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Measurement of the CP violation parameter $|\eta_{+-}|$ and the charge asymmetry in $K^{\pm} \rightarrow 3\pi$ decays by NA48 and NA48/2

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Throughout all periods of data taking, the main goal of the NA48 experiment has been the search for CP violation (CPV) in kaon decays. The observable η_{+-} links the parameters of indirect and direct CPV ($\eta_{+-} = \varepsilon + \varepsilon'$) and is defined as the CP violating amplitude ratio of the neutral kaon decaying into two charged pions: $\eta_{+-} = A(K_L \rightarrow \pi^+\pi^-)/A(K_S \rightarrow \pi^+\pi^-)$. NA48 has determined $|\eta_{+-}|$ via the measurement of the ratio of decay rates $\Gamma(K_L \rightarrow \pi^+\pi^-)/\Gamma(K_L \rightarrow \pi e \nu)$, denoted as $\Gamma_{K2\pi}/\Gamma_{Ke3}$, using a pure K_L beam in 1999. From a sample of 47000 $K_{2\pi}$ and five million K_{e3} decays, we obtained results for $\Gamma_{K2\pi}/\Gamma_{Ke3}$, $\mathrm{BR}(K_L \rightarrow \pi^+\pi^-)$ and $|\eta_{+-}|$.

Complementary with ε'/ε, the observable for direct CPV in the charged kaons sector is the asymmetry $A_g = (g^+ - g^-)/(g^+ + g^-)$ of the linear slope parameter g in the Dalitz plot of $K^{\pm} \rightarrow 3\pi$ decays. The NA48/2 experiment used simultaneous K^+/K^- beams, and from the data samples taken in 2003 and 2004, $3 \times 10^9 K^{\pm} \rightarrow \pi^{\pm}\pi^+\pi^-$ and $9 \times 10^7 K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$ were selected. The charge asymmetry parameter A_g was determined with a total uncertainty of $\sim 2 \times 10^{-4}$ for each mode, ten times more accurate than previous measurements.

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1. Experimental setup

The NA48 experiment at the CERN SPS was originally designed for the precision measurement of direct CPV in neutral kaon decays using simultaneous K_S and K_L beams. The data for the measurement of $|\eta_{+-}|$ were taken during a dedicated run in 1999 with a pure K_L beam, which was derived from the extracted 450 GeV proton beam hitting a beryllium target. After passing the final collimator 126 m downstream of the target, the neutral beam entered the 90 m long evacuated decay volume, which was followed by the NA48 main detector.

The successor experiment NA48/2 used two simultaneous K^+ and K^- beams, which were produced at the same target. An achromatic system of four dipole magnets with zero total deflection selected momenta with (60 ± 3) GeV/c in a charge-symmetric way. Both beams followed the same path in the decay volume, their axes coinciding within $\sim$1 mm.

One of the main components of the NA48 detector is the electromagnetic calorimeter based on liquid krypton with tower readout. The calorimeter is 27 radiation lengths long and fully contains electromagnetic showers with energies up to 100 GeV. The energy resolution for photons at 20 GeV is $\sim 1\,\%$, and the spatial resolution is ~ 1 mm. A magnetic spectrometer, consisting of four drift chambers and a central dipole magnet is used to measure the momenta of charged particles. The spatial resolution per projection is 100 μm, and the vertex can be reconstructed with a transversal resolution of ~ 2 mm. A detailed description of the detector can be found in [1].

2. CP violation parameter $|\eta_{+-}|$

The basic measurement of this analysis is the ratio $R = \Gamma_{K2\pi}/\Gamma_{Ke3}$. After defining a sample of good 2-track events, we separated the two decay channels. To obtain a clean signal of the CP violating decay $K_L \to \pi^+\pi^-$, we had to suppress the main K_L decay modes by several orders of magnitude, unavoidably rejecting also part of the $\pi^+\pi^-$ decays. Inefficiencies of the event selection and signal losses, which were not exactly reproduced by the MC simulation, had to be measured precisely and corrected for. With the ratio $\Gamma_{K2\pi}/\Gamma_{Ke3}$ thus obtained, we determined the branching ratio of the decay $K_L \to \pi^+\pi^-$

$$BR(K_L \to \pi^+\pi^-) = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi e \nu)} \cdot BR(K_L \to \pi e \nu)$$

and the CP violation parameter $|\eta_{+-}|$

$$|\eta_{+-}| \equiv \sqrt{\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}} = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \frac{\tau_{KS}}{\tau_{KL}}}\,.$$

2.1 Event selection

From the sample of good 2-track events, additional cuts were applied to extract the $K_L \to \pi^+\pi^-$ signal, where the two semileptonic K_L decays, K_{e3} and $K_{\mu3}$, are the dominant background sources. 47142 $K_{2\pi}$ candidates were selected with an estimated background of only 0.5%. The left plot in Fig. 1 shows the distribution of the invariant $\pi^+\pi^-$ mass $m_{\pi\pi}$ after all selection requirements except the cut on $m_{\pi\pi}$ itself. The data are well described by the sum of the $K_{2\pi}$ signal MC and the two background MCs.

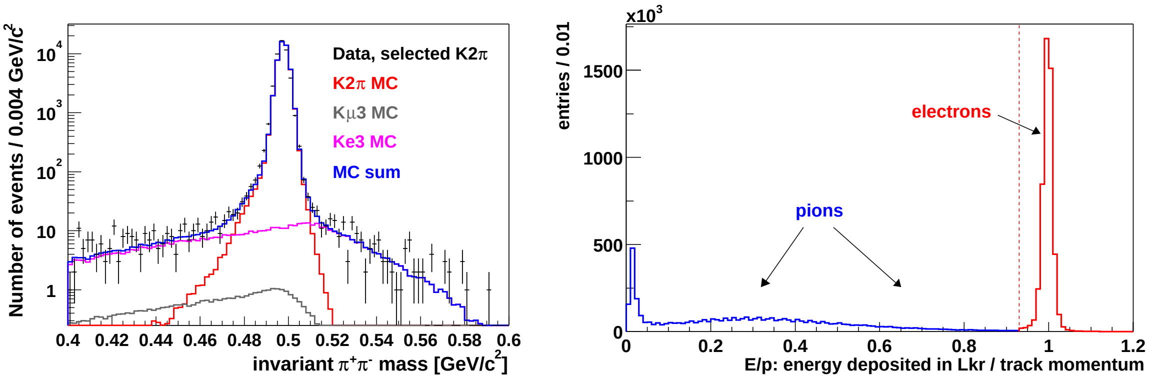

Figure 1: Left: Distribution of the invariant $\pi^+\pi^-$ mass. Right: The ratio of calorimetric energy E over the momentum p for the tracks of all selected K_{e3} events.

Being the only relevant K_L decay channel with an electron in the final state, K_{e3} events can be selected by applying only an E/p criterion, where E is the energy deposited in the electromagnetic calorimeter, and p is the track momentum measured in the magnetic spectrometer. If E/p for any of the tracks exceeded 0.93, the track was tagged as being due to an electron, thus classifying the event as a K_{e3} decay. Nearly five million K_{e3} candidates remained with an equally small background of $\sim 0.5\%$. The quantity E/p is shown in Fig. 1 (right plot).

Various studies have been performed to determine the systematic uncertainties and the event number corrections due to inefficiencies of the trigger and the event selection. The largest contributions to the systematic error come from the imperfect knowledge of the kaon energy spectrum and the cut against muons, which is necessary to suppress the $K_{\mu 3}$ decay channel.

2.2 Results

After applying all corrections, the final result is

$$\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi e \nu)} = (4.835 \pm 0.022_{stat.} \pm 0.016_{syst.}) \times 10^{-3} = (4.835 \pm 0.027) \times 10^{-3}.$$

For the determination of $BR(K_L \to \pi^+\pi^-)$ and $|\eta_{+-}|$, one must subtract the contribution of the CP conserving direct emission process $K_L \to \pi^+\pi^-\gamma(DE)$, leading to a correction of $\sim$0.2 %. We obtained for the $K_{2\pi}$ branching ratio

$$BR(K_L \to \pi^+\pi^-) = (1.941 \pm 0.019) \times 10^{-3},$$

including the CP violating inner bremsstrahlung component $K_L \to \pi^+\pi^-\gamma(IB)$. Using our result for $BR(K_L \to \pi^+\pi^-)$, we determined the CP violation parameter

$$|\eta_{+-}| = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \frac{\tau_{KS}}{\tau_{KL}}} = (2.223 \pm 0.012) \times 10^{-3}.$$

All results are in good agreement with recent measurements by KTeV [3] and KLOE [4], and the three experiments jointly contradict the former PDG values [5]. A detailed description of the analysis is given in [6].

3. Charge asymmetry in $K^{\pm}\rightarrow 3\pi$ decays

Due to their high branching fractions at the level of a few percent and a simple event selection with low background, $K^{\pm}\rightarrow 3\pi$ decays are well suited to search for direct CPV in charged kaon decays. For that, the NA48/2 experiment used simultaneous K^{+}/K^{-} beams and compared the Dalitz plot shapes between K^{+} and K^{-} decays into 3π.

The $K^{\pm}\rightarrow 3\pi$ matrix element squared is conventionally parametrized as

$$|M(u,v)|^2 \propto 1+gu+hu^2+kv^2$$

where g,h,k are the linear and quadratic Dalitz plot slope parameters ($|h|,|k| \ll |g|$), and the two Lorentz invariant variables u and v are defined as

$u=\frac{s_3-s_0}{m_\pi^2},\ v=\frac{s_1-s_2}{m_\pi^2}$ with $s_i=(P_K-P_{\pi_i})^2,\ i=1,2,3\ (3=\text{odd } \pi);\quad s_0=1/3\,(s_1+s_2+s_3)$.

The observable in this measurement is the slope asymmetry $A_g=(g^+-g^-)/(g^++g^-)\approx \Delta g/(2g)$, where Δg is the slope difference, and g is the average linear slope. Any value of $A_g\neq 0$ is a manifestation of direct CP violation. The SM predictions are affected by large uncertainties and range between 10^{-6} and 10^{-5} [7]. However, theoretical calculations involving processes beyond the SM [8] do not exclude enhancements of the asymmetry A_g up to a few 10^{-4}. Mainly limited by systematic effects, previous experiments set upper limits on A_g at the level of a few 10^{-3}. The goal of the NA48/2 experiment was to measure A_g with a precision at least one order of magnitude better, both for charged ($K^{\pm}\rightarrow\pi^{\pm}\pi^{+}\pi^{-}$) and neutral ($K^{\pm}\rightarrow\pi^{\pm}\pi^{0}\pi^{0}$) mode, being in the reach to test models involving new physics.

To measure such a small asymmetry, perfect charge symmetrization in the experimental setup was mandatory. This was achieved by employing for the first time simultaneous superimposed K^{+} and K^{-} beams with similar momentum spectra. In addition, the polarities of all magnets in beam transport (achromat) and the spectrometer had been reversed regularly to equalize local effects on the acceptance.

It is sufficient to take the u-projection of the Dalitz plot to extract the slope difference Δg, comparing the reconstructed u-spectra of K^{+} and K^{-} decays:

$$R(u)=\frac{N^+(u)}{N^-(u)}\sim 1+\frac{\Delta g\,u}{1+gu+hu^2}\,.$$

However, mainly due to the presence of magnetic fields, there are experimental asymmetries which do not cancel in the simple ratio. As a logical expansion of the polarity reversal during data taking, four u-ratios with the four possible combinations of magnetic field polarities were defined, the product of these u-ratios forming the quadruple ratio $R_4(u)$. Finally, Δg was extracted by fitting the quadruple ratio with a function $f(u)=n\cdot\left(1+\frac{\Delta g u}{1+gu+hu^2}\right)^4$ (see Fig. 2). This method leads to a cancellation of global time instabilities, local beamline biases and left-right detector asymmetries. Furthermore, it is independent of the K^{+}/K^{-} flux ratio, and the analysis does not rely on a detailed Monte-Carlo simulation.

A large number of systematic checks have been performed, e.g. the data were divided in bins of data taking periods to test the time stability of the result, and the components of the quadruple ratio were rearranged in control quantities to search for 2nd order effects of possible detector asymmetries. No significant effects were found.

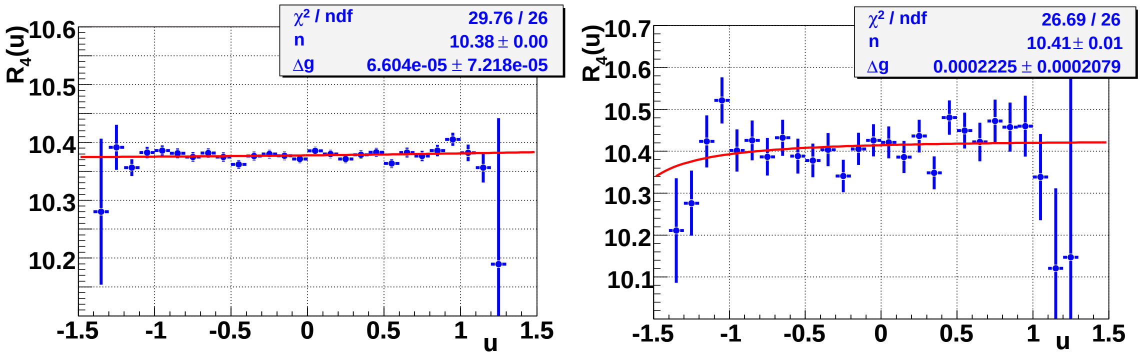

Figure 2: The quadruple ratio in bins of u for charged (left) and neutral (right) mode, with the results of the fit to extraxt Δg. The normalization n is sensitive to the K^+/K^-flux ratio, while Δg is not.

With $3.11 \times 10^9 K^\pm \to \pi^\pm\pi^+\pi^-$ and $9.13 \times 10^7 K^\pm \to \pi^\pm\pi^0\pi^0$ decays selected, the results for the charge asymmetries are:

Charged mode: $\boxed{A_g = (-1.5 \pm 1.5_{stat.} \pm 0.9_{trig.} \pm 1.1_{syst.}) \times 10^{-4} \; = \; (-1.5 \pm 2.1) \times 10^{-4}}$

Neutral mode: $\boxed{A_g = (1.8 \pm 1.7_{stat.} \pm 0.9_{syst.}) \times 10^{-4} \; = \; (1.8 \pm 1.9) \times 10^{-4}}$

As proposed, the results are ten times more precise than any previous measurement; in both modes, the statistical errors dominate. The results are compatible with the SM predictions, i.e. no evidence for direct CP violation of the order 10^{-4} has been found.

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