First observation of
\[ K_S \rightarrow \pi^0 e^+ e^- \text{ and } K_S \rightarrow \pi^0 \mu^+ \mu^- \]
at NA48/1.

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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: $\Lambda, \lambda, \eta, \rho$;
Kaon decays sensitive to $\rho$ and $\eta \rightarrow$ Direct CPV

\[ K_L \rightarrow \pi^0 \nu \bar{\nu} \]
\[ K_L \rightarrow \pi^0 l^+ l^- \]
\[ K_S \rightarrow \pi^0 l^+ l^- \]
\[ K_L \rightarrow \pi^0 \gamma \gamma \]
\[ K_L \rightarrow l l \gamma \gamma \]

- $K_L \rightarrow \pi^0 \nu \bar{\nu}$ 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.

\[ (\rho, \eta) \]
\[ (0,0) \quad (1.4,0) \]
\[ (1,0) \]

\[ \gamma \]
\[ \beta \]

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]
\[ K_L \rightarrow \pi^0 l^+ l^- \]

Theoretical predictions:

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

Three amplitudes contribute to the decays:

- **CP conserving**
  
  NA48 measurement \( BR(K_L \rightarrow \pi^0 \gamma \gamma) \):

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

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

- **direct CP violating**
  
  Proportional to \( \eta \) or \( \Im(\lambda_t) \)

  \[ \Im(\lambda_t) = \eta A^2 \lambda^5 \quad \lambda_t = V_{ts}^* V_{td} \]

- **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 $\eta$ 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: $m_{\gamma\gamma l^+ l^-} \text{ vs. } m_{\gamma\gamma}$

- 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.
CERN SPS. NA48 beamline modified: $K_S$ target only.

$5 \times 10^{10}$ protons per cycle (4.8 s/16 s)

400 GeV/c protons on 40cm Beryllium target

4.2 mrad production angle

Pt photon converter followed by sweeping magnet

90m vacuum tank.

$\sim 2.5 \times 10^5 K_S / \text{burst}$

Integrated: $\sim 4 \times 10^{10} K_S$ decays in fiducial volume.
NA48 DETECTOR

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

- Charged hodoscope: \( \sigma(t) \simeq 200\text{ps} \)
  \( \sigma(M_{\pi^+\pi^-}) \simeq 3\text{MeV} \) from \( K_S \rightarrow \pi^+\pi^- \)

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

- Muon counters:
  2+1 planes \((X,Y)\) \(25\text{cm} \times 25\text{cm} \) cells.
  \( \sigma(t) \simeq 350\text{ps} \)

- Upgraded R/O for DCH and LKR allows 50K evts/burst.
  Active Level 3: reduct fact \( \simeq 3 \), 50 TB recorded.
SELECTIVE 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 vertices:**
  - **CDA-vertex** and **$\pi^0$-vertex**.
  - **Neutral vertex:** imposing $m_{ee\gamma\gamma} = m_k$
    $\rightarrow$ determine $m_{\gamma\gamma}$
  - **Charged vertex:** intersection point of tracks and kaon line of flight
    $\rightarrow$ 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 $\pi^0 \pi_D^0$ 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.
   - $K_S \to \pi^0 \pi^0_{Dalitz} \to \gamma \gamma e^+ e^-$ with lost $\gamma$
   - $K_S \to \pi^0_{Dalitz} \pi^0_{Dalitz} \to e^+ e^- e^+ e^-$ with lost $e^+ e^-$
   - Event rejected if:
     \[ m_{e^+e^-} > 0.165 \text{MeV}/c^2 = m_{\pi^0} + 30 \text{MeV} \left( \simeq 8\sigma(m_{ee}) \right) \]
     Both combinations $m_{e\gamma_1}$ and $m_{e\gamma_2}$ are less than $165 \text{MeV}/c^2$

   ![Graph](image)

   - 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.
- Suppressed 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 $\rightarrow 0.08^{+0.03}_{-0.02}$ 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 $\pi^0$ is lost and the $\pi$ 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 $\rightarrow 0.07^{+0.07}_{-0.03} \text{ events expected.}$
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 $K_S \rightarrow \pi^0\pi^0_D$ and computing model independent acceptance:

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

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

- 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 $\sigma_{m_{\mu\mu\gamma\gamma}} = 3 \text{ MeV}/c^2$ $\sigma_{m_{\gamma\gamma}} = 0.8 \text{ MeV}/c^2$, 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 $\rightarrow 0.04^{+0.04}_{-0.03}$ events expected.
BACKGROUND SOURCES FOR $K_S \rightarrow \pi^0 \mu^+ \mu^-$: Accidental background

- 3. Two significant sources:

  \[ K_S \rightarrow \pi^0 \pi^0 \text{ and } K_S \rightarrow \pi^+ \pi^- \]
  \[ K_S \rightarrow \pi^0 \pi^0 \text{ and } K_L \rightarrow \pi^\pm \mu^\mp \nu \]

  with $\pi$ DIF or mis-identified.

  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 $\rightarrow 0.18^{+0.18}_{-0.11}$ events expected.
RESULT

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

- Using flux from $K_S \rightarrow \pi^+ \pi^-$ corrected by acceptance and trigger efficiency:
  $$BR(K_S \rightarrow \pi^0 \mu^+ \mu^-) = (2.8^{+1.5}_{-1.2}(stat) \pm 0.2(syst)) \times 10^{-9}$$
SUMMARY OF THE RESULTS.

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

- 7 events found in signal region.
- Background:
  - $K_S \rightarrow \pi^0_{Dalitz} \pi^0_{Dalitz} < 0.01$
  - $K_L \rightarrow e^+ e^- \gamma \gamma \quad 0.08^{+0.03}_{-0.02}$
  - Accidentals \quad 0.07^{+0.07}_{-0.03}
- Total background \quad 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 0.02^{+0.02}_{-0.00}
  - $K_L \rightarrow \mu^+ \mu^- \gamma \gamma \quad 0.04^{+0.04}_{-0.03}$
  - Accidentals: \quad 0.18^{+0.18}_{-0.11}
- Total background: \quad 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 $\chi$PT.
  \[
  BR(K_S \to \pi^0 e^+ e^-) = [0.01 - 0.76a_s - 0.21b_s + 46.5a_s^2 + 12.9a_s b_s + 1.44b_s^2] \times 10^{-10}
  \]
  \[
  BR(K_S \to \pi^0 \mu^+ \mu^-) = [0.07 - 4.52a_s - 1.50b_s + 98.7a_s^2 + 57.7a_s b_s + 8.95b_s^2] \times 10^{-11}
  \]

- Assuming VMD $|a_s|$ can be extracted from both channels independently.
  \[
  BR(K_S \to \pi^0 e^+ e^-) \approx 5.2 \times 10^{-9}a_s^2 \rightarrow |a_s|_{\pi^0 e^+ e^-} = 1.06^{+0.26}_{-0.21} \pm 0.07
  \]
  \[
  BR(K_S \to \pi^0 \mu^+ \mu^-) \approx 1.2 \times 10^{-9}a_s^2 \rightarrow |a_s|_{\pi^0 \mu^+ \mu^-} = 1.53^{+0.38}_{-0.32} \pm 0.05
  \]
  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:
  \[
  a_s = -1.6^{+2.1}_{-1.8} \quad b_s = 10.7^{+5.4}_{-7.7}
  \]
  \[
  a_s = 1.8^{+1.6}_{-2.4} \quad b_s = -11.2^{+8.8}_{-4.5}
  \]
IMPLICATIONS FOR $K_L \to \pi^0 l^+ l^-$. 

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

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

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

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