Towards results on direct CP violation in Kaon decays from the CERN-SPS experiment NA48

Augusto Ceccucci *

CERN CH-1211, Genève 23

*On behalf of the NA48 Collaboration: Cagliari, Cambridge, CERN, Dubna, Edinburgh, Ferrara, Firenze, Mainz, Orsay, Perugia, Pisa, Saclay, Siegen, Torino, Vienna and Warsaw.

Abstract. The NA48 experiment aims to measure the direct CP violation parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$ using the method of the double ratio with a precision of 2×10^{-4}. The experiment has collected data during 1997 and during 1998 and plans to produce a result based on the 1997 statistics soon. The status of the analysis and the perspectives for the future are outlined in this paper.

INTRODUCTION

The NA48 experiment [1] aims to measure the direct CP violation in the decay of neutral kaons into two pions. Defining the usual amplitude parameters [2]:

$$\frac{<\pi^+\pi^-|\mathrm{K_L}>}{<\pi^+\pi^-|\mathrm{K_S}>} = \eta_{+-} \sim \varepsilon + \varepsilon', \qquad \frac{<\pi^0\pi^0|\mathrm{K_L}>}{<\pi^0\pi^0|\mathrm{K_S}>} = \eta_{00} \sim \varepsilon - 2\varepsilon' \tag{1}$$

one gets the following double ratio expression for the direct CP violating parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$:

$$\mathrm{Re}(\varepsilon'/\varepsilon) \sim \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2\right) = \frac{1}{6}\left\{1 - \frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0)}{\Gamma(\mathrm{K_S} \to \pi^0\pi^0)} \Big/ \frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K_S} \to \pi^+\pi^-)}\right\}. \tag{2}$$

A non zero value of $\mathrm{Re}(\varepsilon'/\varepsilon)$ signals CP violation in a decay amplitude. Using the technique of the double ratio, NA48 plans to achieve a total error of 2×10^{-4} on $\mathrm{Re}(\varepsilon'/\varepsilon)$. Precision measurements available so far come from the CERN-NA31 Collaboration [3] which reported $\mathrm{Re}(\varepsilon'/\varepsilon) = (2.0 \pm 0.7) \times 10^{-3}$, a 3σ effect, and from the FNAL-E731 Collaboration which on the other hand [4] found, with comparable precision, a result compatible with no direct CP violation: $\mathrm{Re}(\varepsilon'/\varepsilon) = (7.4 \pm 5.9) \times 10^{-4}$. NA48 collects the four decay modes concurrently, in the same detector and from the same decay region. To achieve the required statistical precision we have to collect a few million $\mathrm{K_L} \rightarrow 2\pi^0$ decays. With a $BR(\mathrm{K_L} \rightarrow \pi^0\pi^0) = (9.36 \pm 0.20) \times 10^{-4}$ this is the statistical limitation of the experiment.

THE $\mathrm{K_L}$ AND $\mathrm{K_S}$ BEAMS

Clean, intense neutral kaon beams are necessary to accumulate the required statistics [5]. The main parameters for the two beams are reported in Table 1. An intense proton beam of 1.5×10^{12} protons per pulse (ppp) strikes a one interaction length Be target. A neutral beam is selected by collimation with a production angle of 2.4 mrad. A small fraction of the non-interacting protons are turned away from the dump by means of channelling in a bent silicon crystal [6]. These protons are steered on the $\mathrm{K_L}$ beam axis and aimed to a second target $\sim$ 120 m downstream. By then the $\mathrm{K_S}$ component of the long neutral beam has decayed. The second neutral beam is selected with a production angle of 4.2 mrad. At the centre of the $\mathrm{K_S}$ target the two beams are vertically separated by 72 mm. The 0.6 mrad angle between the two beams allows them to converge at the detector. The $\mathrm{K_S}$ is identified by the time coincidence between the detectors and the tagging counter placed on the proton beam upstream of the $\mathrm{K_S}$ target. Two pions decays from the short beam come mostly from $\mathrm{K_S}$ decays. The $\mathrm{K_L}$ contamination in one $\mathrm{K_S}$ lifetime is in fact suppressed by a factor $\Gamma(\mathrm{K_L} \rightarrow 2\pi)/\Gamma(\mathrm{K_S} \rightarrow 2\pi) \sim 5 \times 10^{-6}$. The choice of the targeting angle and the distance between the $\mathrm{K_S}$ target and the final collimator contribute to make the momentum spectra of the accepted $\mathrm{K_S}$ and $\mathrm{K_L}$ quite similar.

THE DETECTORS

Charged decays are reconstructed by a magnetic spectrometer formed by four large drift chambers [7] and by a dipole magnet which provides a p_{T} kick of 250 MeV/c. A plastic scintillator hodoscope is used to provide the charged first level trigger and the charged event time. A hadronic calorimeter made of Fe and plastic scintillator sandwiches is used as part of the charged first level trigger. Three large plastic scintillation planes separated from each other by about 0.8 m of iron are used to reject $\mathrm{K}_{\mu3}$ decays.

Neutral decays are reconstructed by means of a liquid krypton electro-magnetic calorimeter [8]. This is formed by 13212 squared towers of ~ 4 cm^2 cross section. The geometry of the calorimeter points to the centre of the $\mathrm{K_L}$, $\mathrm{K_S}$ decay region $\sim$ 110 m upstream. The calorimeter is read out by FADCs at 40 MHz sampling frequency [9]. The energy resolution of the calorimeter is better than 1 % for photons above 20 GeV. The position resolution is better than 1 mm and the time resolution for a single photon is of the order of 200 ps [10]. A scintillating fibre

TABLE 1. Characteristics of the K_L and K_S beams

Beam Parameter	K_L	K_S
Primary protons per pulse on target	1.5×10^{12}	3×10^{7}
Proton Momentum, p_0 (GeV/c)	450	450
Production angle of K^0 beam (mrad)	2.4	4.2
Length of K^0 beam:		
target to final collimator/AKS (m)	126.00	6.07
target to front of e.m. calorimeter (m)	241.10	121.10
Angle of convergence of beam (mrad)	0.0	-0.6
Angular acceptance of beam (mrad)	± 0.15	± 0.375
R.M.S. radius at e.m. calorimeter (mm)	~ 26	~ 39
K^0 flux per pulse at exit final coll.	$\sim 2 \times 10^{7}$	$\sim 2 \times 10^{2}$
decays between collimators and detector	$\sim 1.4 \times 10^{6}$	$\sim 2 \times 10^{2}$
K^0 flux per pulse in useful p_K range 70 170 GeV/c	6.4×10^{6}	1.5×10^{2}
decay per pulse		
($70 < p_K < 170$ GeV/c and $c\tau < 4\lambda_S$)	4.4×10^{4}	1.5×10^{2}
decay per pulse to $\pi^0\pi^0$		
($70 < p_K < 170$ GeV/c and $c\tau < 4\lambda_S$)	40	45
Detector acceptance for $\pi^0\pi^0$ decays	~ 0.20	~ 0.20
Useful $K^0 \to \pi^0\pi^0$ per pulse	~ 8	~ 9

hodoscope is inserted in the LKr structure at approximately the shower maximum depth. This device provides a down-scaled trigger to measure the efficiency of the main $\pi^0\pi^0$ trigger. In addition it provides a cross-check for the time reconstruction of the calorimeter to tag the $K_S \to \pi^0\pi^0$ events.

TRIGGER AND DAQ

The experiment runs in a high rate K_L decay environment. Only one in a thousand of the decayed K_L represents an interesting CP violating decay. In order to measure the trigger efficiency, down-scaled trigger with relaxed criteria are logged.

A charged level one trigger is issued when hits in opposite quadrants of the charged hodoscope are found in coincidence with a large energy deposit in the calorimeters ($E_{TOT} > 30$ GeV). The second level trigger is a hardware based coordinate builder using data from the first, second and fourth drift chamber followed by a microprocessor based system [11]. Data from the first two chambers are used to reconstruct the position of the decay vertex. Events with an opening angle greater than 15 mrad are rejected. Data from the fourth chamber, placed downstream of the dipole magnet, is used to calculate the momentum of the tracks and the invariant mass of the two pairs in the hypotheses of a $\pi^+\pi^-$ decay. Events with $c\tau$ shorter than 4.5 K_S lifetimes and with an invariant mass larger than 472 MeV/c^2 are kept.

The 40 MHz pipelined neutral trigger [12] sums the energy deposits in the electromagnetic calorimeter in X and Y projections of 2 cm width. The trigger criteria require the total energy for a decay (E_K) to be larger than 50 GeV, the centre of gravity (COG) to be less than 15 cm and $c\tau$ to be shorter than 4.5 $\mathrm{K_S}$ lifetimes (5.5 during the 1997 run). To further reduce the $3\pi^0$ background the number of on time energy peaks found in each of the two projections must be smaller than six (seven for the X projection during the 1997 run).

The NA48 DAQ system is described elsewhere [14]. During the 1998 run a PC farm was used as event builder [15].

STATISTICS COLLECTED SO FAR

During the 1997 run 650,000 $\mathrm{K_L} \rightarrow \pi^0\pi^0$ events were collected over four $\mathrm{K_S}$ lifetimes in the momentum range between 70 and 170 GeV/c. The statistical precision on $\mathrm{Re}(\varepsilon'/\varepsilon)$ from this data sample is expected to be $4 \div 5 \times 10^{-4}$. This makes a preliminary result based on the 1997 data competitive with respect to the already published values. A second physics run took place in 1998. During this run in excess of two million $\mathrm{K_L} \rightarrow \pi^0\pi^0$ were collected over a decay region of 3.5 $\mathrm{K_S}$ lifetimes. A new run will begin in May 1999 and should yield an amount of decays comparable to the 1998 statistics. An option for $\mathrm{Re}(\varepsilon'/\varepsilon)$ running during the year 2000 is available.

SYSTEMATIC ERRORS

Most of the potential sources of errors cancel out in the double ratio. However to reach the required high precision the careful design of the experiment is essential. In addition, great care is placed to control the tagging errors, the $\mathrm{K_L}$ background subtraction, the relative (charged versus neutral) momentum/distance and lateral scales, and the accidental correction. In the next subsections the most relevant aspects of the $\mathrm{Re}(\varepsilon'/\varepsilon)$ analysis are outlined, highlighting the key features of the experiment to keep the systematic error small.

Tagging

A $\mathrm{K_S}$ is identified by the time coincidence between the tagging counter [13] and the detectors. For a $\pi^0\pi^0$ decay the quantity $\Delta t = t_{\mathrm{LKr}} - t_{\mathrm{TAG}}$ is defined. For a $\pi^+\pi^-$ event the charged hodoscope instead of the calorimeter is used: $\Delta t = t_{\mathrm{HOD}} - t_{\mathrm{TAG}}$. In the above t_{TAG} is the time of the nearest proton in the tagging counter with respect to the event time. A $\mathrm{K_S}$ is defined by the relation: $|\Delta t| \leq 2$ ns. Tagging inefficiencies are a few 10^{-4}. For charged decays they are measured directly distinguishing $\mathrm{K_S}$ and $\mathrm{K_L}$ by the vertical position of the decay vertex. For the neutral events checks using $\mathrm{K_S} \rightarrow \pi^0 e^+ e^- \gamma$ events and $\mathrm{K_S}$ *only* runs are made. Only an uncontrolled inefficiency due to the detectors can create an artificial $\mathrm{Re}(\varepsilon'/\varepsilon)$ different from zero. An inefficiency in the tagging counter itself is not harmful since the tagging counter does not know if the $\mathrm{K_S}$ will decay in a charged or in a neutral final state. If $|\Delta\ t\ |\ >\ 2$ ns the event is defined to be a $\mathrm{K_L}$ decay. Accidental activity in the tagging counter causes $\mathrm{K_L} \rightarrow \mathrm{K_S}$ migration which dilutes $\mathrm{Re}(\varepsilon'/\varepsilon)$. The dilution ($\sim$ 11.5 %) is precisely measured selecting $\mathrm{K_S}$ charged decays by the vertex vertical position.

Background subtractions

Semileptonic $\mathrm{K}_{\mu 3}$ and $\mathrm{K_{e3}}$ are respectively ~ 131 and ~ 188 times more frequent than $\mathrm{K_L} \rightarrow \pi^+\pi^-$ decays. The background under the signal region has to be kept to a few per mill. Selected samples of $\mathrm{K_S}$, $\mathrm{K_{e3}}$ and $\mathrm{K}_{\mu 3}$ are used to fit the $\mathrm{K_L}$ distributions. The background extrapolated underneath the $\mathrm{K_L} \rightarrow \pi^+\pi^-$ peak is $\sim\ 3\ \times\ 10^{-3}$ with a statistical error ten times smaller. Figure 2 shows the p_{T}^2 distribution for $\mathrm{K_L} \rightarrow \pi^+\pi^-$ events together with the distributions for signed $\mathrm{K}_{\mu 3}$ and $\mathrm{K_{e3}}$. Also the sum of the two backgrounds is shown. The background curve with the steeper p_{T}^2 dependence is the the $\mathrm{K}_{\mu 3}$ component.

$\mathrm{K_L} \rightarrow 3\pi^0$ decay mode is ~ 221 times more frequent than $\pi^0\pi^0$ and can mimic it if two photons are missed. The kaon mass is used as constraint to calculate the neutral decay vertex. Photons are then paired in order to form the best $\pi^0\pi^0$ combination. Events with five photons are allowed only if the 5th cluster is more than 3 ns apart from the event time. The signal region is defined as $R_{ell} < 1.5$, where R_{ell} is:

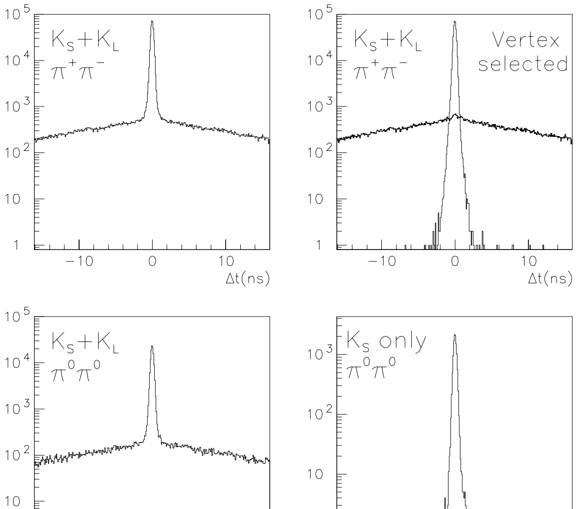

FIGURE 1. Proton tagging

$$R_{ell} \equiv \frac{1}{9}\left\{\left(\frac{\frac{m_1+m_2}{2}-m_{\pi^0}}{\sigma_{\frac{m_1+m2}{2}}}\right)^2+\left(\frac{\frac{m_1-m_2}{2}}{\sigma_{\frac{m_1-m2}{2}}}\right)^2\right\}. \tag{3}$$

The background is $\sim 3\times\ 10^{-3}$ if no lifetime weighting is applied. Applying weighting the background drops to $\sim 1\times\ 10^{-3}$. This is because $3\pi^0$ decays with missing photons tend to be reconstructed closer to the calorimeter.

Lifetime weighting and acceptance corrections

To make the vertex distributions for $\mathrm{K_L}$ and $\mathrm{K_S}$ similar we apply a momentum dependent statistical weight to the $\mathrm{K_L}$ events:

$$\exp(-z/\lambda(p)), \qquad \lambda(p) = (p/\mathrm{m_K})\cdot c\tau_\mathrm{S}/(1-\tau_\mathrm{L}/\tau_\mathrm{S}). \tag{4}$$

Applying this technique, the acceptance formally cancels except for the leftover 0.6 mrad angle between the two beams. This is important for the $\pi^+\pi^-$ decays since the two tracks obey strict two body kinematics and therefore the $\mathrm{K_S}$ and $\mathrm{K_L}$ illumination is not completely symmetric in the area around the beam hole. To minimise this acceptance correction, an asymmetry cut is applied on the relative difference between the two charged tracks momenta. This cut also effectively removes the $\Lambda\rightarrow\pi^-\mathrm{p}$ and $\bar{\Lambda}\rightarrow\pi^+\bar{\mathrm{p}}$ backgrounds which affect the $\mathrm{K_S}$ beam.

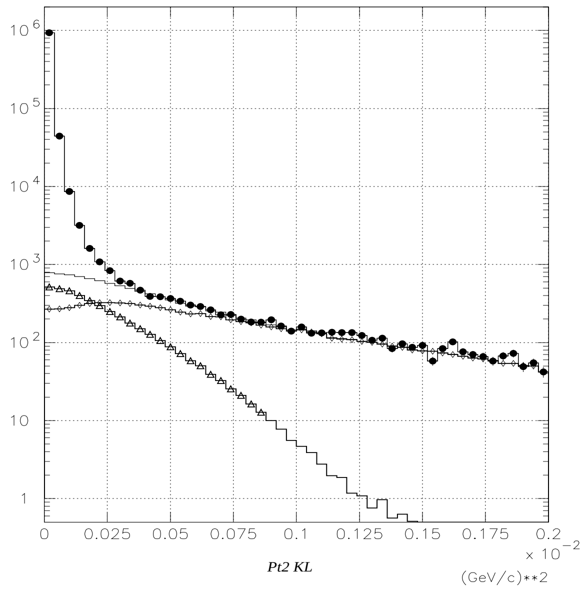

FIGURE 2. Charged background

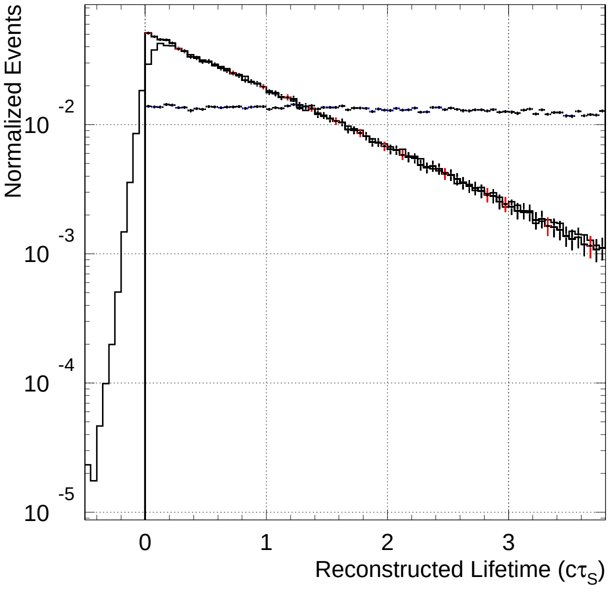

FIGURE 3. Lifetime weighting

Relative momentum scale

The momentum of the charged events is reconstructed using the opening angle of the two charged tracks, the kaon and the charged pion masses, and the ratio of the two charged track momenta (r) as measured by the magnetic spectrometer:

$$E_{\pi^+\pi^-} = \frac{\sqrt{(M_{\mathrm{K}}^2 - m_\pi^2 \mathrm{R})\,\mathrm{R}}}{\theta}\ , \tag{5}$$

where θ is the opening angle formed by the two charged tracks and $\mathrm{R} = \frac{1}{\mathrm{r}} + \mathrm{r} + 2$. In addition to the kaon and charged pion masses, the charged momentum scale is therefore determined by the transverse scale of the drift chambers, and by the longitudinal distance between the first two drift chambers.

For the neutral decays one measures the sum of the photon energies to get the kaon momentum. To measure the the distance (D) between the decay vertex and the calorimeter one uses the impact points of the photons, the photon energies, and the kaon mass:

$$D = \frac{1}{m_{\mathrm{K}}}\sqrt{\sum_{i\neq j} E_i E_j d_{i,j}^2}\ , \qquad d_{i,j}^2 = (x_i - x_j)^2 + (y_i - y_j)^2\ . \tag{6}$$

To calibrate the neutral momentum scale one fits the upstream vertex distribution for $\mathrm{K_S} \rightarrow \pi^0\pi^0$ decays requiring no hits in the $\mathrm{K_S}$ anti-counter (AKS). This counter is placed on the K_S beam just downstream of the final collimator. It consists of a photon converter followed by plastic scintillators and vetoes the K_S decaying before it. The vertex distribution is fitted by an exponential convoluted with a Gaussian smearing. The fitted position of the AKS is adjusted to its known position.

A powerful cross-check for the momentum scale is provided by special runs during which a π^- beam is sent to two short polyethylene targets placed at precisely known positions. The first target is placed just downstream of the K_L final collimator and the other is placed towards the end of the decay region. The prompt decays of $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ allow the cross check of the distance/momentum scale. In this case the function to be fitted is just a Gaussian with no convoluted exponential. The position of the charged vertex reconstruction is also checked collecting events with two or more charged tracks. The downstream target is important to check the linearity of the calorimeter.

To measure the double ratio one has to define a useful momentum range and a decay region. The lower and upper bounds of the accepted momentum range are optimised to minimise the sensitivity to the relative momentum scale uncertainty. A good choice for NA48 is to accept kaon momenta from 70 to 170 GeV/c. A standard choice for the decay region is to accept kaon decays between 0 and 3.5 K_S lifetimes. A cut on the reconstructed lifetime is applied to the K_L events at both the upstream and the downstream end of the decay region. An error on the relative momentum scale shifts the weights applied to the K_L events effectively shifting the selected decay region. Since the K_L vertex distribution is reasonably flat, the gains or losses of K_L events due to the shift of the upstream lifetime cut are compensated, to large extent, by the gains and losses due to the shift of the downstream lifetime cut. Quite different is the situation for the K_S events. Since the vertex distribution is quite steep, the effect of displacing the upstream cut is not compensated by the same shift of the downstream end. To keep under control the systematics, the beginning of the decay region for K_S decays is defined requiring no hits in the AKS counter.

RELATIVE TRANSVERSE SCALE

All of the above assumes that the transverse position scales for the drift chambers and the calorimeter are the same. To cross-check the relative lateral scale electrons from K_{e3} decays and/or electrons from the e^- calibration beam are used. The shower maximum depth for electrons and photons of the same energy is displaced by roughly one radiation length. This implies a correction to the reconstructed position of photons with respect to electrons if the particles impinge on the calorimeter with a nonzero angle. The fact that the calorimeter electrode structure points to the centre of the decay region, $\sim$ 110 m upstream, greatly reduces this correction.

Accidental correction

Neutral and charged decays are collected simultaneously and the losses and gains of events due to accidental kaon decays and muons cancel to first order. Since however we employ two beams and two targets, the correlation of the relative intensity of the two beam must be demonstrated. In order to do this we collect events proportional to $\mathrm{K_S}$ and $\mathrm{K_L}$ beam intensities but uncorrelated with detectors activities. From the study of these events the accidental $\mathrm{K_S}$ and $\mathrm{K_L}$ gains and losses are evaluated.

CONCLUSIONS ON THE $\mathrm{Re}(\varepsilon'/\varepsilon)$ ANALYSIS

A new result on $\mathrm{Re}(\varepsilon'/\varepsilon)$ competitive with the already published data should be available soon. In the mean time we keep accumulating statistics and we are confident to achieve the proposed precision in the $\mathrm{Re}(\varepsilon'/\varepsilon)$ determination.

$\mathrm{K_L}$ RARE DECAYS AND DIRECT CP VIOLATION

In the CKM description of CP violation, some very rare $\mathrm{K_L}$ decays have a large CP violating component. The Standard Model prediction for the direct CP violating contribution to $\mathrm{BR}(\mathrm{K_L} \rightarrow \pi^0 e^+ e^-)$ is a few 10^{-12} [16]. The single event sensi-

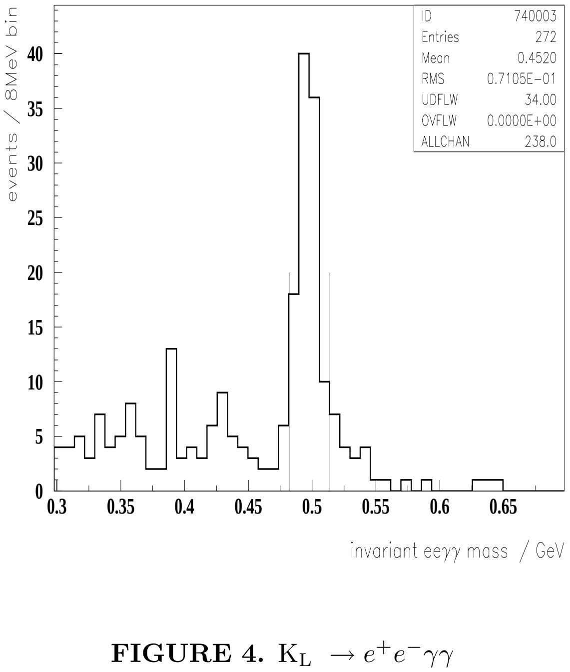

FIGURE 4. $\mathrm{K_L} \rightarrow e^+ e^- \gamma\gamma$

tivity for such a small branching ratio is out of range for the NA48 experiment in its current configuration. However NA48 can measure with precision rare $\mathrm{K_L}$ decays which represent a serious background for future attempts to measure direct CP violation in the $\mathrm{K_L} \rightarrow \pi^0 e^+ e^-$ decay. They are the $\mathrm{K_L} \rightarrow \pi^0 \gamma\gamma$ (which contributes to the CP conserving amplitude to $\mathrm{K_L} \rightarrow \pi^0 e^+ e^-$) and the $\mathrm{K_L} \rightarrow e^+ e^- \gamma\gamma$ [17]. On this latter decay mode, NA48 presents a preliminary result extracted from the 1997 data sample and based on 106 events in the signal region shown in figure 4. The Preliminary result is $\mathrm{BR}(\mathrm{K_L} \rightarrow e^+ e^- \gamma\gamma) = (4.6 \pm 0.7 \pm 1.4) \times 10^{-7}$ with the conditions $E_\gamma > 5$ MeV and $m_{e\gamma} > 1$ MeV.

REFERENCES

1. Barr D.G. et al., CERN/SPSC/90-22/P253.
2. Wu T. T., and Yang C. N., *Phys. Rev. Lett.* **13**, 380 (1964).
3. Barr G. D. et. al, *Phys. Lett.* **B317**, 233, (1993).
4. Gibbons L. K. et al., *Phys. Rev. Lett.* **70**, 1203 (1993).
5. Biino C., Doble N., Gatignon L., Grafström P., and H. Wahl, The Simoultaneous and Nearly-collinear K^0 Beams for Experiment NA48, presented at the 6th European Particle Accelerator Conference, Stockholm, Sweden, 22-26 June 1998.
6. Doble N., Gatignon L., and Grafström P., *Nucl. Instr. and Meth.* **B119** (1996) 181.
7. Bédérède D. et al., *Nucl. Instr. and Meth.* **A367**, 88 (1995).
8. Barr G.D. et al., *Nucl. Instr. and Meth.* **A370**, 413 (1996).
9. Hallgren B. et al., The NA48 LKr Calorimeter Digitizer Electronics Chain, presented at the Wirechamber Conference 1998, Vienna, Austria, February 23-27, 1998 / CERN-EP/98-48.
10. Martini M., Performance of the NA48 Liquid Krypton Calorimeter for the $\mathrm{Re}(\varepsilon'/\varepsilon)$ Measurement at the CERN SPS, presentet at the CALOR97 Conference, Tucson, AZ, USA, November 9-14, 1997.
11. Anvar S. et al., *IEEE Transactions on Nuclear Science* **45**, 1776 (1998).
12. Fischer G. et al., A 40 MHz-Pipelined Trigger for $\mathrm{K}^0 \rightarrow 2\pi^0$ Decays for the CERN NA48 Experiment, presented at the Wire Chamber Conference 1998, Vienna, Austria, February 23-27, 1998.
13. T. Beier et al, *Nucl. Instr. and Meth.* **A360**, 390 (1995).
14. Bal F. et al., The NA48 Data Acquisition System, presented at the 10th IEEE Real Time Conference, Beaune, France, September 22-26, 1997.
15. Luitz S., The NA48 Data Acquisition PC Farm, presented at the CHEP98 Conference, Chicago, IL, USA, August 31 - September 4, 1998.
16. Donoghue J.F. and Gabbiani F., *Phys. Rev.* **D51**, 2187 (1995).
17. Greenlee H. B. , *Phys. Rev.* **D42**, 3724 (1990).