 2 \text{ mm} \qquad \sigma_z \approx 50 \text{ cm}$$

plane efficiency > 99%

Liquid-Krypton Calorimeter

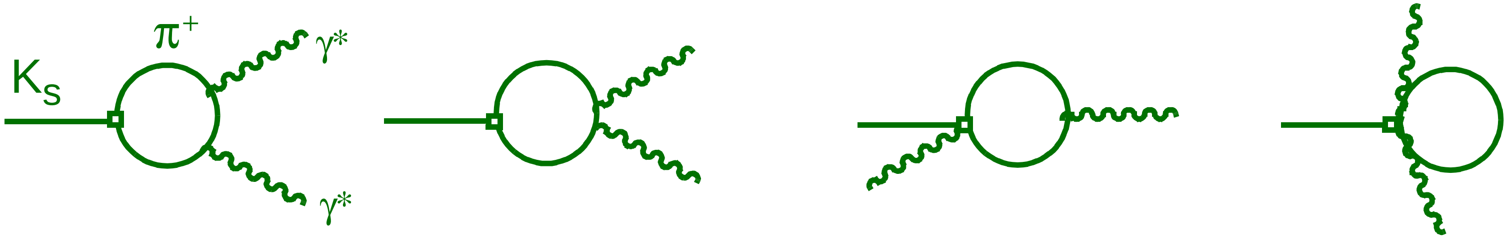
$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.1}{E} \oplus 0.5\%$$

$$\sigma_{x,y} < 1.3 \text{ mm}$$

$$\sigma_{\pi^0} < 1 \text{ MeV}$$

$K_S \to \gamma\gamma$ - Physics Motivation

Decay of $K_S \to \gamma\gamma$ is computed in χPT. Main contributions to $K_S \to \gamma\gamma$ are loops of charged pions:



Importance of this decay is due to :

No short distance contribution
Finite and unambiguous prediction for $Br(K_S \to \gamma\gamma)$

thus, measurement of $Br(K_S \to \gamma\gamma)$ is a test of χPT

Theoretical prediction $Br(K_S \to \gamma\gamma) = (2.3 \pm 0.2) \times 10^{-6}$

NA31 (CERN) $Br(K_S \to \gamma\gamma) = (2.4 \pm 0.9) \times 10^{-6}$

$K_S \to \gamma\gamma$ - Data & Event Selection

Data

- 1999 K_S High Intensity data

Event selection

- $3 < E_{cl} < 100$ GeV; Distance between two clusters $d > 10$ cm; $|t_{cl} - t_{event}| < 5$ ns
- No extra cluster with $E_{cl} > 1.5$ GeV within ± 3 ns
- Center of gravity (cog) < 7 cm; $60 < E_{kaon} < 170$ GeV
- Decay region, $0 < z_v < 5$ m. The end of K_S collimator defines the beginning of decay region

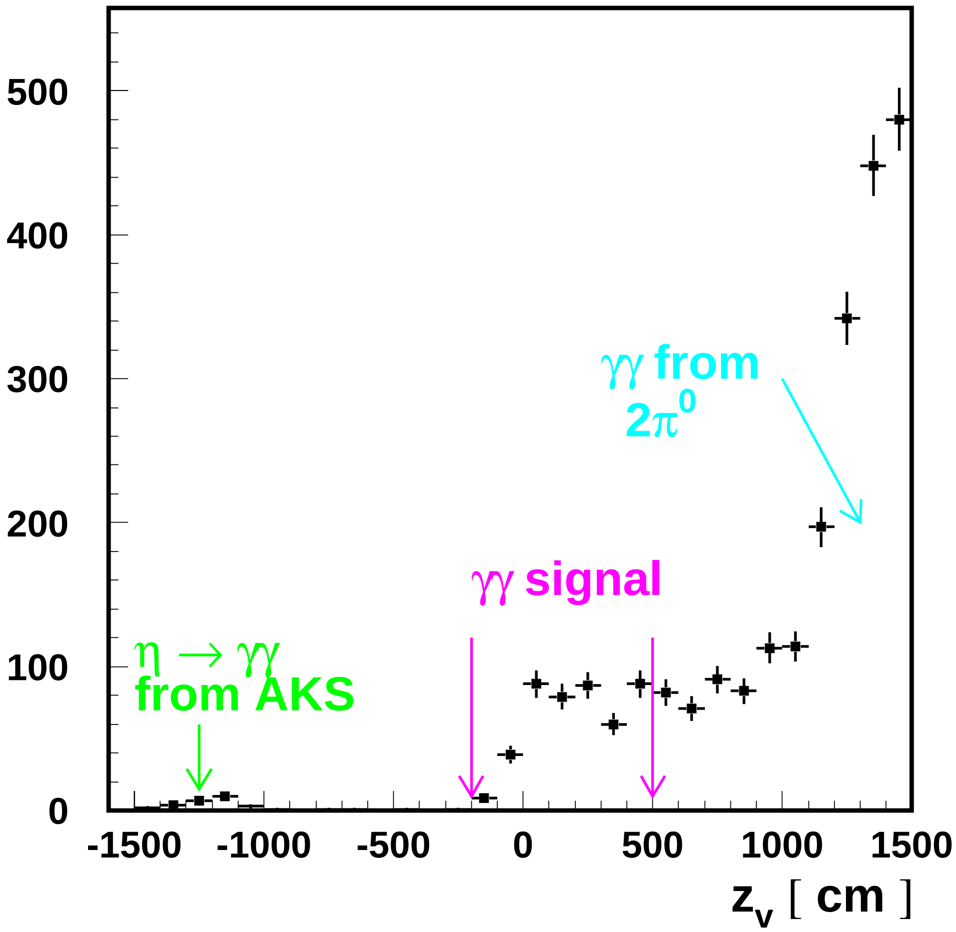
for background rejection

- $K_L \to \gamma\gamma$ contribution is estimated by the flux computed from $K_S \to 2\pi^0$ decay.
- $\Lambda \to n\pi^0$ decays are rejected by in time HAC cluster energy > 3 GeV, and shower width cut in LKr.
- $K_S \to 2\pi^0$ decays are suppressed by the z_v cut because the maximum invariant mass originating from $2\pi^0$ cannot produce a vertex position less than 9 m.

$K_S \to \gamma\gamma$ - Results

Decay vertex: $$z_v = z_{LKr} - \frac{\sqrt{\Sigma E_i E_j d_{ij}}}{M_K}$$

d_{ij} : transverse distance between two cluster



$$N(K \to \gamma\gamma) = 450 \text{ events}$$

$K_S \to \gamma\gamma$ - Results cont'd

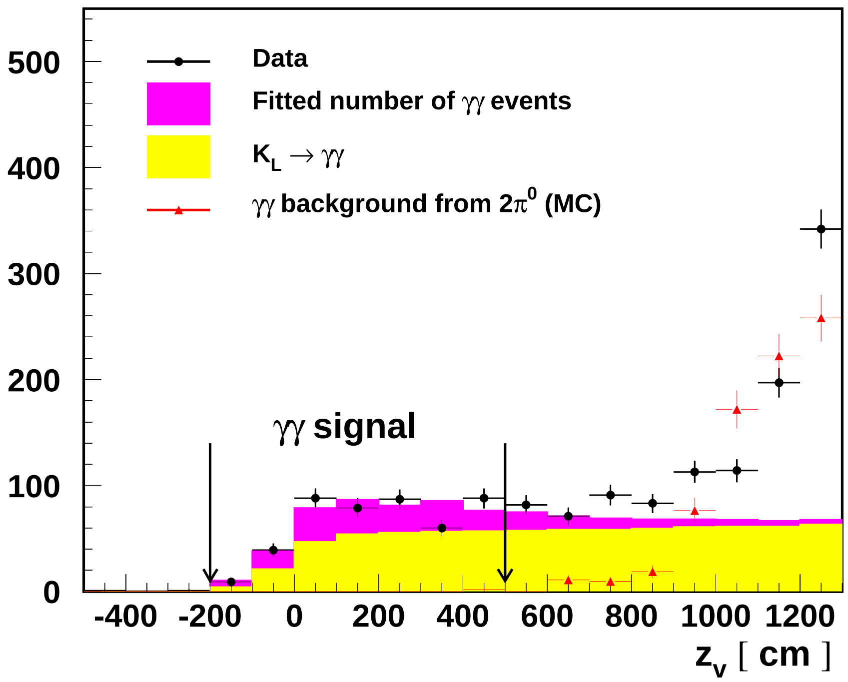
The number of $K_S \to \gamma\gamma$ events in $K \to \gamma\gamma$ sample and Branching ratio of $BR(K_S \to \gamma\gamma)$ are estimated by binned maximum log likelihood method.

Normalization channel $2\pi^0$, $N(K_S \to 2\pi^0) = 7.5\times10^6$

Backgrounds: $N(K_L \to \gamma\gamma) = 294$, $N(\Lambda \to n\pi^0) = 11$,

$N(K_S \to 2\pi^0) = 2$

Acceptance: 49% for $K_S \to \gamma\gamma$ and 22% for $K_S \to 2\pi^0$



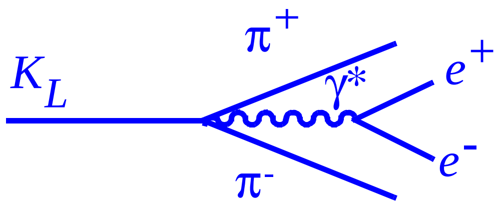
$$N(K_S \to \gamma\gamma) = 149 \pm 21$$

$$BR(K_S \to \gamma\gamma) = (2.58 \pm 0.36(stat) \pm 0.22(sys))\times10^{-6}$$

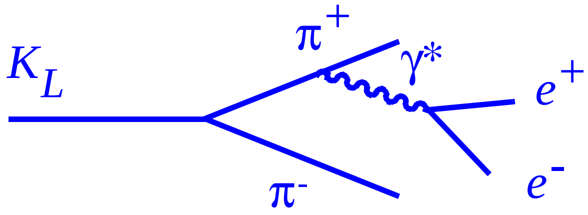
$$R = \frac{\Gamma(K_S \to \gamma\gamma)}{\Gamma(K_L \to \gamma\gamma)} = 2.53 \pm 0.35(stat) \pm 0.22(sys)$$

$K_{L,S} \rightarrow \pi^+\pi^- e^+ e^-$ - Physics Motivations

Main contributions to the K_L decay:



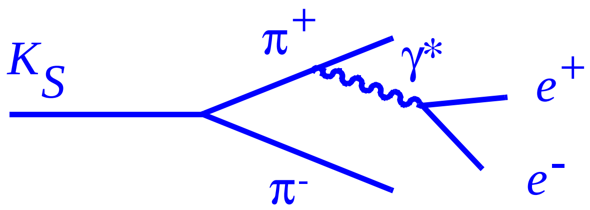
CP-conserving
Direct Emission (E1, M1)



CP-violating
IB (Inner Bremsstrahlung)

Interference between dominant M1 and IB gives large CP-violating asymmetry in the ϕ distribution between normals to the $\pi^+\pi^-$ and e^+e^- planes in the kaon center of mass system $A_\phi \approx 14\%$ (P.Heiliger and L.M. Sehgal, Phys. Rev. D48 (1998) 4146)

K_S decay:



CP-conserving
IB (Inner Bremsstrahlung)

No CP -violating asymmetry is expected

$K_S \to \pi^+\pi^- e^+ e^-$ - Data & Event Selection

Data

- 1998 and 1998+1999

Trigger

- Four track trigger efficiency ~70% for 1998 and ~90% for 1999

Event Selection

- In time two positive and two negative tracks
- Electron ($0.85 \le E/p < 1.15$) and pion ($E/p < 0.85$) identification
- p_{track} > 2 GeV; E_{kaon} > 40 GeV; cog of 4 tracks < 8 cm; no in time hits AKS
- K_S events are identified by using tagger

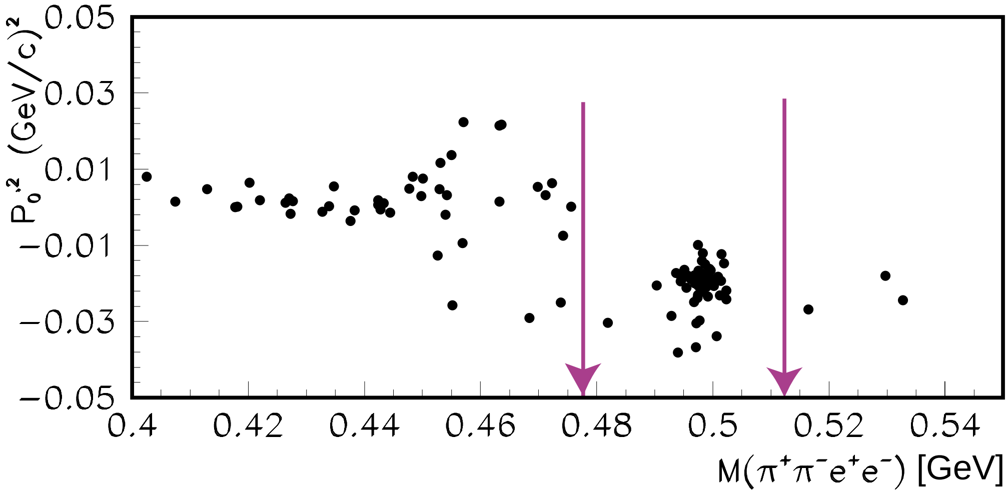
for background rejection

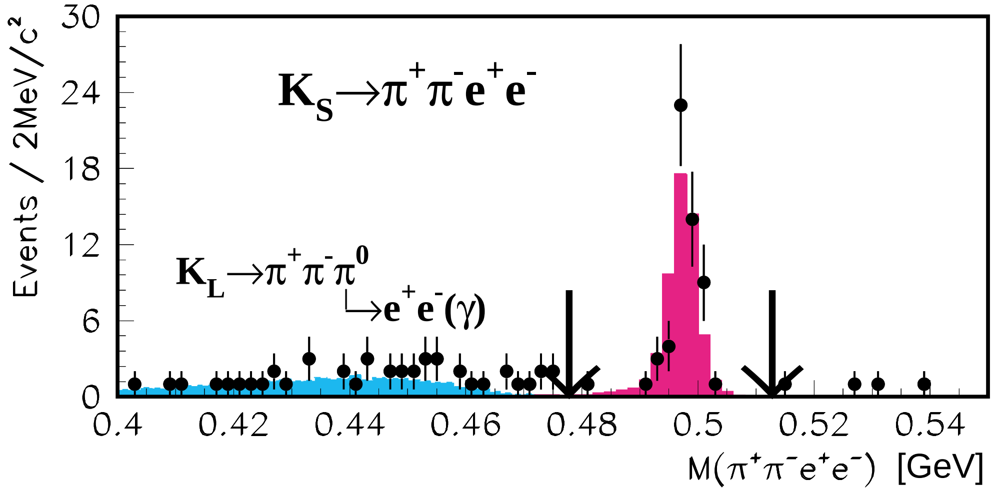
- $K_S \to \pi^+\pi^-$ with in time γ conversion is rejected if $490.7 < m_{\pi\pi} < 504.7$ MeV
- $K_L \to \pi^+\pi^-\pi^0_D$ decays are suppressed by $P^2_\perp < 0.02$ GeV²
- $\Xi^0 \to \Lambda\pi^0_D$, $\pi^0_D \to e^+e^-\gamma$, $\Lambda \to p\pi$ — $m_{p\pi}$ is 4 MeV around m_Λ events are rejected

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

First observation of $K_S \to \pi^+\pi^-e^+e^-$ events in 1998

$$P_0'^2 = \frac{(M_K^2 - M_{\pi^0}^2 - M_{\pi\pi}^2)^2 - 4M_{\pi^0}^2 M_{\pi\pi}^2 - 4(P_\perp^2)_{\pi\pi} M_K^2}{4(M_{\pi\pi}^2 + (P_\perp^2)_{\pi\pi})}$$





In the region of $477.7 < m_{\pi\pi ee} < 512.7$ MeV

$N(K_S \to \pi^+\pi^-e^+e^-) = 56$ events

$K_S \to \pi^+\pi^- e^+ e^-$ - Results cont'd

Branching ratio of $K_S \to \pi^+\pi^- e^+ e^-$

- $K_L \to \pi^+\pi^-\pi^0_D$ normalization channel $N(K_L \to \pi^+\pi^-\pi^0_D) = 105$
- acceptance for $K_S \to \pi^+\pi^- e^+ e^-$ ~ 3.7% and for $K_L \to \pi^+\pi^-\pi^0_D$ ~ 1.56%
- ratio of the trigger efficiencies : $\varepsilon_{\pi^+\pi^-\pi^0_D} / \varepsilon_{\pi^+\pi^- e^+ e^-} \sim 1.01$ is determined from the trigger simulation.

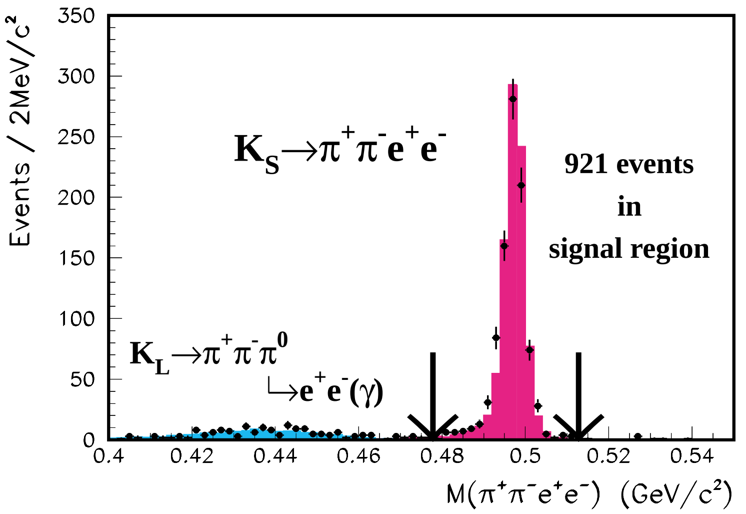
$$BR(K_S \to \pi^+\pi^- e^+ e^-) = (4.5 \pm 0.7(stat) \pm 0.4(sys)) \times 10^{-5}$$

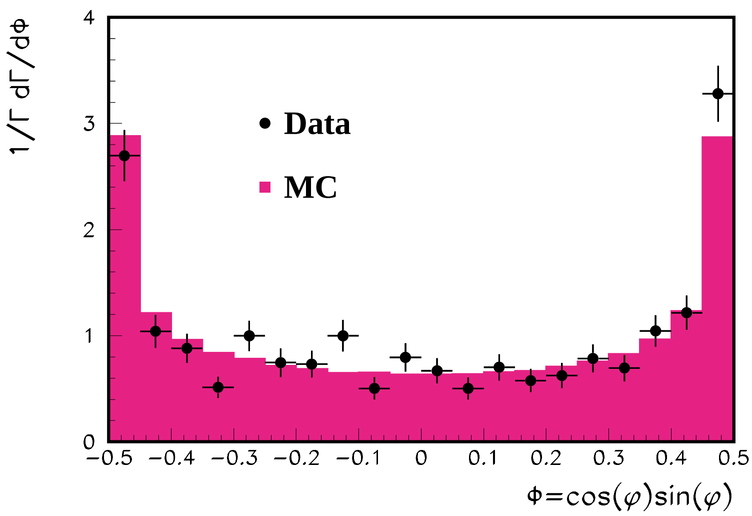
$$BR(K_L \to \pi^+\pi^- e^+ e^-)_{IB} = (1.4 \pm 0.2) \times 10^{-7}$$

K_S branching ratio is two orders of magnitude larger than K_L.

$K_S \rightarrow \pi^+\pi^-e^+e^-$ - Results

Combined 1998 and 1999 data (including K_S high intensity data)





Preliminary results:

$$BR(K_S \rightarrow \pi^+\pi^-e^+e^-) = (4.3 \pm 0.2(stat) \pm 0.3(sys)) \times 10^{-5}$$

$$BR(K_L \rightarrow \pi^+\pi^-e^+e^-)_{IB} = (1.3 \pm 0.1) \times 10^{-7}$$

No asymmetry is observed

$$A^S_{\pi\pi ee} = (-0.2 \pm 3.4(stat) \pm 1.4(sys))\%$$

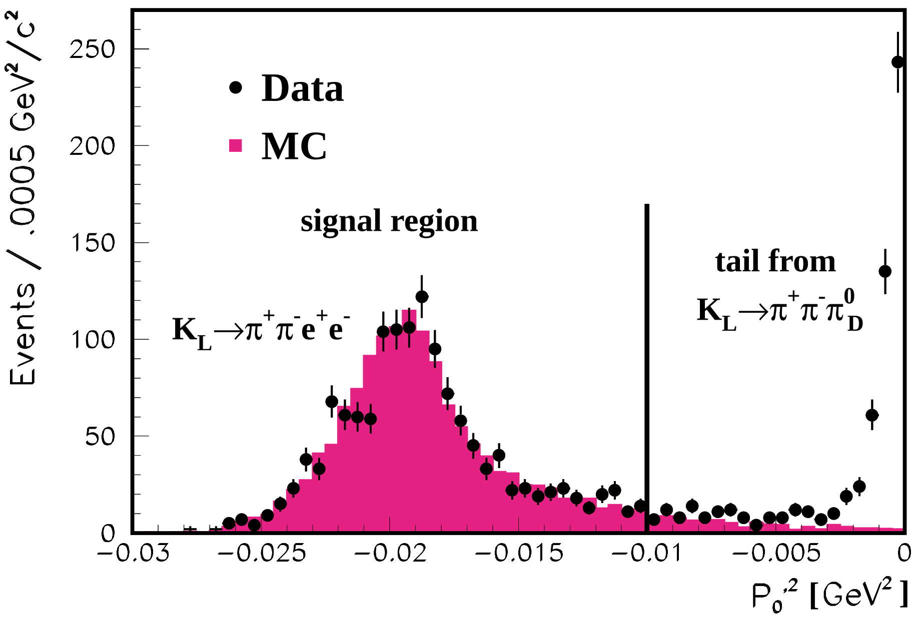
$K_L \to \pi^+\pi^- e^+ e^-$ - Results

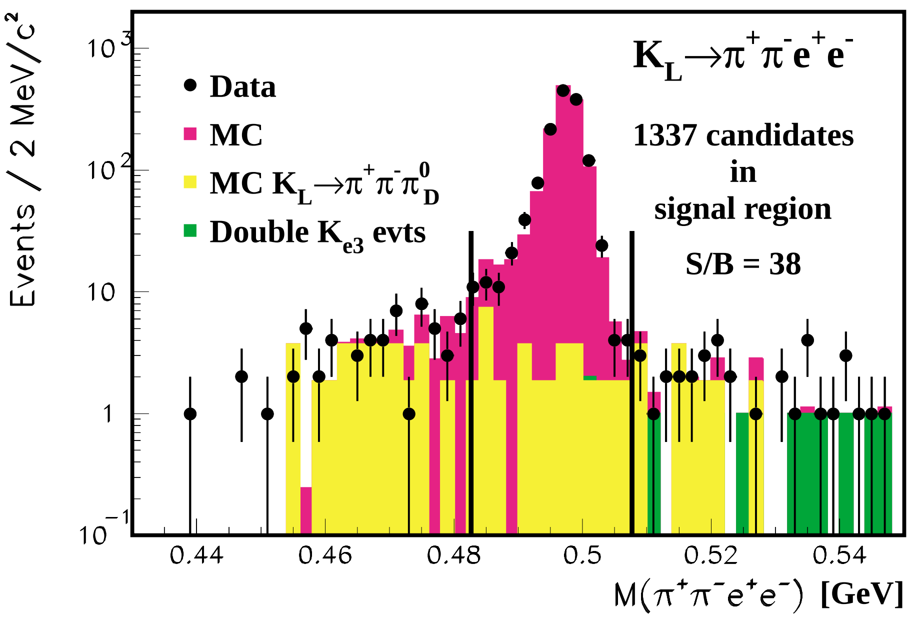
Data: 1998 and 1999

Applying the similar cuts used in K_S and additionally,

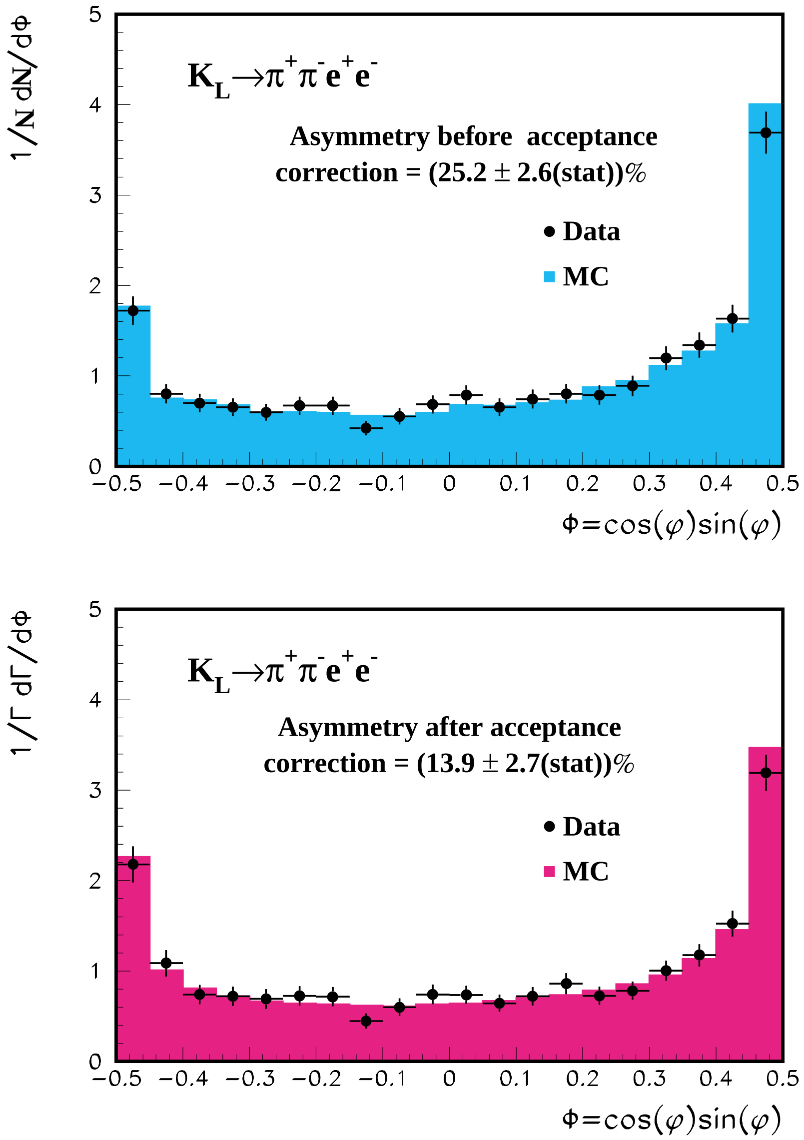
$$482.7 < m_{\pi\pi ee} < 507.7 \text{ MeV}$$

$$p_\perp^2 < 5\times10^{-4} \text{ GeV}^2 \text{ and } P_0'^2 < -0.01 \text{ GeV}^2$$





$K_L \to \pi^+\pi^-e^+e^-$ - Results cont'd



Preliminary result:

$$A^L_{\pi\pi ee} = (13.9 \pm 2.7(stat) \pm 2.0(sys))\%$$

Using $\tilde{g}_{M1} = 1.35 \pm^{0.20}_{0.17}$ and $a_1/a_2 = -0.72 \pm 0.03\,\text{GeV}^2$ measured by KTeV (Phys. Rev. Lett. 84(2000) 408)

$$BR(K_L \to \pi^+\pi^-e^+e^-) = (3.1 \pm 0.1(stat) \pm 0.2(sys)) \times 10^{-7}$$

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

Measurement of Branching ratio of $K_S \to \pi^0 e^+ e^-$ is important to improve the limit on the indirect CP violating term in $K_L \to \pi^0 e^+ e^-$

Theoretical prediction

$$BR(K_S \to \pi^0 e^+ e^-) = 5.2 \times 10^{-9} a_S^2$$

a_S : strength of the indirect CP violating component in the K_L

$$BR(K_L \to \pi^0 e^+ e^-)_{CPV} = \left[15.3 a_S^2 - 6.8 \frac{Im(\lambda_t)}{10^{-4}} a_S + 2.8 \left(\frac{Im(\lambda_t)}{10^{-4}} \right)^2 \right]$$

where $\lambda_t = V_{td} V_{ts}{}^*$

NA31 : $BR(K_S \to \pi^0 e^+ e^-) < 1.1 \times 10^{-6}$ at 90% CL

$K_S \to \pi^0 e^+ e^-$ - Data & Event Selection

Data

- 1999 K_S High Intensity data

Event Selection

- Two tracks ($e^+ e^-$) and four clusters in LKr
- Charged tracks $0.9 \le E/p < 1.1$, distance between two tracks >2 cm in DCH1
- $60 < E_{kaon} < 190$ GeV, $6 < z_v < 45$ m, center of gravity cog < 10 cm
- $|m_{\gamma\gamma} - M_{\pi^0}| < 2.5$ MeV and $|m_{ee\gamma\gamma} - M_K| < 10$ MeV
- Cluster energy in HAC < 6 GeV

for background rejection

- $K_S \to \pi^0_D \pi^0_D$ with $\pi^0_D \to e^+ e^- \gamma$ and one electron and positron in each pion lost, such events are rejected $|m_{e\gamma} - M_{\pi^0}| > 30$ MeV.
- $K_S \to \pi^0 \pi^0_D$ with $\pi^0_D \to e^+ e^- \gamma$ and lost γ, m_{ee} cannot exceed m_{π^0}.
- $K_{L,S} \to e^+ e^- \gamma\gamma$ and $K_S \to \pi^0 \pi^0_{DD}$ with $\pi^0_{DD} \to e^+ e^- e^+ e^-$ are simulated.

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

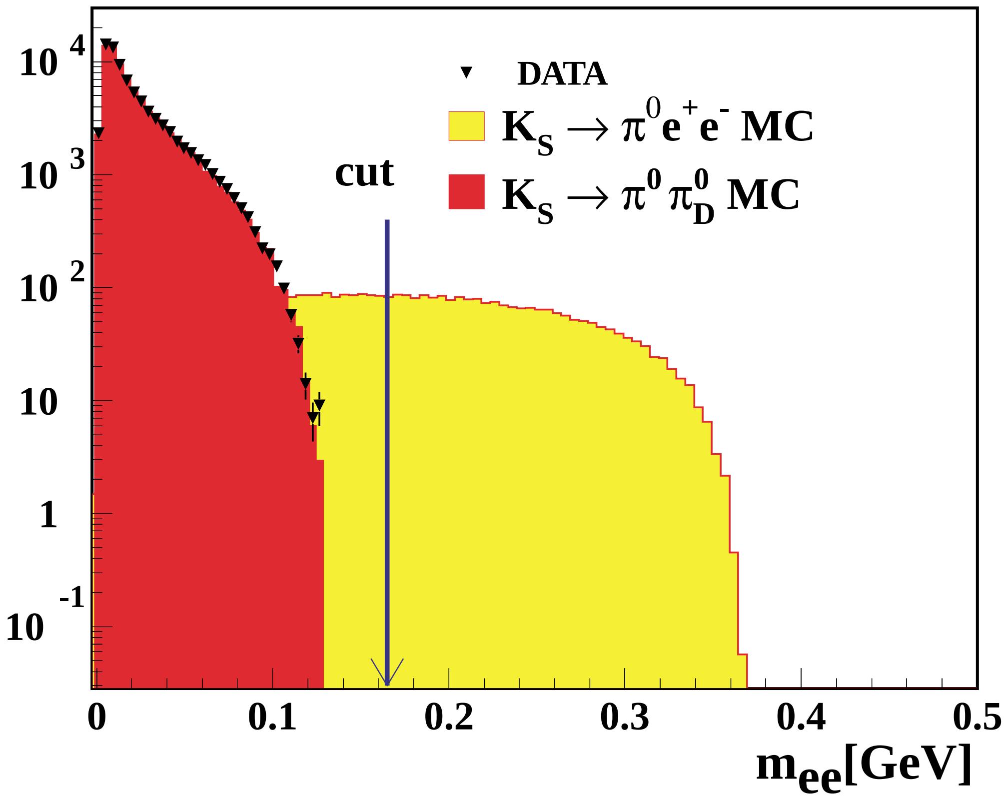
Normalization channel: $N(K_S \to \pi^0 \pi^0_D) = 79516$

The possible backgrounds: $K_S \to \pi^0 \pi^0_D$ < 0.3 events

$K_S \to \pi^0_D \pi^0_D$ < 0.03 events, $K_{L,S} \to e^+ e^- \gamma\gamma$, negligible

Trigger efficiency: 98.3% ($K_S \to \pi^0 e^+ e^-$) and 99.7% ($K_S \to \pi^0 \pi^0_D$)

Acceptance: 7.4% ($K_S \to \pi^0 e^+ e^-$), 4.2% ($K_S \to \pi^0 \pi^0_D$)



New result:
No events survive after all cuts. The upper limit on branching ratio

$$BR(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7} \quad \text{at 90\% CL}$$

Conclusions

- $K_S \to \gamma\gamma$ (published in Phys. Lett. B493(2000) 29-35)
  $$BR(K_S \to \gamma\gamma) = (2.58 \pm 0.36(stat) \pm 0.22(sys)) \times 10^{-6}$$
- $K_S \to \pi^+\pi^- e^+ e^-$
  $$BR(K_S \to \pi^+\pi^- e^+ e^-) = (4.5 \pm 0.7(stat) \pm 0.4(sys)) \times 10^{-5}$$
  based on 1998 data (published in Phys. Lett. B496 (2000) 137-144)
  $$BR(K_S \to \pi^+\pi^- e^+ e^-) = (4.3 \pm 0.2(stat) \pm 0.3(sys)) \times 10^{-5}$$
  $$A^S_{\pi\pi ee} = (-0.2 \pm 3.4(stat) \pm 1.4(sys))\%$$
  preliminary result for combined 1998 and 1999.
- $K_L \to \pi^+\pi^- e^+ e^-$ preliminary result for combined 1998 and 1999
  $$A^L_{\pi\pi ee} = (13.9 \pm 2.7(stat) \pm 2.0(sys))\%$$
  $$BR(K_L \to \pi^+\pi^- e^+ e^-) = (3.1 \pm 0.1(stat) \pm 0.2(sys)) \times 10^{-7}$$
- $K_S \to \pi^0 e^+ e^-$ (final result to be published soon)
  $BR(K_S \to \pi^0 e^+ e^-) < 1.4 \times 10^{-7}$ at 90% CL.