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UPDATE ON THE $Re(\epsilon\,'/\epsilon)$ MEASUREMENT BY THE NA48 EXPERIMENT AT CERN

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ABSTRACT

The NA48 experiment at CERN has been designed to reach an ultimate error of 2×10^{-4} on the measurement of the direct CP violation parameter $Re(\epsilon\,'/\epsilon)$. The most recent preliminary NA48 result is $Re(\epsilon\,'/\epsilon) = (12.2 \pm 4.9)\times10^{-4}$, based on the analysis of the data collected in 1998. The principle of the measurement, the analysis strategy and the main systematics are discussed in this paper.

1 Physics Motivation

The two pions decays of the $\mathrm{K_L}$ established the violation of the CP symmetry. The main component of this violation is described by the ϵ parameter, which represents the size of the asymmetric mixing of the CP eigenstates K_1 and K_2 into the mass eigenstates $\mathrm{K_S}$ and $\mathrm{K_L}$. This indirect violation is accounted within the Standard Model through $\mathrm{K^0}$–$\overline{\mathrm{K}}^0$ oscillations, described with box diagrams. However, the Standard Model also predicts a much smaller CP violating effect, occurring directly in the decay process. This effect is due to an asymmetry in the decay amplitudes of neutral kaon decays into two pion final states with different isospin values. The direct CP violation is quantified by the $\epsilon\,'$ parameter. A value of $\epsilon\,'$ different from zero arises naturally in the Standard Model from the complex phase of the CKM matrix, in processes described through penguin diagrams. A review of theoretical predictions for $Re(\epsilon\,'/\epsilon)$ is presented in [1]. A detailed description of CP violation physics and the main experimental results can be found in [2]. The $Re(\epsilon\,'/\epsilon)$ measurements available so far [3] [4] [5] are accomplished by comparing the relative decay rates of $\mathrm{K_S}$ and $\mathrm{K_L}$ into two pions, combined in the *double ratio* R:

$$R = \frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)} \cdot \frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-)} \simeq 1 - 6\,Re(\epsilon\,'/\epsilon)$$

2 The NA48 experimental method

The measurement of $Re(\epsilon\,'/\epsilon)$ proceeds in NA48 by counting the number of events in each of the four decay modes $K_S, K_L \to \pi^0\pi^0, \pi^+\pi^-$ and computing the double ratio R. An ultimate precision of 2×10^{-4} on the $Re(\epsilon\,'/\epsilon)$ measurement is the aim of the NA48 experiment.

The statistical error is limited by the occurence of the $K_L \to \pi^0\pi^0$ decay, with the smallest branching ratio among the four modes. A few million of $K_L \to \pi^0\pi^0$ events will be collected to achieve the required precision.

The systematics uncertainties are controlled at high accuracy by exploiting cancellations of effects which contribute symmetrically to the different components of the double ratio R. Effects due to the sensitivity to detector efficiency, to variations in beam intensity and to accidental activity are minimized by collecting the data simultaneously in the four decay channels. This is achieved with a suitable beam configuration and a precise definition of the decay region.

The $\mathrm{K_S}$ and $\mathrm{K_L}$ beams are produced concurrently, and coincide in space at the position of the detector. Only those decays occurring in the same fiducial volume for both $\mathrm{K_S}$ and $\mathrm{K_L}$ are used to compute R. The choice of the production angles makes the $\mathrm{K_S}$ and $\mathrm{K_L}$ momentum spectra similar in the accepted range of kaon energy, i.e. $70 \leq E_K \leq 170$ GeV. The definition of the beginning of the fiducial decay region for both $\mathrm{K_L}$ and $\mathrm{K_S}$ requires an accurate knowledge of the energy scale. The longitudinal position distributions of the decay vertex are made equal for $\mathrm{K_S}$ and $\mathrm{K_L}$ by applying an event–weighting procedure. In this way, the acceptance correction, due to the large difference in average decay lenghts, is small, at the price of a loss in event statistics. Background effects are reduced by a suitable detector design. The corrections applied to R are due to several systematics effects: $\mathrm{K_S}$ and $\mathrm{K_L}$ misidentification by proton tagging; trigger inefficiency; background subtraction; acceptance correction; energy scale; accidental activity. Each effect is not larger than a few per mill. The final value for R is calculated indipendently in kaon energy bins.

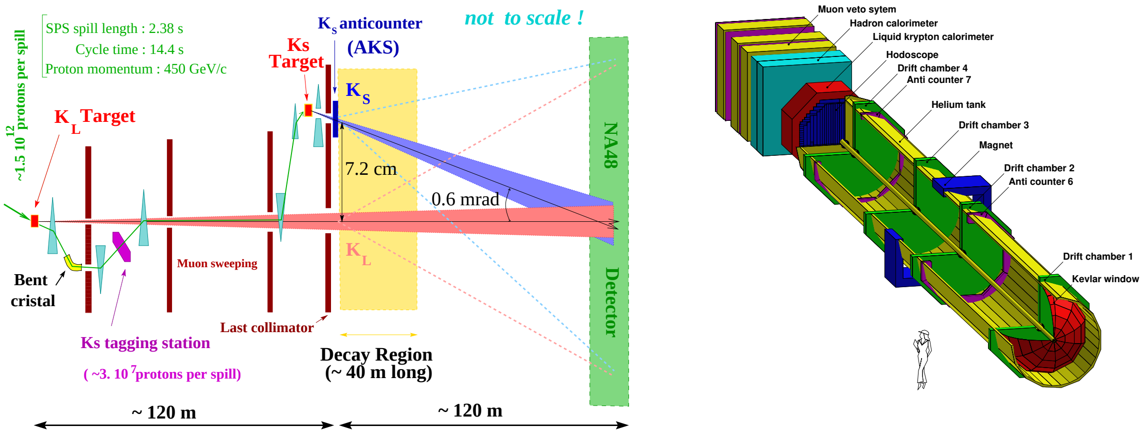

Figure 1: *Schematics layout of the NA48 beams and the detector.*

2.1 The K_S and K_L beams

The NA48 beam steering is shown in fig.1 A SPS primary proton beam, at an energy of 450 GeV and an intensity up to 1.5×10^{12} *ppp* (protons per 2.4 s SPS pulse), hits a beryllium target, and produces a neutral beam, the K_L one, at an angle of 2.4 mrad. A fraction of the non–interacting protons is steered and deflected onto a bent silicon crystal. In this way, an attenuated proton beam of 3×10^7 *ppp* is produced, suitable to generate the K_S component. A set of scintillator foils is installed downstream of the crystal, to tag protons and distinguish K_S from K_L. The protons are transported toward a second beryllium target, 120 m downstream, where the K_S beam is produced at an angle of 4.2 mrad. The two kaon beams enter the decay region at the same longitudinal position, with a 72 mm vertical separation. An anticounter (AKS) is installed in the K_S beam line to define the beginning of the decay region. The kaons converge toward the detector 120 m after the beginning of the decay region at an angle of 0.6 mrad. This value, comparable to the beam divergence, is chosen to obtain the same detector illumination from both kaons.

2.2 The NA48 detector

The NA48 detector, shown in fig.1, is located downstream of the decay volume.

The charged $\pi^+\pi^-$ decays are detected in a magnetic spectrometer. Four large drift chambers are installed at the end of the vacuum decay volume, two on each side of a dipole magnet with 256 MeV/c transverse momentum kick. They provide 90 μm space–point resolution, and ~ 2.5 MeV/c^2 resolution on the reconstructed kaon mass. A two–plane scintillator hodoscope, downstream the spectrometer, per-

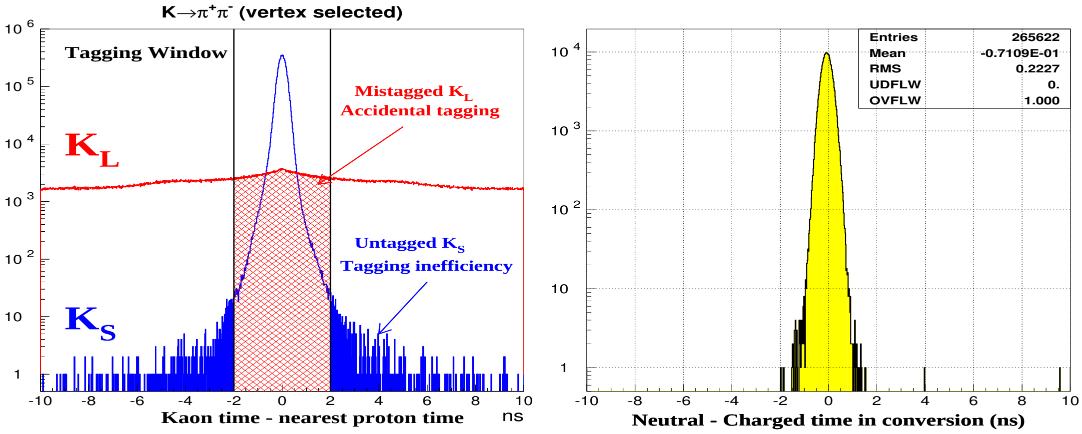

Figure 2: *Left: difference between $\pi^+\pi^-$ events time and proton time in the tagger (vertex selection); Right: difference in event time for neutral decays with tracks.*

forms fast triggering and event time measurement for the charged decays with a precision better than 200 ps.

A liquid krypton (LKr) electromagnetic calorimeter detects the $\pi^0\pi^0$ decays. It provides high quality measurements of the photon energy, position, and arrival time, and performs triggering for the neutral decays. The active volume of about 8 m^3 of LKr is segmented by copper–berillyium ribbon electrodes into 13212 cells, 2×2 cm^2 each, with a tower structure. The recostructed π^0 mass resolution is 1.1 MeV/c^2. The space resolution is ~ 1 mm, the event time resolution is better than 250 ps. The energy resolution, measured with 1998 data, is:

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{100MeV}{E} \oplus 0.5\% \ .$$

A hadronic lead–scintillator calorimeter, a muon detector made by scintillator counters and iron, and seven rings of scintillator anti–counters, covering the solid angle outside the detector acceptance, are used for the background rejection.

3 The $Re(\epsilon\,'/\epsilon)$ analysis

3.1 The data samples

NA48 has been taking physics data for the $Re(\epsilon\,'/\epsilon)$ measurement since 1997.

The analysis of the data collected in 1997, corresponding to 0.49×10^6 reconstructed $K_L \to \pi^0\pi^0$, leads to the published result [5]:

$$Re(\epsilon\,'/\epsilon) \ = (18.5 \pm 4.5(stat) \pm 5.8(syst)) \times 10^{-4} = (18.5 \pm 7.3) \times 10^{-4}.$$

In the 1998 run, the improvements in charged trigger and data aquisition systems allowed for a 30% increase in beam intensity with respect to 1997, with a typical value of 1.4 $\times$ 10^{12} *ppp* on the $\mathrm{K_L}$ target. The LKr calorimeter was operating at the nominal high voltage value of 3 kV, higher than the 1.5 kV used in 1997. A carbon fibre beam pipe, with thin walls, was installed to reduce showers in the detector. The preliminary $Re(\epsilon\,'/\epsilon)$ analisys result on the 1998 data sample, based on 1.14×10^6 reconstructed $K_L \to \pi^0\pi^0$, is described in this paper.

A highly efficent run took place in 1999, with $\sim$ 2×10^6 $K_L \to \pi^0\pi^0$ reconstructed events. The data analysis is in progress.

3.2 The analysis of 1998 data

3.2.1 Analysis strategy and event selection

The fiducial ranges in kaon energy and proper time used to count the events are $70 \le E_K \le 170$ GeV and $0 \le \tau \le 3.5\tau_S$, starting from the AKS position ($\tau = 0$). For the $\mathrm{K_L}$, the decay time cut is applied on the recontructed τ. For the $\mathrm{K_S}$, the $\tau = 0$ cut is applied using the AKS anticounter to veto decays occurring upstream.

All the events are required to satisfy a symmetric cut on the position of the centre of gravity. For $\pi^0\pi^0$ decays, the centre of gravity is defined as the energy–weighted average x, y positions of the four showers at the face of the LKr calorimeter. For $\pi^+\pi^-$ decays it is the momentum–weighted average position of the track segments, measured upstream of the spectrometer magnet, and projected onto the face of the LKr calorimeter. The radial position of the centre of gravity is required to be within 10 cm from the beam axes.

In order to keep a symmetric collection of neutral and charged decay modes, all the events collected when a dead time condition was present are rejected. This includes a $\sim$ 4 % effect due to the charged trigger and a $\sim$ 25 % effect due to an overflow condition in the drift chamber readout.

3.2.2 Proton tagging

The $\mathrm{K_S}$ decays are distinguished from the $\mathrm{K_L}$ decays with a time of fligh technique: the $\mathrm{K_S}$ decays are in coincidence with a proton crossing the tagger scintillators, within a time window of 4 ns. The misidentification α_{SL} of $\mathrm{K_S}$ into $\mathrm{K_L}$ is due to tagging inefficiency and errors in the event time measurement. The transitions α_{LS} of $\mathrm{K_L}$ into $\mathrm{K_S}$ are due to accidental activity in the tagger counters.

For $\pi^+\pi^-$ events, the rates of inefficiency and of accidental coincidences are measured applying a selection on the vertex position. Fig.2(*Left*) shows the distribution of the minimum time difference between the tagger and the detector for charged events identified with the vertex. The peak corresponds to $\mathrm{K_S}$ events. In

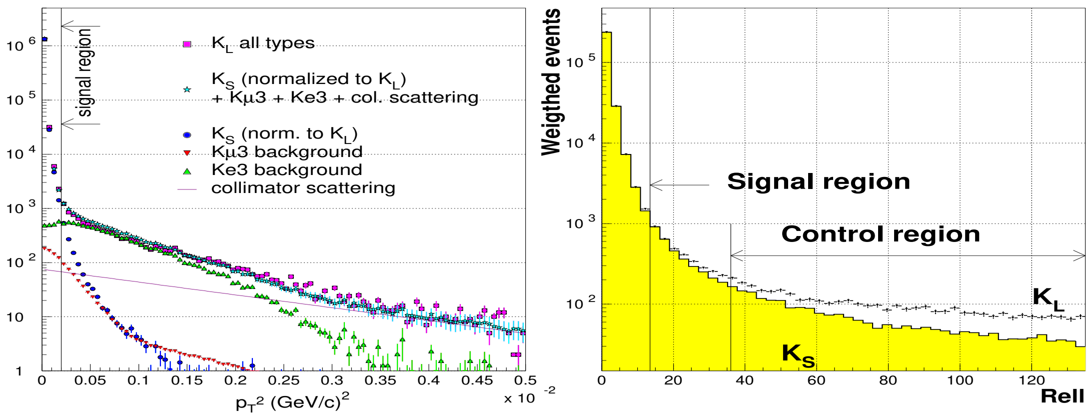

Figure 3: *Left:* ${P'_T}^2$ *distribution for* $\pi^+\pi^-$ *candidates and for background events; Right:* R_{ell} *distribution for* K_L *candidates and normalized* $K_S \to \pi^0\pi^0$ *events.*

1998 the $\mathrm{K_S}$ tagging inefficiency is $\alpha_{\mathrm{SL}}^{+-} = (1.97 \pm 0.05) \times 10^{-4}$. The probability of $\mathrm{K_L}$ accidental tagging is $\alpha_{\mathrm{LS}}^{+-} = (11.05 \pm 0.01)\%$.

For $\pi^0\pi^0$ decays, the accidental tagging is measured in off–set time intervals. A limit on the difference of the tagging efficiency for charged and neutral decays is obtained by comparing the time measurement in the LKr calorimeter and the scintillator hodoscope for neutral events with tracks. Fig.2(*Right*) shows the difference of charged and neutral event time for neutral decays with photon conversions.

The double ratio R is affected by the difference of tagging errors between neutral and charged decays. The inefficiency difference is $|\alpha_{SL}^{00} - \alpha_{SL}^{+-}| < 0.5 \times 10^{-4}$ in 1998. It induces an uncertainty of $\pm 3 \times 10^{-4}$ on R. The difference in accidental tagging probability for charged and neutral decays is $\alpha_{LS}^{00} - \alpha_{LS}^{+-} = (0.5 \pm 4)\ 10^{-4}$, which corresponds to a correction $\Delta R = (1 \pm 8) \times 10^{-4}$.

3.2.3 *Trigger efficiency*

In $\pi^+\pi^-$ decays, the first level trigger is based on the scintillator hodoscope, the track multiplicity in the spectrometer, and the total energy in the calorimeter. Its inefficiency is at the per mill level. The second level trigger uses drift chamber data to reconstruct vertices and to compute invariant masses and decay times. The efficiency measured in 1998 is $(97.75 \pm 0.05)\%$, and contributes to R with a correction $\Delta R = (-1 \pm 11) \times 10^{-4}$.

The $\pi^0\pi^0$ decays are triggered in a 40 MHz pipeline, which uses the LKr cell information to compute number of clusters, total energy, centre of gravity and proper time, with negligible dead time. The neutral trigger efficiency measured in 1998 is $(99.93 \pm 0.02)\%$ and has no effects on R.

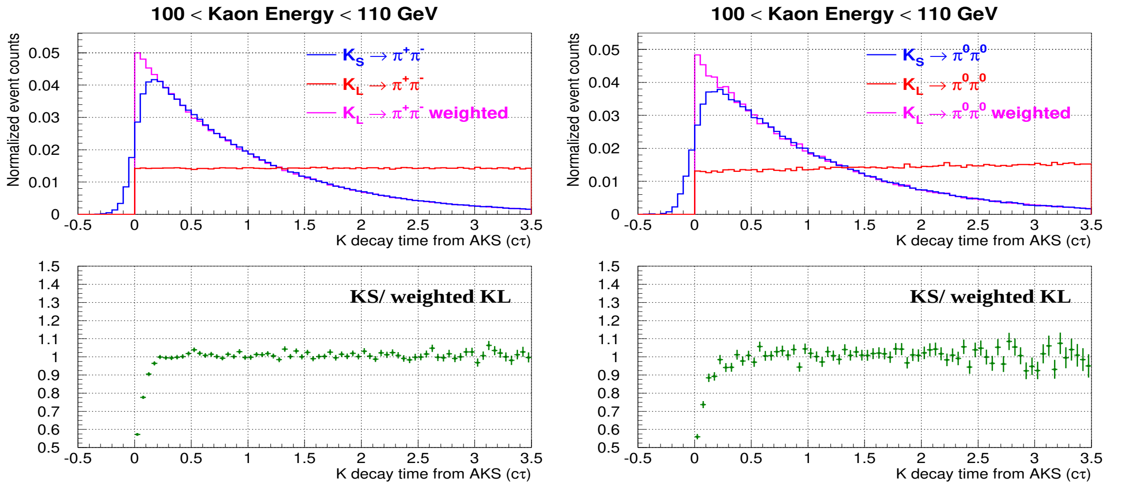

Figure 4: *Vertex position distributions of* $\pi^+\pi^-$ *and* $\pi^0\pi^0$ *decays for* $\mathrm{K_S}$, $\mathrm{K_L}$ *and weighted* $\mathrm{K_L}$ *(kaon energy: 100-110 GeV), and their ratio* $\mathrm{K_S}$ *to weighted* $\mathrm{K_L}$ *events.*

3.2.4 Background estimation

The background to the $\pi^+\pi^-$ events is due to the $\mathrm{K_L}$ semileptonic decays K_{e3} and $K_{\mu 3}$. The rejection of events with leptons is made with the E/p comparison and using the muon veto detector. A further selection is applied by requiring a $\pi^+\pi^-$ invariant mass consistent with the kaon mass, and a small kaon transverse momentum P'_T. The P'_T variable is a projection of the kaon momentum which does not depend on the target position, and is, therefore, similar for $\mathrm{K_L}$ and $\mathrm{K_S}$. Fig.3(*Left*) shows the ${P'_T}^2$ distribution for the $\pi^+\pi^-$ candidates and for samples of selected background events. The background to the $\mathrm{K_L}$ signal is estimated from the data, by extrapolating the shape of the identified background events from control regions, at higher ${P'_T}^2$, into the low ${P'_T}^2$ signal region. The contribution of true $\pi^+\pi^-$ decays is determined from the shape of the $K_S \to \pi^+\pi^-$ events. The resulting background is $(19 \pm 3) \times 10^{-4}$.

A small fraction of $K \to \pi^+\pi^-$ are found in the $\mathrm{K_L}$ beam at large P'^2_T values, due to kaons scattered on the collimator. These events are removed from the $\pi^+\pi^-$ sample by the ${P'_T}^2$ cut, but are kept in the $\pi^0\pi^0$ sample. A correction $\Delta R = (-10 \pm 3) \times 10^{-4}$ is applied to R to account for this.

The background to the $\pi^0\pi^0$ mode is dominated by the $\mathrm{K_L} \to 3\pi^0$ decay with two missing photons. Candidate events are selected by requiring four in–time photons. The four identified photons are then paired in order to get the two values of the $\gamma\gamma$ invariant masses $m_1^{\gamma\gamma}$ and $m_2^{\gamma\gamma}$ closest to the π^0 mass. Being the two masses $m_1^{\gamma\gamma}$ and $m_2^{\gamma\gamma}$ correlated for true $\pi^0\pi^0$ events, an estimator R_{ell} is defined to study

Table 1: Re($\epsilon\,'/\epsilon$) *analysis 1998: data statistics (Units:* 10^6 *events).*

$K_S \to \pi^+\pi^-$	$K_L \to \pi^+\pi^-$	$K_S \to \pi^0\pi^0$	$K_L \to \pi^0\pi^0$
7.46	4.87	1.80	1.14

the neutral background contamination. Fig.3(*Right*) shows the R_{ell} distribution for the $\mathrm{K_L}$ events and $\mathrm{K_S}$ normalized events. Signal events populate the region at small R_{ell}. Background events are reduced through a cut at high R_{ell}, and rejecting decays with extra in–time photons. The correction due to the neutral background fraction in the signal region is $\Delta R = (-7 \pm 2) \times 10^{-4}$, estimated with an extrapolation of the background contribution from control regions at high R_{ell}. The extrapolation factor is calculated with simulated events.

3.2.5 Acceptance

The difference between the $\mathrm{K_L}$ and $\mathrm{K_S}$ decay distributions in the 3.5 τ_S region implies a difference in their acceptance. Similar acceptances for the $\mathrm{K_L}$ and $\mathrm{K_S}$ decays are obtained by exploiting the technique of weighting $\mathrm{K_L}$ according to the $\mathrm{K_S}$ proper time. The result is a longitudinal vertex distribution of weighted $\mathrm{K_L}$ events equal to the $\mathrm{K_S}$ one, as shown in fig.4. The residual acceptance differences, studied with a complete simulation of the beam and the detector, contribute to R with a correction $\Delta R = (31 \pm 6(MCstat) \pm 3(syst)) \times 10^{-4}$. The cost for the weighting procedure is a loss of events which correspond to a 35% increase of the statistical error.

3.2.6 Energy scale

The measurements of the kaon energy, the decay vertex and the proper time for the $\pi^0\pi^0$ mode depend on the measurement of the photon energies and positions in the LKr calorimeter. The absolute neutral energy scale is adjusted within $\pm 5 \times 10^{-4}$ by comparing the beginning of the reconstructed longitudinal vertex position with the known position of the AKS counter, using $K_S \to \pi^0\pi^0$ events. The absolute energy scale is stable within $\pm 5 \times 10^{-4}$ throughout the entire 1998 run. The calorimeter performances are continuously checked and tuned with $\pi^0\pi^0$ events, electrons from K_{e3} decays, and special calibration data. The total contribution to the systematic error in R due to the neutral reconstruction in 1998 data is $\pm 10 \times 10^{-4}$.

The energy and the decay vertex position for a $\pi^+\pi^-$ decay is completely determined by the geometry of the drift chambers. The uncertainty on R due to the charged reconstruction in 1998 is $\Delta R = (2 \pm 2) \times 10^{-4}$.

Table 2: *Corrections applied to R and systematics uncertainties (Units = 10^{-4}).*

Mistagging probability	$+1 \pm 8$
Tagging efficiency	$- \pm 3$
Charged trigger	-1 ± 11
Neutral background	-7 ± 2
Charged background	$+19 \pm 3$
Beam scattering	-10 ± 3
Acceptance and AKS efficiency	$+31 \pm 9$
Neutral scale	$- \pm 10$
Charged vertex	$+2 \pm 2$
Accidental activity and in–time background	$+2 \pm 12$
Total correction and systematics on R	$+37 \pm 24$

3.2.7 *Accidental activity*

The effect of accidental activity is minimized by taking data simultaneously in the four decay channels. The rate of accidentals is equal for K_S and K_L within an error of ~ 1 %. The correction to R due to this effect is computed using a sample of events overlayed with data selected by random triggers. Events with an artificially doubled accidental activity are thus produced. Gains and losses of events among the four decay modes in R are obtained by comparing the counts of non–overlayed events with the overlayed ones. The correction applied is $\Delta R = (+2 \pm 6) \times 10^{-4}$, due essentially to geometrical beam effects. The contribution of residual variations in K_S/K_L intensity, which could induce an asymmetric loss of charged and neutral events, is estimated to be $\Delta R < 10 \times 10^{-4}$.

3.2.8 *Results*

The calculation of the double ratio R is done in 20 kaon energy bins, in order to be insensitive to the $\sim 10\%$ difference of the beam spectra in the accepted range 70–170 GeV. The number of candidates in the four event samples, after correcting for accidental tagging, is shown in tab.1 . The corrections to R due to systematics effects are applied separately in each energy bin. Fig.5 shows the result for R in the different kaon energy bins. The overall average over the 20 bins in 1998 is:

$$R = 0.99267 \pm 0.00173(stat.) \pm 0.00238(syst.) \ ,$$

where the first error is the statistical fluctuation in the event samples, and the second error comes from the uncertainties listed in tab.2 . The preliminary result for the direct CP violating parameter $Re(\epsilon\,'/\epsilon)$ using 1998 data is:

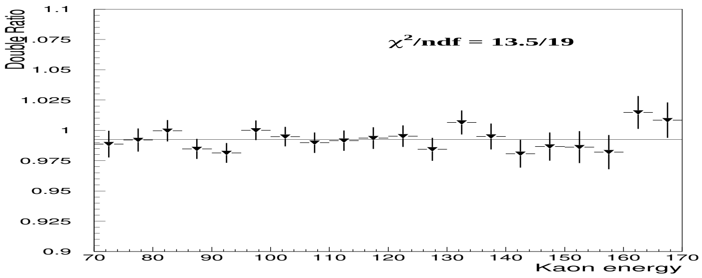

Figure 5: *The double ratio R as a function of the kaon energy (1998 data)*

$$Re(\epsilon\,'/\epsilon) \;= (12.2\;\pm\;2.9(stat) \pm 4.0(syst)) \times 10^{-4} = (12.2\;\pm\;4.9) \times 10^{-4}\;.$$

This value, combined with the pubblished 1997 measurement, leads to the result:

$$Re(\epsilon\,'/\epsilon) \;= (14.0 \pm 4.3) \times 10^{-4}\;.$$

4 Prospects and conclusions

The present result on $Re(\epsilon\,'/\epsilon)$ from NA48 confirms the occurrence of direct CP violation in the decays of neutral kaons in two pions. The analysis of 1998 data is still in progress, and some systematics are expected to be reduced. The 1999 data analysis is also well advanced, with a data sample twice larger. The completion of the $Re(\epsilon\,'/\epsilon)$ program in NA48 has been delayed of one year, after the implosion of the carbon fiber beam pipe. In this accident, occurred at the end of 1999, all the four drift chambers have been damaged. The chambers repair is already started and the NA48 collaboration will be ready to complete the $Re(\epsilon\,'/\epsilon)$ physics program in the year 2001. Systematics effects in the neutral reconstruction and the accidental tagging procedure in the neutral mode are under study in the current 2000 run.

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