

First observation of
 $K_S \rightarrow \pi^0 e^+ e^-$ and $K_S \rightarrow \pi^0 \mu^+ \mu^-$
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

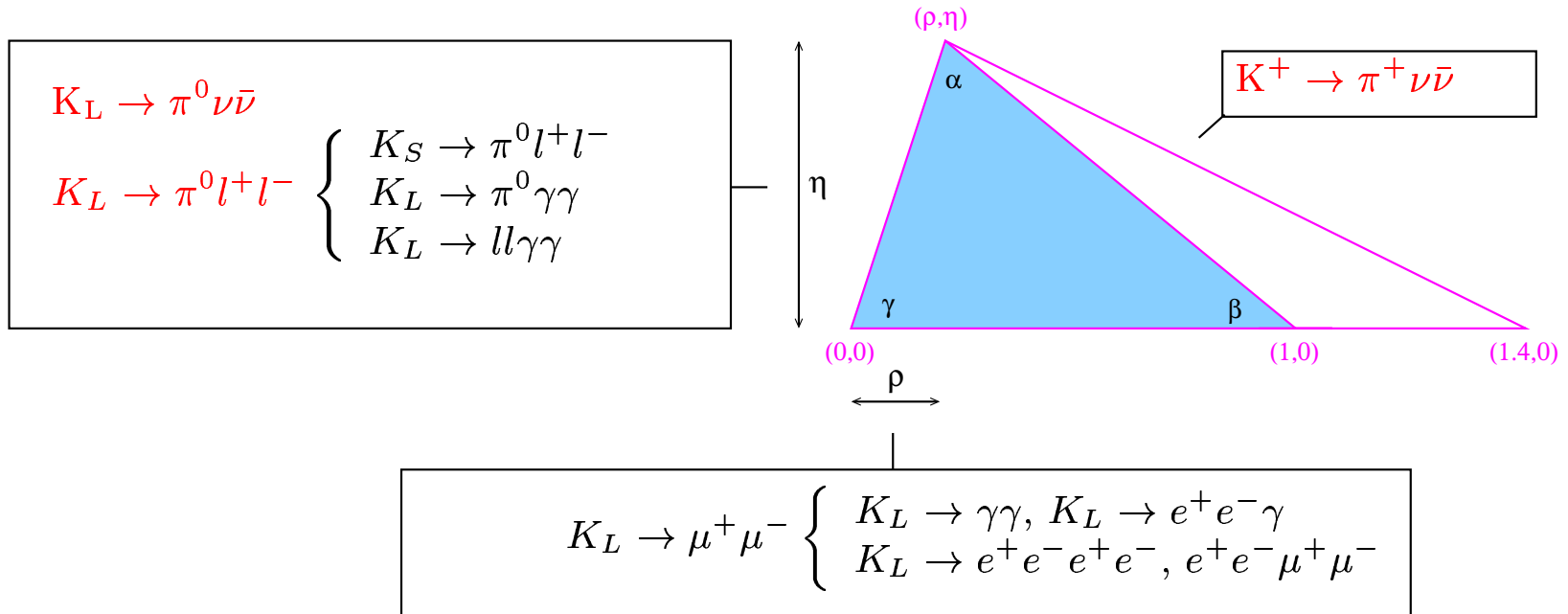
- Motivation for the measurements.
- NA48/1 beamline and detector.
- Background and event selection for $K_S \rightarrow \pi^0 e^+ e^-$.
- Background and event selection for $K_S \rightarrow \pi^0 \mu^+ \mu^-$.
- Results.
- Interpretation.

MOTIVATION.

In SM CPV is embedded as phase in CKM matrix.

Wolfenstein parametrization: A, λ, η, ρ ;

Kaon decays sensitive to ρ and $\eta \longrightarrow$ Direct CPV



- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ and $K^+ \rightarrow \pi^+ \nu \bar{\nu}$:
Theoretically very clean.
Determine the triangle.
Experimentally very challenging.
- $K_L \rightarrow \pi^0 l^+ l^-$
Not so clean theoretically.
More accessible experimentally.

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

Theoretical predictions:

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

Three amplitudes contribute to the decays:

- CP conserving

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

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

Negligible for $K_L \rightarrow \pi^0 e^+ e^-$, not for $K_L \rightarrow \pi^0 \mu^+ \mu^-$

- direct CP violating

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

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

- indirect CP violating

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

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

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 $Im(\lambda t)$ 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 $K_S \rightarrow \pi^0 l^+ l^-$

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

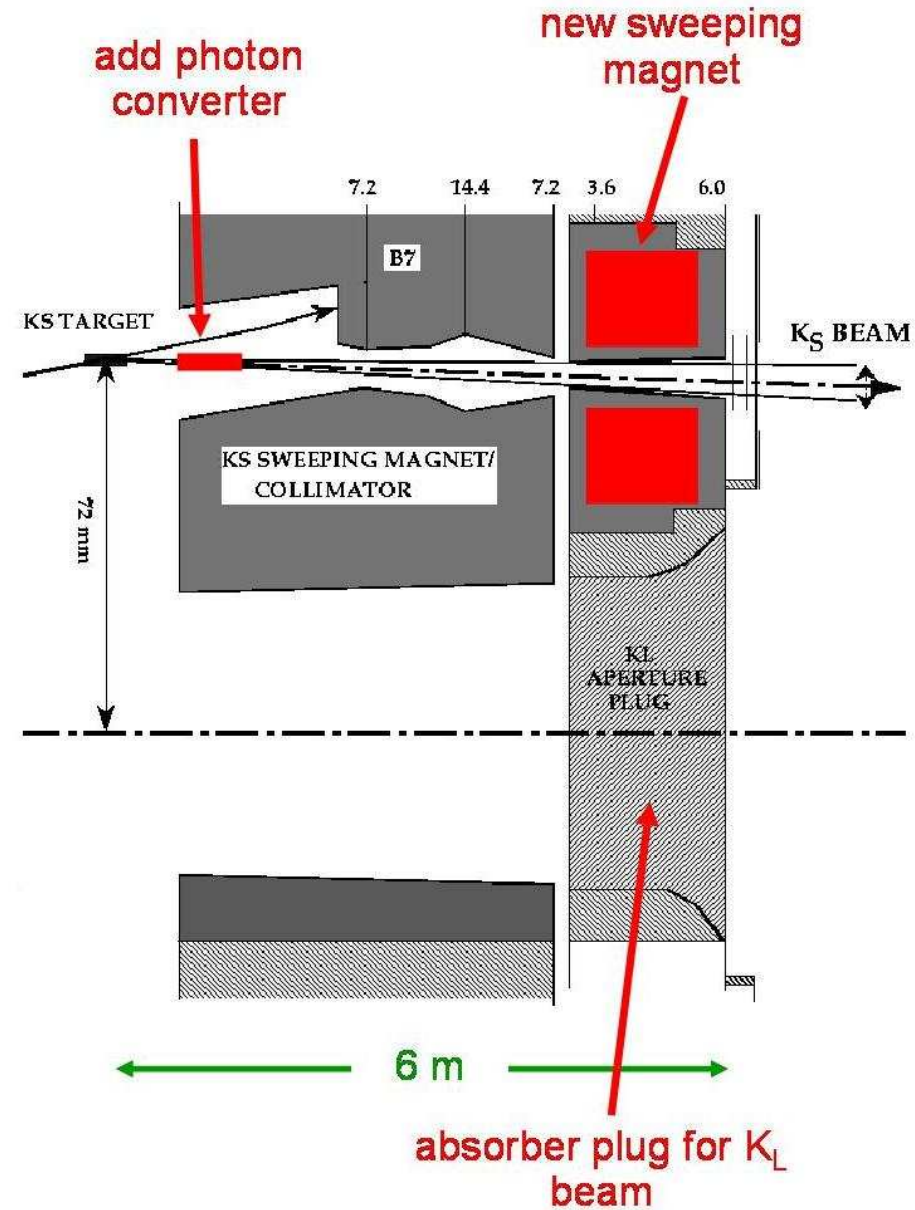
4.2 mrad production angle

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.



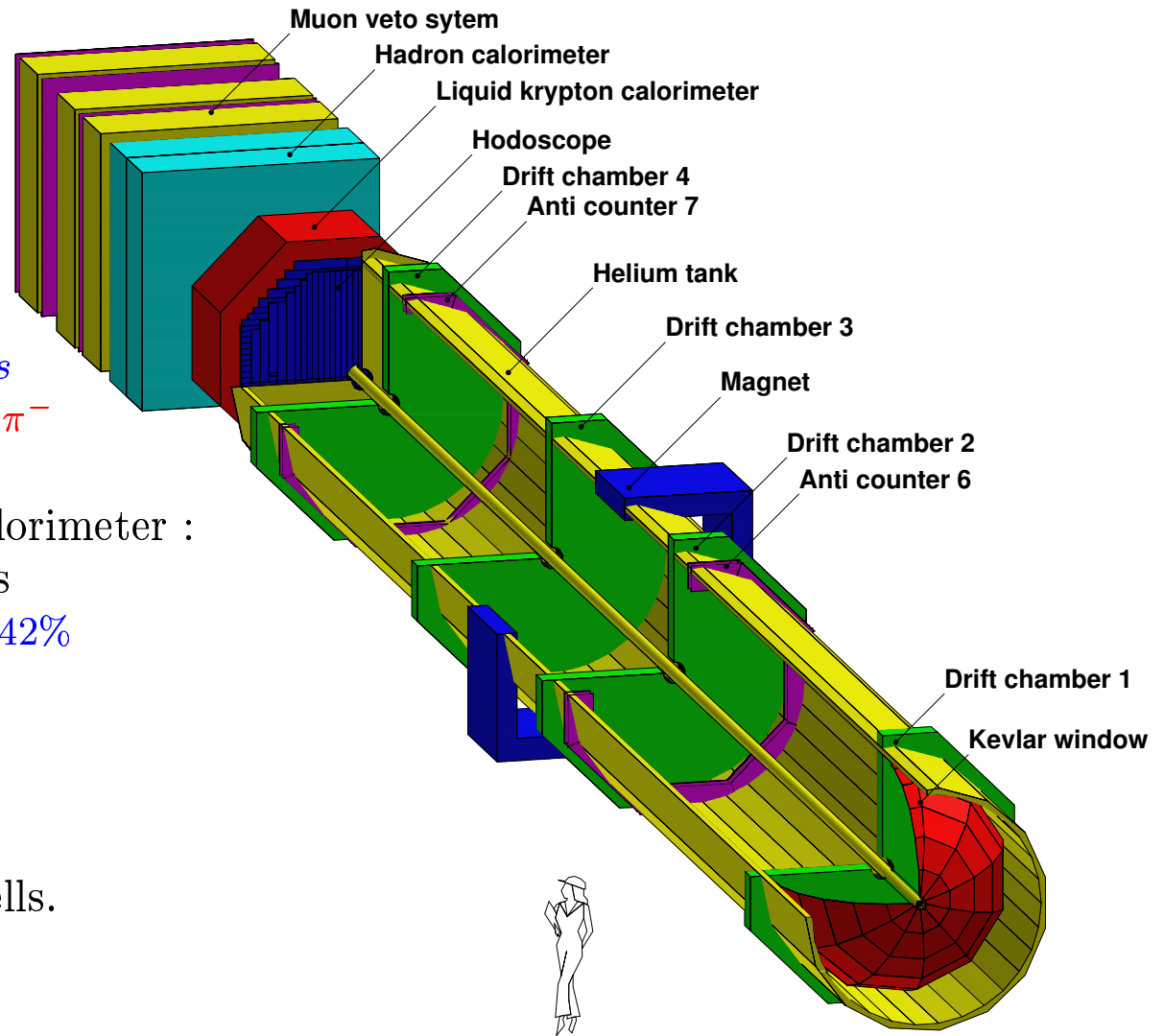
NA48 DETECTOR

- Magnetic spectrometer :
 - 3 DCH, 4 views, 2 planes/view
 - $\sigma(p)/p \simeq 0.5 \% \oplus 0.009 p[GeV/c] \%$
 - $(P_{\perp}^{kick} \sim 265MeV/c)$
 - $\sigma(t) \simeq 1.4ns.$
 - 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 cm² 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 \times 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 $K_S \rightarrow \pi^0 e^+ e^-$.

- **Trigger:** Two tracks and energy deposit on Lkr. **Eff: 99.0%**, using $\pi^0 \pi_D^0$
- 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 vertexes:

CDA-vertex and π^0 -vertex.

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

→ determine $m_{\gamma\gamma}$

Charged vertex: intersection point of tracks and kaon line of flight

→ determine $m_{ee\gamma\gamma}$

- **Control region:**

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

- **Signal region:**

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

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

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

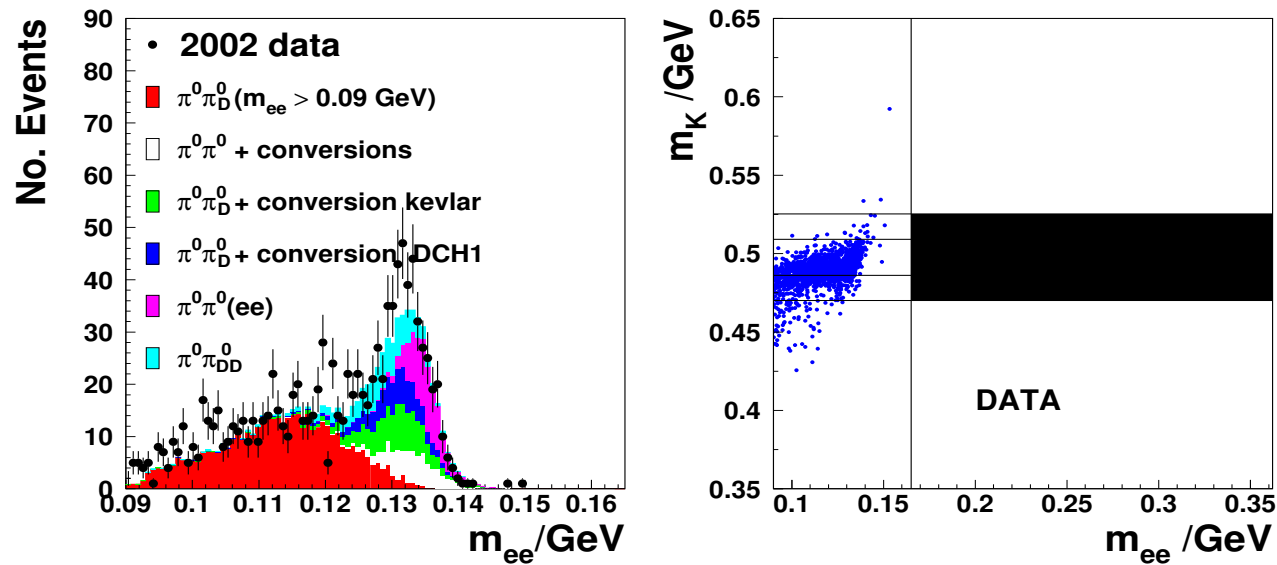
BACKGROUND SOURCES FOR $K_S \rightarrow \pi^0 e^+ e^-$: Physical background.

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

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

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

Both combinations $m_{e\gamma_1}$ and $m_{e\gamma_2}$ are less than $165 \text{ MeV}/c^2$

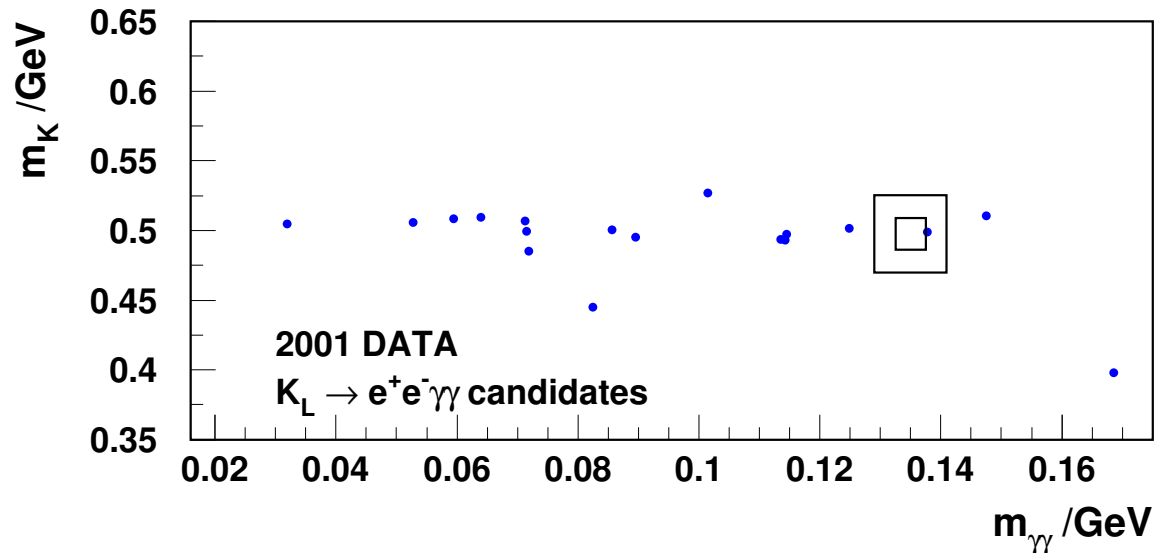


- Limit given by MC $\rightarrow < 0.01$ events expect. on signal region.
- Good check possible with same sign events.

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

2. $K_L \rightarrow e^+ e^- \gamma \gamma$ 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 $K_S \rightarrow \pi^0 e^+ e^-$: Accidental background.

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

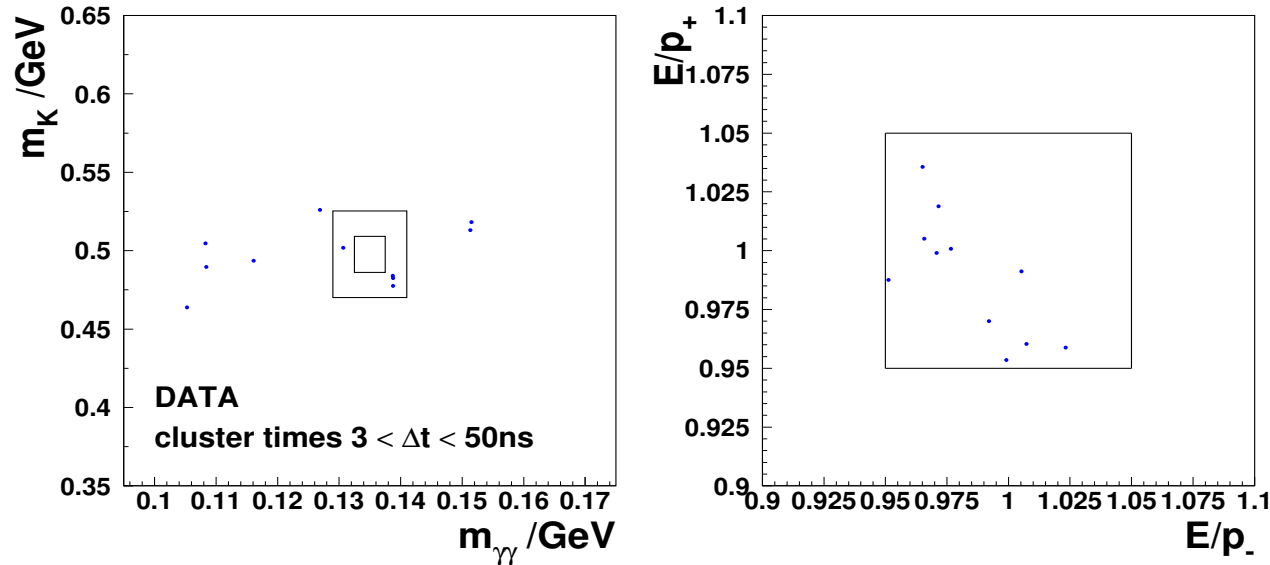
$$p_1 + Be \rightarrow K_S + X \text{ and } p_2 + Be \rightarrow K_L + X$$

$$K_S \rightarrow \pi^0 \pi^0 \text{ and } K_L \rightarrow \pi^\pm e^\pm \nu$$

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

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

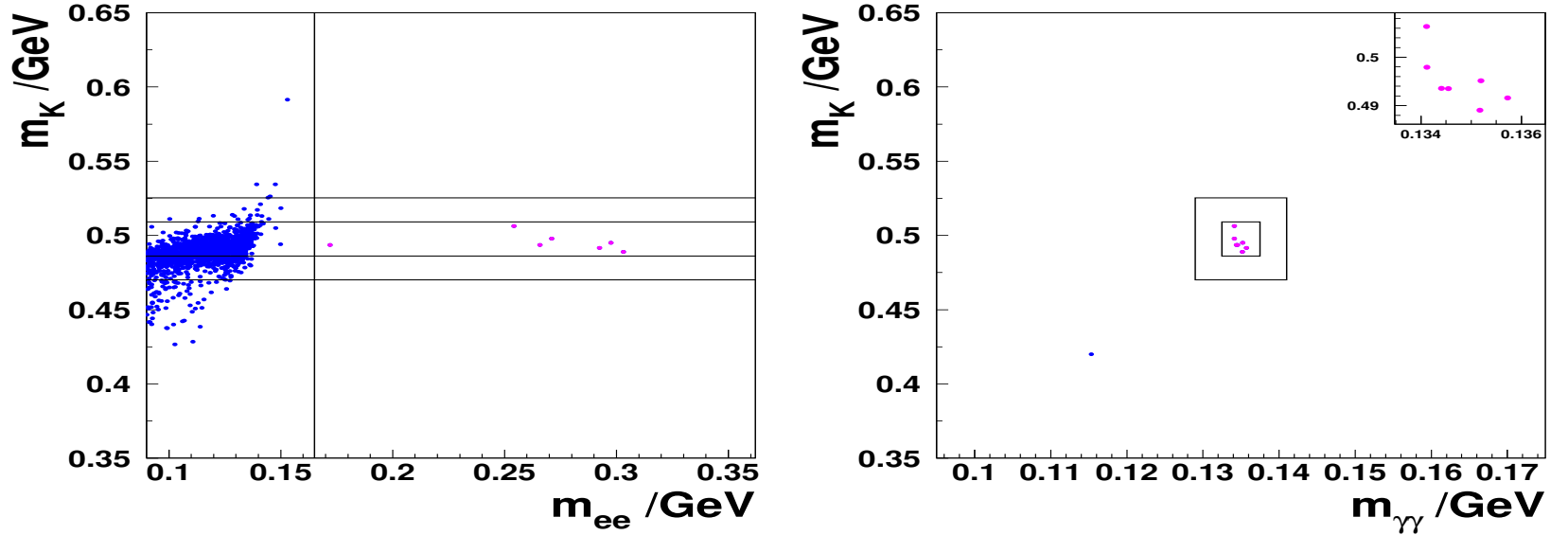
Signal region: $|\text{LKR time of } \gamma\gamma\text{-track time}| < 3 \text{ ns}$



Extrapolate from out-of-time control region to out-time signal region with Toy MC.
 Linear extrapolation to in-time signal region $\rightarrow 0.07_{-0.03}^{+0.07}$ 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 \rightarrow **7 events found.**



- Using flux from $K_S \rightarrow \pi^0 \pi_D^0$ and computing model independent acceptance:

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

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

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

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:**

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

- **Signal region:**

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

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

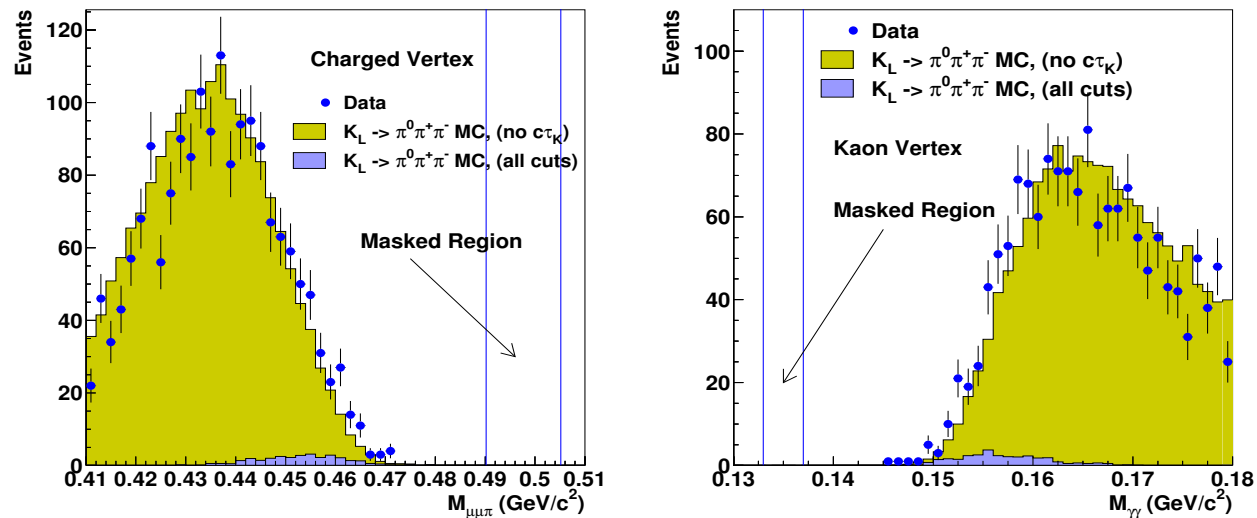
- Fid volume: $60 \text{ GeV} < E_{kaon} < 200 \text{ GeV}$ and $0 < c\tau_{K_S} < 3.0$

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 \rightarrow **<0.018 events expected on signal region.**



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

Expectation given by MC \rightarrow **$0.04_{-0.03}^{+0.04}$ events expected.**

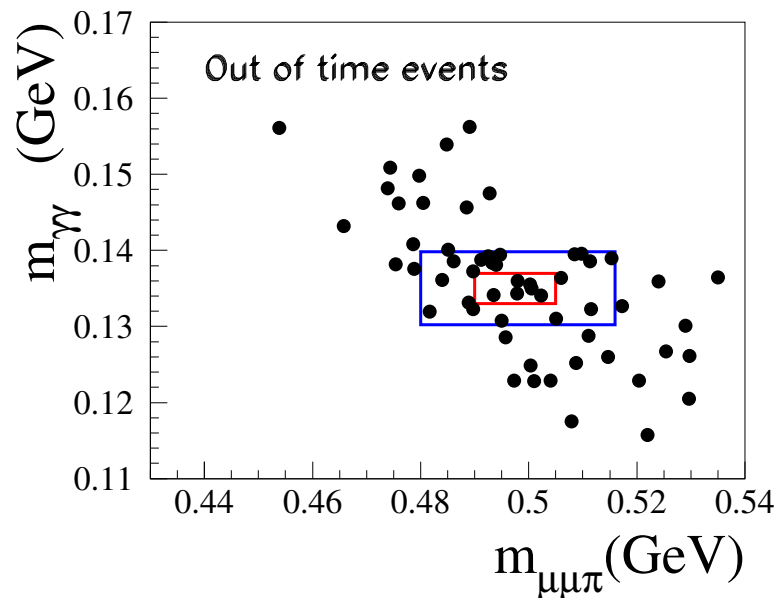
BACKGROUND SOURCES FOR $K_S \rightarrow \pi^0 \mu^+ \mu^-$: Accidental background

- 3. Two significant sources:

$$\begin{aligned} &K_S \rightarrow \pi^0 \pi^0 \text{ and } K_S \rightarrow \pi^+ \pi^- \\ &K_S \rightarrow \pi^0 \pi^0 \text{ and } K_L \rightarrow \pi^\pm \mu^\pm \nu \\ &\text{with } \pi \text{ DIF or mis-identified.} \end{aligned}$$

Control region: $-115 \text{ ns} < \Delta t < -3 \text{ ns}$ and $3 \text{ ns} < \Delta t < 60 \text{ ns}$

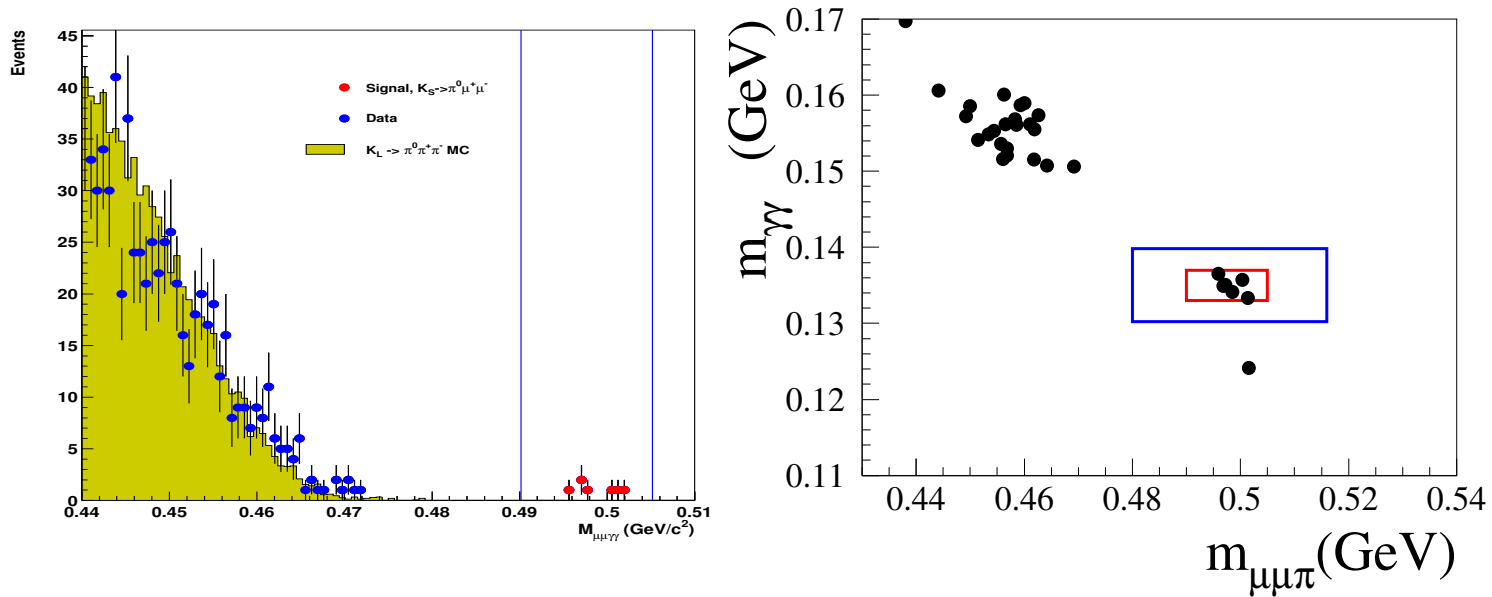
Signal region: $-1.5 \text{ ns} < \Delta t < 1.5 \text{ ns}$



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

RESULT

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



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

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

SUMMARY OF THE RESULTS.

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

- 7 events found in signal region.

- Background:

$$K_S \rightarrow \pi_{Dalitz}^0 \pi_{Dalitz}^0 < 0.01$$

$$K_L \rightarrow e^+ e^- \gamma \gamma \quad 0.08^{+0.03}_{-0.02}$$

$$\text{Accidentals} \quad 0.07^{+0.07}_{-0.03}$$

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

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

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

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

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

- 6 events found in signal region.

- Background:

$$K_L \rightarrow \pi^0 \pi^+ \pi^- \quad 0^{+0.02}_{-0.00}$$

$$K_L \rightarrow \mu^+ \mu^- \gamma \gamma \quad 0.04^{+0.04}_{-0.03}$$

$$\text{Accidentals:} \quad 0.18^{+0.18}_{-0.11}$$

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

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

INTERPRETATION.

- Branching ratio predictions from χ PT.

$$BR(K_S \rightarrow \pi^0 e^+ e^-) = [0.01 - 0.76a_s - 0.21b_s + 46.5a_s^2 + 12.9a_s b_s + 1.44b_s^2] \times 10^{-10}$$

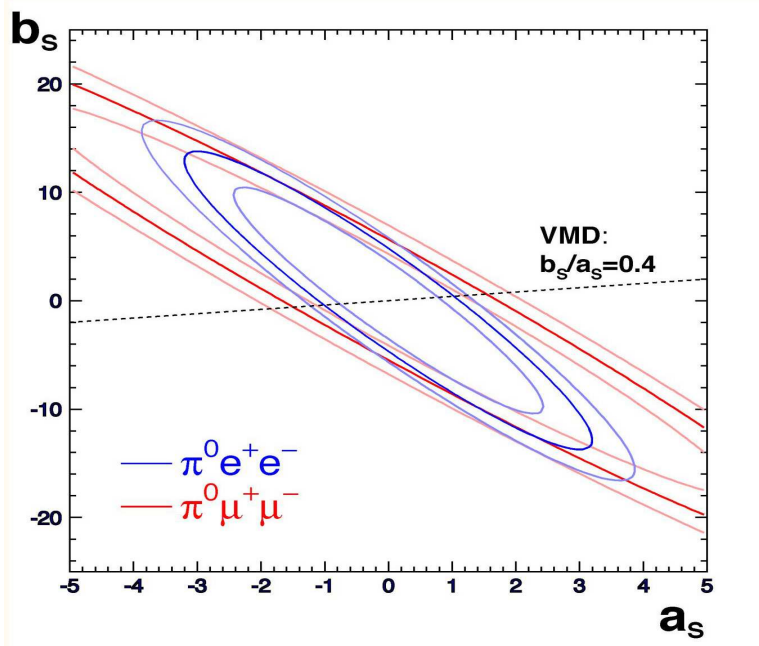
$$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-) = [0.07 - 4.52a_s - 1.50b_s + 98.7a_s^2 + 57.7a_s b_s + 8.95b_s^2] \times 10^{-11}$$

- Assuming VMD $|a_s|$ can be extracted from both channels independently.

$$BR(K_S \rightarrow \pi^0 e^+ e^-) \simeq 5.2 \times 10^{-9} a_s^2 \longrightarrow |a_s|_{\pi^0 ee} = 1.06_{-0.21}^{+0.26} \pm 0.07$$

$$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-) \simeq 1.2 \times 10^{-9} a_s^2 \longrightarrow |a_s|_{\pi^0 \mu\mu} = 1.53_{-0.32}^{+0.38} \pm 0.05$$

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 VMD.
- Both results combined in log-likelihood fit:

$$a_s = -1.6_{-1.8}^{+2.1} \quad b_s = 10.7_{-7.7}^{+5.4}$$

$$a_s = 1.8_{-2.4}^{+1.6} \quad b_s = -11.2_{-4.5}^{+8.8}$$

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

From the measurement of $K_S \rightarrow \pi^0 l^+ l^-$, taking $\text{Im}(\lambda_t)$ world average

$$\text{Im}(\lambda_t) = (1.36 \pm 0.12) \times 10^{-4}$$

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

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

