PROCEEDINGS

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A new measurement of ϵ'/ϵ by the NA48 experiment at CERN

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Abstract: The NA48 collaboration at CERN has measured the direct CP violation in two pion decays of neutral kaons. The CP violation parameter $\epsilon'/\epsilon = (15.3 \pm 2.6) \times 10^{-4}$ is the result of three years of data taking (1997, 1998, 1999). The experiment principles, the data analysis features and the systematic error evaluation will be described. The result by the FNAL KTEV collaboration will also be quoted.

1. Introduction

Neutral kaons form a quantum system in which we can define the following eigenstates:

$$\text{Flavor}: \quad \mathrm{K^0}\ (\bar{\mathrm{s}}\mathrm{d}), [S=+1]; \qquad \overline{\mathrm{K^0}}\ (\mathrm{s}\bar{\mathrm{d}}), [S=-1] \tag{1.1}$$

$$\text{CP}: \quad \mathrm{K_1} = \tfrac{1}{2}(\mathrm{K^0} + \overline{\mathrm{K^0}}), [CP=+1]; \quad \mathrm{K_2} = \frac{1}{2}(\mathrm{K^0} - \overline{\mathrm{K^0}}), [CP=-1] \tag{1.2}$$

$$\text{Lifetime}: \mathrm{K_S} \simeq \mathrm{K_1} + \varepsilon \mathrm{K_2}, [\mathrm{c}\tau = 2.67\ \mathrm{cm}]; \ \mathrm{K_L} \simeq \mathrm{K_2} + \varepsilon \mathrm{K_1}, [\mathrm{c}\tau = 15.5\ \mathrm{m}] \tag{1.3}$$

where $\varepsilon = (2.28 \pm 0.02) \times 10^{-3}$ and S is the strangeness quantum number.

The $\mathrm{K_L}$ decays mainly into semileptonic channels and into 3 pion states with $CP = -1$; in few per mille of the cases it decays into 2 pion states with $CP = +1$. This so called indirect CP violation is due to the $\mathrm{K^0}\ \overline{\mathrm{K^0}}$ mixing. If there is also a component of CP violation in the decay process, the rate of CP violation in $\pi^0\pi^0$ and in $\pi^+\pi^-$ can be different, provided that the interference of two decay amplitudes is available. $\pi\pi$ from $\mathrm{K^0}$ can have isospin $\mathrm{I} = 0, 2$. The decay amplitude $\mathrm{A_0}, \mathrm{A_2}$ are:

$$\mathrm{A}(\mathrm{K^0} \to \pi\pi, \mathrm{I}) = \mathrm{A_I} \exp(\mathrm{i}\delta_\mathrm{I}); \qquad \mathrm{A}(\overline{\mathrm{K^0}} \to \pi\pi, \mathrm{I}) = \mathrm{A_I^*} \exp(\mathrm{i}\delta_\mathrm{I}) \tag{1.4}$$

where δ_I are strong phases. The so called direct CP violation is parametrised by:

$$\varepsilon' = \frac{i}{\sqrt{2}} \mathrm{Im} \frac{A_2}{A_0} \exp(i(\delta_2 - \delta_0)) \tag{1.5}$$

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The ratios of the CP violating decay w.r.t. the CP conserving one are:

$$\eta_{+-} \equiv \frac{A(\mathrm{K_L} \to \pi^+\pi^-)}{A(\mathrm{K_S} \to \pi^+\pi^-)} \simeq \varepsilon + \varepsilon'; \qquad \eta_{00} \equiv \frac{A(\mathrm{K_L} \to \pi^0\pi^0)}{A(\mathrm{K_S} \to \pi^0\pi^0)} \simeq \varepsilon - 2\varepsilon' \tag{1.6}$$

$$\mathrm{R} = \frac{\frac{\Gamma(\mathrm{K_L} \to \pi^0\pi^0)}{\Gamma(\mathrm{K_S} \to \pi^0\pi^0)}}{\frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K_S} \to \pi^+\pi^-)}} \simeq 1 - 6\mathrm{Re}(\epsilon'/\epsilon) \tag{1.7}$$

R is called the Double Ratio.

2. The NA48 experiment

The double ratio of the decay widths reduces to the double ratio of number of decays if all the four modes are collected simultaneously[1] (the fluxes cancel in the ratio) and in the same decay region (the fraction of accepted decays cancels in the ratio). The Double Ratio measurement is performed by the NA48 experiment in two steps:

$$\mathrm{R} = 1 - \Delta\mathrm{R}^{(1)} + \Delta\mathrm{R}^{(2)} \tag{2.1}$$

The first order term ($\approx 1\%$) is obtained from the NA48 prescription, which is described in the following, the second order term ($\approx$ few‰) contains small corrections due to the remaining backgrounds, trigger inefficiency, acceptance differences and so on.

In the NA48 experiment a 450 GeV/c proton beam from the CERN SPS accelerator impinges on a primary target ($\mathrm{K_L}$ target) and after about 120 m of magnet sweeping and collimation forms a neutral beam dominated by $\mathrm{K_L}$ decays.

Protons not interacting in the $\mathrm{K_L}$ target reach a bent silicon crystal where a small fraction (about 10^{-5}) follows the bent crystal planes forming a secondary beam which impinges on a secondary target ($\mathrm{K_S}$ target) and after 6 m of magnet sweeping and collimation forms a neutral beam dominated by $\mathrm{K_S}$ decays.

The two kaon beams share the same fiducial decay volume, they are separated by about 7 cm at the exit of the last collimator and converge at the position of the detectors, about 120 m downstream.

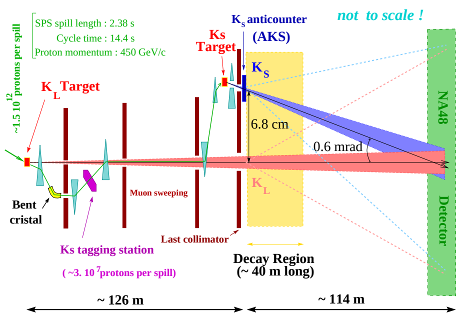

Figure 1: The NA48 beam setup.

In this way the four decay modes are collected simultaneously; long term variations on the $\mathrm{K_S}/\mathrm{K_L}$ ratio (with a RMS of about 9%) are taken into account by reweighting $\mathrm{K_S}$ events to keep such a ratio constant[2].

$\mathrm{K_L}, \mathrm{K_S} \to \pi^+\pi^-$ are detected by a magnetic spectrometer made of 4 drift chambers and a dipole magnet providing 265 MeV p_t kick. The track momentum resolution is:

$$\sigma(p)/p \simeq 0.5\% \oplus 0.009\, p\%; \; p \text{ in GeV/c} \tag{2.2}$$

The $\pi^+\pi^-$ trigger reduces in two stages the 500 KHz input to a 2 KHz output with an efficiency of $(97.896 \pm 0.024)\%$ (the error is of pure statistical nature due to the control sample used). The correction on R induced by the trigger inefficiency is:

[1] In principle, it is already true if at least two modes are collected simultaneously, but of course there is then a bigger sensitivity to systematic effects

[2] $\mathrm{K_S}$ reweighting is a small effect on R: about 3×10^{-4}

$$\Delta \mathrm{R} = (-3.6 \pm 5.2) \times 10^{-4} \tag{2.3}$$

$\mathrm{K_L}, \mathrm{K_S} \to \pi^0\pi^0$ are detected by a Liquid Krypton electromagnetic calorimeter made of 13212 cells ($2 \times 2\ \mathrm{cm}^2 \times 27\ X_0$, $X_0 = 4.7$ cm). The energy resolution is:

$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.09}{E} \oplus 0.42\%,\ E \text{ in GeV} \tag{2.4}$$

The cells are made in projective geometry pointing to the middle of the decay region (about 114 m upstream).

The $\pi^0\pi^0$ trigger reduces the 500 KHz input to a 2 KHz output with an efficiency of $(99.920 \pm 0.009)\%$.

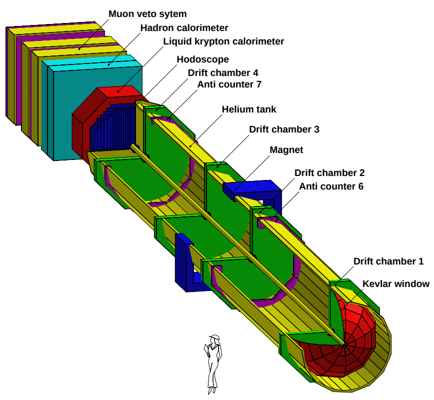

Figure 2: The NA48 detectors.

An hadron calorimeter used for the total energy measurement, a muon veto system to suppress $K\mu3$ decays, an out-of-acceptance veto system and some intensity monitors complement the apparatus.

Dead time conditions are due mainly to the charged apparatus and include about 1.5% from the $\pi^+\pi^-$ trigger and about 20% from the drift chamber multiplicity limit; these conditions are recorded and applied offline to all the events (in particular to $\pi^0\pi^0$ events) in such a way that all the events are collected under the same conditions.

3. Decay region definition

The beginning of the $\mathrm{K_S}$ decay region is sharply defined by a counter (AKS[3]) which rejects all the upstream decays both for $\pi^+\pi^-$ and for $\pi^0\pi^0$. The correction on R due to the AKS inefficiency is:

$$\Delta \mathrm{R} = (1.1 \pm 0.4) \times 10^{-4} \tag{3.1}$$

The end of the $\mathrm{K_S}$ decay region, the beginning and the end of the $\mathrm{K_L}$ decay region are defined by the decay position reconstructed by the detectors. The decay position is measured w.r.t. the AKS position; the fiducial volume is defined by the proper time of the decay, measured in $\mathrm{K_S}$ lifetime units. The downstream cut has been chosen at 3.5 $\mathrm{K_S}$ lifetimes, the $\mathrm{K_L}$ upstream cut is in the same position as the AKS.

The kaon energy range is $70 \le E_K \le 170$ GeV where the $\mathrm{K_L}/\mathrm{K_S}$ variation is smaller than 20%. Nevertheless R is measured in kaon energy bins (5 GeV wide) and then averaged, to be insensitive to $\mathrm{K_S} - \mathrm{K_L}$ energy spectrum differences.

The center of gravity R_{COG} is the kaon impact point extrapolated to the calorimeter. The cut $R_{COG} \le 10$ cm is used to reject background decays and beam halo particles.

[3] the AKS is made by a photon converter (an iridium crystal 3 mm thick, corresponding to 1.79 X_0 at 0 angle), followed by a track veto (a scintillator counter)

4. Tagging

K_S and K_L are distinguished by a time of flight tecnique: all the protons of the secondary beam cross a stack of scintillating counters (TAGGER) which measure their crossing time.

A K_S decay will be in coincidence with a proton seen by the TAGGER. The coincidence window is 4 ns wide to minimize the probabilty that a K_S is out of coincidence because of tails in the time measurement and the probability that a K_L falls inside the coincidence because of the high proton rate (see fig.3).

The tagging inefficiency (α_{SL}) is the probability that a K_S is mistagged as a K_L due to a bad time measurement. In $\pi^+\pi^-$ it can be measured very precisely because K_S and K_L can also be separated by the vertex position:

$$\alpha_{SL}^{+-} = (1.6 \pm 0.03) \times 10^{-4} \tag{4.1}$$

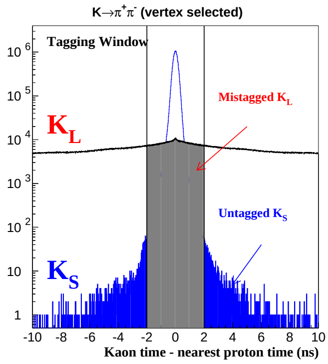

Figure 3: Tagging definition.

α_{SL}^{+-} is dominated by the tagger inefficiency, which is $\pi^+\pi^-$ and $\pi^0\pi^0$ symmetric. $\Delta\alpha_{SL} = \alpha_{SL}^{00} - \alpha_{SL}^{+-}$ is due to difference in the tails between $\pi^+\pi^-$ and $\pi^0\pi^0$ event time measurements.

We can compare directly charged and neutral measurements using events with γ's and e^+e^- from γ conversion (see fig.4):

$$\Delta\alpha_{SL} = (0 \pm 0.5) \times 10^{-4} \tag{4.2}$$

which corresponds to an uncertainty on R:

$$\Delta R = (0 \pm 3.0) \times 10^{-4} \tag{4.3}$$

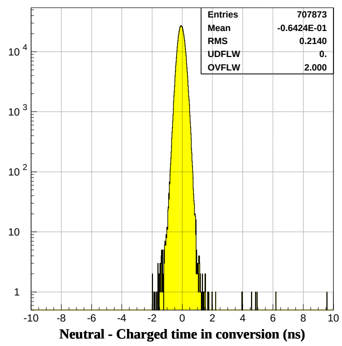

Figure 4: γ conversions

The accidental tagging (α_{LS}) is the probability that a K_L is mistagged as a K_S because of an accidental proton coincidence. In $\pi^+\pi^-$, where K_S and K_L can be separated by the vertex position, it is measured to be:

$$\alpha_{LS}^{+-} = (10.649 \pm 0.008)\% \tag{4.4}$$

The difference between $\pi^0\pi^0$ and $\pi^+\pi^-$ can be checked in events tagged as K_L looking at the proton intensity outside the coincidence window (proton sidebands). The extrapolation (W) from the sidebands to the tagging window is performed in $\pi^+\pi^-$ using pure K_L events selected by the vertex position, while $3\pi^0$ (which can come only from K_L decays) are used in the neutral case.

$$\Delta\alpha_{LS}^{\text{sidebands}} = (3.0 \pm 1.0) \times 10^{-4} \tag{4.5}$$

$$\Delta W = (1.3 \pm 1.1) \times 10^{-4} \tag{4.6}$$

$$\Delta\alpha_{LS} = (4.3 \pm 1.8) \times 10^{-4} \tag{4.7}$$

which[4] implies a correction on R:

$$\Delta R = (8.3 \pm 3.4) \times 10^{-4} \tag{4.8}$$

[4] 1×10^{-4} has been added to the error to take into account the variation w.r.t. the choice of the sidebands

5. $\pi^+\pi^-$ reconstruction

The $\pi^+\pi^-$ invariant mass resolution is about 2.5 MeV and the applied cut is at 3 σ's.

The background is due to $\mathrm{K_L}$ semileptonic decays in which an electron or a muon is identified as a pion. These backgrounds are suppressed by the E/p cut[5] and by the μ-veto counters. Further background suppression is achieved cutting on the kaon transverse momentum ($P_T^2 < 200$ (MeV/c)^2) to remove three-body decays with a missing neutrino and on the tracks momentum asymmetry to suppress Λ decays.

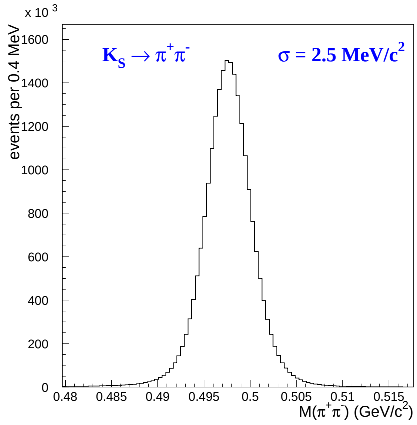

Figure 5: $\pi^+\pi^-$ inv. mass

The kaon energy is calculated by the $\pi^+\pi^-$ opening angle and tracks energy ratio:

$$E_K^2 = \frac{C}{\theta^2}\left\{m_K^2 - C\ m_\pi^2\right\} \tag{5.1}$$

$$C = 2 + \frac{E_{\pi 1}}{E_{\pi 2}} + \frac{E_{\pi 1}}{E_{\pi 2}} \tag{5.2}$$

so that the charged energy understanding is reduced to the knowledge of the drift chambers geometry. This geometry can be checked reconstructing the position of the AKS anticounter for not vetoed $\pi^+\pi^-$ ($\Delta z = 2$ cm). The correction to R due to this geometry is:

$$\Delta\mathrm{R} = (2.0 \pm 2.8) \times 10^{-4} \tag{5.3}$$

The background is estimated in two control regions of $M_{\pi\pi}$ and P_T^2, comparing the distributions of $\mathrm{K_L} \to \pi^+\pi^-$ and of $\mathrm{K_L} \to \pi e\nu$ (the electron is identified by a high E/p value) and $\mathrm{K_L} \to \pi\mu\nu$ (the muon is identified by a μ-veto hit) decays and then extrapolating to the signal region.

The first control region ($M_{\pi\pi} \gg M_K$) is dominated by K_{e3} decays, while the second one ($M_{\pi\pi} \ll M_K$) contains K_{e3} and $K_{\mu 3}$ decays in a similar amount. The $M_{\pi\pi}$ and P_T^2 tails of $\mathrm{K_L} \to \pi^+\pi^-$ in the two control regions are estimated using $\mathrm{K_S}$ decays.

The background is $(16.9 \pm 3.0) \times 10^{-4}$, where the systematic error evaluation comes from a variation of control regions borders and by the modelling of the P_T^2 shape.

The correction to R is:

$$\Delta\mathrm{R} = (16.9 \pm 3.0) \times 10^{-4} \tag{5.4}$$

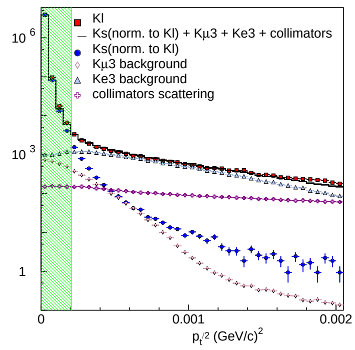

Figure 6: P_T distrib.

$\mathrm{K_L}$ beam scatterings in the final collimator produce $\pi\pi$ events with high P_T which are removed in the $\pi^+\pi^-$ sample by the P_T cut, but are kept in the $\pi^0\pi^0$ sample, inducing a correction on R. $\mathrm{K_S}$ beam scattering are instead removed by the $\mathrm{R_{COG}}$ cut which is $\pi^+\pi^-$ and $\pi^0\pi^0$ symmetric.

[5] For each track a cluster in the calorimeter is associated; the E/p is the ratio of the cluster energy and the track momentum

The collimator background is estimated using $\pi^+\pi^-$ events with $P_T^2 > 200(MeV/c)^2$ with $M_{\pi\pi} = M_K$ and it is cross-checked in $\pi^0\pi^0$ $\mathrm{R_{COG}}$ distribution. The beam scattering background is $(9.6 \pm 2.0) \times 10^{-4}$. The correction to R is:

$$\Delta \mathrm{R} = (-9.6 \pm 2.0) \times 10^{-4} \tag{5.5}$$

6. $\pi^0\pi^0$ reconstruction

From the four detected photons in the calorimeter, the distance D of the decay from the calorimeter is given by:

$$D = \frac{\sqrt{\sum E_i E_j \times (r_{ij})^2}}{M_K} \tag{6.1}$$

where E_i are the photons energies and r_{ij} the distances between photons in the calorimeter. The two photons invariant mass is:

$$m_{ij} = \frac{\sqrt{E_i E_j} \,.\, r_{ij}}{D} \tag{6.2}$$

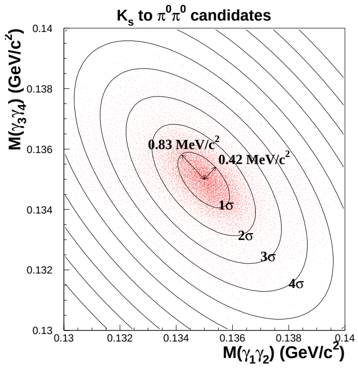

Figure 7: $\pi^0\pi^0$ χ^2

The best combination of two photons couples which minimizes the χ^2 of the two photons invariant masses w.r.t. the π^0 mass is chosen and a cut on the χ^2 is applied to suppress $3\pi^0$ decays with missing photons. Events with extra photons in time are rejected.

From the $\mathrm{K_S} \to \pi^0\pi^0$ decay distribution the AKS position can be reconstructed: the calorimeter energy scale is adjusted to match the AKS nominal position. In this way the neutral energy knowledge is again converted into geometry.

The stability of the reconstructed AKS position is checked as a function of the kaon energy (non linearity check). In K_{e3} decays the electron energy measured by the calorimeter can be checked w.r.t. the momentum measured by the magnetic spectrometer: E/p is constant within $\approx 0.1\%$ from a few GeV to 100 GeV.

In special runs a π^- beam is directed onto two thin targets (one at the beginning of the kaon fiducial decay region, one at the end), producing π^0 and η with known decay position. $\gamma\gamma$ decays are used to reconstruct the decay position assuming π^0 or η masses.

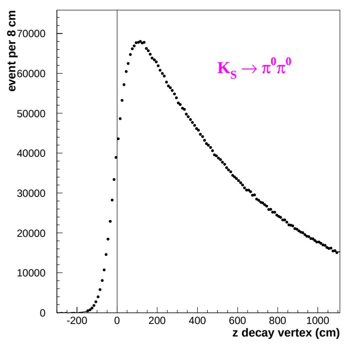

Figure 8: $\pi^0\pi^0$ z distrib.

Using $\eta \to 3\pi^0 \to 6\gamma$, M_η/M_{π^0} can be measured without the uncertainty due to the energy scale knowledge. The new preliminary NA48 result on M_η is:

$$M_\eta = (547.823 \pm 0.020_{stat} \pm 0.055_{syst}) \text{ MeV} \tag{6.3}$$

The total uncertainty on R induced by the neutral energy scale is:

$$\Delta \mathrm{R} = \pm 5.8 \times 10^{-4} \tag{6.4}$$

The background in $\pi^0\pi^0$ events is due to $\mathrm{K_L} \to 3\pi^0$ where two photons are outside the calorimeter acceptance or overlap with the other clusters. The background is estimated using a control region in χ^2 (the $3\pi^0$ background is almost flat because of its combinatorial nature) and using $\mathrm{K_S}$ events to evaluate resolution tails.

The background is $(5.9 \pm 2.0) \times 10^{-4}$, where the systematic error evaluation comes from the uncertainty in the background extrapolation from the control to the signal region. The extrapolation correction factor is calculated by a Montecarlo. Photon conversions and photon hadron-productions are also taken into account by the Montecarlo.

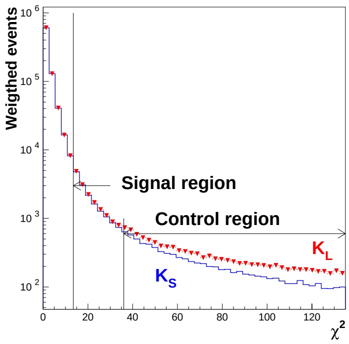

Figure 9: χ^2 distrib.

The correction to R is:

$$\Delta \mathrm{R} = (-5.9 \pm 2.0) \times 10^{-4} \tag{6.5}$$

7. The Lifetime weighting principle and the acceptance correction

For a given decay position, the acceptances for $\mathrm{K_S}$ and $\mathrm{K_L}$ are the same. But $\mathrm{K_S}$ and $\mathrm{K_L}$ have very different decay lenghts because $\tau_{\mathrm{K_L}} \approx 600 \times \tau_{\mathrm{K_S}}$, so the total acceptance for $\mathrm{K_S}$ and $\mathrm{K_L}$ is quite different and this would imply a large correction on R. To avoid this, $\mathrm{K_L}$ events are weighted w.r.t. their proper time on a event by event basis to make their decay distribution similar to the $\mathrm{K_S}$ one. The weight is $\approx e^{-z/(\beta\gamma c)(1/\tau_{\mathrm{K_S}} - 1/\tau_{\mathrm{K_L}})}$. The acceptance correction almost cancels in the double ratio using the $\mathrm{K_L}$ lifetime weighting but in this way the statistical error on R increases by about 35%.

A small residual acceptance effect comes from the 0.6 mrad angle between the $\mathrm{K_S}$ and the $\mathrm{K_L}$ beam, especially in $\pi^+\pi^-$ events which at the first drift chamber are still separated by about 1 cm. The acceptance correction to R is estimated by a Montecarlo:

$$\Delta \mathrm{R} = (26.7 \pm 4.1_{\mathrm{MCstat}} \pm 4.0_{\mathrm{syst}}) \times 10^{-4} \tag{7.1}$$

where the first error is due to Montecarlo statistics and the systematic error comes from the knowledge of the beams geometry and by the comparison of two different Montecarlos.

8. Accidental activity

The accidental activity from the beam can induce event losses. This effect cancels to first order in R but a residual correction on R can be due to:

$$\Delta \mathrm{R} \approx \Delta(\pi^+\pi^- - \pi^0\pi^0) \times \Delta(\mathrm{K_L} - \mathrm{K_S}) \tag{8.1}$$

where $\Delta(\pi^+\pi^- - \pi^0\pi^0)$ is the difference between neutral and charged losses; it is minimized by applying dead time conditions to all the modes and is estimated to be $(1.4 \pm 0.7)\%$.

$\Delta(\mathrm{K_L} - \mathrm{K_S})$ is the difference in the accidental activity seen by $\mathrm{K_L}$ and $\mathrm{K_S}$ events; it is small by the design of the experiment because the two beams are simultaneous and so $\mathrm{K_L}$ and $\mathrm{K_S}$ events see the same activity, within 1% (checked directly in data).

The intensity difference uncertainty corresponds to $\Delta\mathrm{R} = (0 \pm 3) \times 10^{-4}$. The residual illumination difference uncertainty corresponds to $\Delta\mathrm{R} = (0 \pm 3) \times 10^{-4}$ (estimated using random events overlayed to $\pi\pi$ Montecarlo and data events). The total uncertainty is:

$$\Delta\mathrm{R} = \pm 4.4 \times 10^{-4} \tag{8.2}$$

9. First and second order result

The number of events (corrected for mistagging) collected in the years 1998 and 1999 are:

$$\mathrm{K_L} \to \pi^0\pi^0 : 3.29 \times 10^6, \quad \mathrm{K_S} \to \pi^0\pi^0 : 5.21 \times 10^6, \tag{9.1}$$

$$\mathrm{K_L} \to \pi^+\pi^- : 14.45 \times 10^6, \; \mathrm{K_S} \to \pi^+\pi^- : 22.22 \times 10^6. \tag{9.2}$$

The double ratio is calculated in bins of energy and averaged. The first order result is:

$$\mathrm{R} = 1 - (1.261 \pm 0.101)\% + \Delta\mathrm{R}^{(2)} \tag{9.3}$$

The sum of all the corrections to R, quoted in (3.1), (2.3), (5.3), (6.4), (5.4), (6.5), (5.5), (4.3), (4.8), (7.1) and (8.2) gives the second order result:

$$\Delta\mathrm{R}^{(2)} = (+35.9 \pm 12.6) \times 10^{-4} \tag{9.4}$$

$$\mathrm{R} = 1 - (1.261 \pm 0.101)\% + (0.359 \pm 0.126)\% \tag{9.5}$$

$$\mathrm{R} = 0.99098 \pm 0.00101_{stat} \pm 0.00126_{syst} \tag{9.6}$$

where the first error is statistical and the second systematic. The systematic error is partially of statistical nature because some of the corrections (i.e. trigger efficiency) depends on a sample of downscaled unbiased triggers.

$$\mathrm{Re}(\epsilon'/\epsilon) \; = (15.0 \pm 2.7) \times 10^{-4} \; [1998 + 1999] \tag{9.7}$$

The already published NA48 result [4], based on the data collected in 1997, was:

$$\mathrm{Re}(\epsilon'/\epsilon) \; = (18.5 \pm 7.3) \times 10^{-4} \; [1997] \tag{9.8}$$

Taking into account the correlated part of the systematic error between (9.8) and (9.7), the combined result is:

$$\mathrm{Re}(\epsilon'/\epsilon) \; = (15.3 \pm 2.6) \times 10^{-4} \; [1997 + 1998 + 1999] \tag{9.9}$$

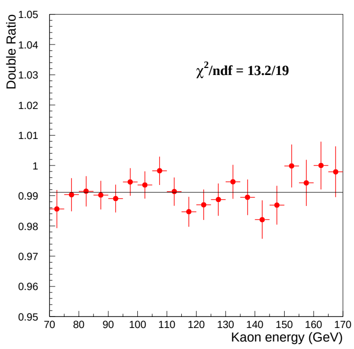

Figure 10: R vs energy

Fig.10 shows the Double Ratio in bins of kaon energy after all the corrections.

10. KTeV experiment

The KTEV experiment at Fermilab was designed to measure $\mathrm{Re}(\epsilon'/\epsilon)$ using a different technique w.r.t. NA48. It has two $\mathrm{K_L}$ beams: the first one ("Vacuum") is the true $\mathrm{K_L}$ beam, the second one ("Regenerator") produces a $\mathrm{K_S}$ beam thanks to a regenerator. This regenerator is continuously moved from one beam to the other.

$\pi^+\pi^-$ detection is accomplished by a magnetic spectrometer, while $\pi^0\pi^0$ are reconstructed by a CsI crystals calorimeter.

The regenerator-vacuum beam identification is obtained by the extrapolated kaon impact point at the calorimeter because the two beams are parallel and separated by about 20 cm.

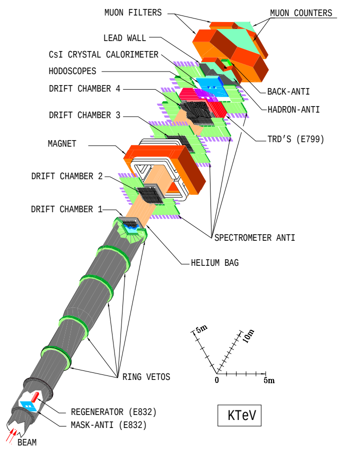

Figure 11: KTEV

The total background in $\pi^+\pi^-$ events is 0.1% in the vacuum beam and 0.9% in the regenerator one; the total background in $\pi^0\pi^0$ events is 0.5% in the vacuum beam and 1.2% in the regenerator beam.

The acceptance is calculated by a very detailed Montecarlo, cross-checked by high statistics samples of K_{e3} and $3\pi^0$. The acceptance correction on R is about 5% but it is mostly due just to simple geometry.

A cross-check of the acceptance correction has been performed doing the analysis with a $\mathrm{K_L}$ lifetime weighting (similar to the NA48 approach). The change in R w.r.t. the standard analysis is:

$$\Delta\mathrm{R} = -9 \pm 13_{(stat)} \pm 18_{(syst)} \times 10^{-4} \tag{10.1}$$

showing no significant bias.

The result from data collected in 1997 (statistically independent from the published result [3]) is:

$$\mathrm{Re}(\epsilon'/\epsilon) \ = (19.8 \pm 1.7_{stat} \pm 2.3_{syst} \pm 0.6_{MC}) \times 10^{-4} \tag{10.2}$$

The published result [3](based on 1996 data) has been reanalyzed and the new number is:

$$\mathrm{Re}(\epsilon'/\epsilon) \ = (23.2 \pm 3.0_{(stat)} \pm 3.2_{(syst)} \pm 0.7_{(MCstat)}) \times 10^{-4} \tag{10.3}$$

The combined result for the 1996-1997 dataset is:

$$\mathrm{Re}(\epsilon'/\epsilon) \ = (20.7 \pm 1.5_{(stat)} \pm 2.4_{(syst)} \pm 0.5_{(MCstat)}) \times 10^{-4} \tag{10.4}$$

where the error due only to Montecarlo statistics has been isolated.

$$\mathrm{Re}(\epsilon'/\epsilon) \ = (20.7 \pm 2.8) \times 10^{-4} \tag{10.5}$$

The 1996+1997 statistics is:

$$\mathrm{K_L} \to \pi^0\pi^0 : 3.4 \times 10^6, \ \ \mathrm{K_S} \to \pi^0\pi^0 : 5.6 \times 10^6, \tag{10.6}$$

$$\mathrm{K_L} \to \pi^+\pi^- : 11.2 \times 10^6, \ \mathrm{K_S} \to \pi^+\pi^- : 19.4 \times 10^6. \tag{10.7}$$

11. Experimental results comparison

The first generation of experiments published the following results (1], [2]):

$$\text{NA31(CERN)} : \text{Re}(\tfrac{\epsilon'}{\epsilon}) = (23.0 \pm 6.5) \times 10^{-4} \quad (11.1)$$
$$\text{E731(FNAL)} : \text{Re}(\tfrac{\epsilon'}{\epsilon}) = (7.4 \pm 5.9) \times 10^{-4} \quad (11.2)$$

The $\text{Re}(\epsilon'/\epsilon)$ world average, including (11.1), (11.2), (9.9), (10.5), is:

$$\text{Re}(\epsilon'/\epsilon) \ = (17.2 \pm 1.8) \times 10^{-4} \quad (11.3)$$

with $\chi^2/\text{ndf} = 5.5/3$ (14% probability).

The direct CP violation in the neutral kaon system is now firmly established with a significance more than 9 σ's.

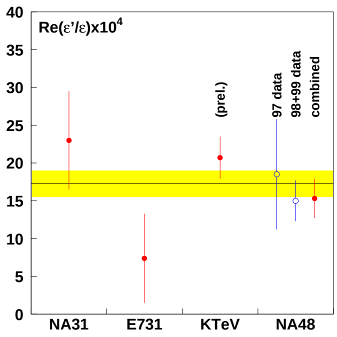

Figure 12: world average

References

[1] G.Barr et al., *Phys. Lett.* **B 3** (1) 7, 233 (1993).

[2] L.K.Gibbons et al, *Phys. Rev. Lett.* **7** (0) , 1203 (1993).

[3] A.Alavi-Harati et al, *Phys. Rev. Lett.* **8** (3) , 22 (1999).

[4] V.Fanti et al., *Phys. Lett.* **B 4** (6) 5, 335 (1999).