New results on kaon decays from NA48

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We report on recent results on rare and semileptonic kaon decays from NA48 and NA48/2.

Using data from a minimum bias run in 1999 we present a new measurement of the CP violating decay $K_L \to \pi^+\pi^-$ with over 40000 selected events. We measured the ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi^\pm e^\mp \nu) = (4.835 \pm 0.038) \times 10^{-3}$ leading to the precise determination of the CP violation parameter $|\eta_+ -| = (2.223 \pm 0.013) \times 10^{-3}$.

From the same data we selected over 2×10^6 $K_L \to \pi^\pm \mu^\mp \nu$ decays. Preliminary results from a dalitz plot fit yield the values for the form factors $\lambda_+ = 0.0260 \pm 0.0007_{stat} \pm 0.0010_{syst}$ and $\lambda_0 = 0.0120 \pm 0.0008_{stat} \pm 0.0015_{syst}$.

In one month of data taking in 2003 the NA48/2 experiment collected over 2×10^5 $K^\pm \to \pi^\pm \pi^0 \gamma$ decays. A measurement of the relative contributions of Inner Bremsstrahlung, Direct Emission, and their interference is presented which results in $frac(DE) = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\%$ and $frac(INT) = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\%$ showing for the first time a non-zero value of the interference term.

1. Beam line and Detector description

1.1. The NA48 experiment

After the discovery of direct CP violation it was the task of the NA48 experiment to perform a precise measurement of direct CP violation which was done with data taken from 1997 to 2001 [1].

To produce the kaons a proton beam from the CERN-SPS accelerator with a momentum of 450 Gev/c per proton was directed onto a target 126 m before the decay region preceding the detector. Thus after cleaning the secondary beam from charged particles all K_S decayed before reaching the detectable volume and only K_L remained in the beam. To achieve a simultaneous K_S beam a fraction of the remaining proton beam was lead onto a second target displaced by 7.2 cm with respect to the K_L beam and situated immediately before the decay region. After passing a final collimator, both beams entered an evacuated tank with a length of 114 m which was fitted with rings of scintillators as veto counters.

In 1999, no protons were directed onto the K_S target for three days thus resulting in a pure K_L beam. We report on two analyses using the data collected in this special run.

The NA48 detector is separated from the vacuum decay region by a thin kevlar window (see fig. 1). Its first part is a magnet spectrometer consisting of a dipole magnet and four drift chambers, two before and after the magnet, respectively. The magnet introduces a momentum kick perpendicular to the beam axis. Each drift chamber consists of eight wire planes: two in vertical, horizontal, and the two diagonal directions, respectively. The achieved momentum resolution is $\sigma(p)/p \approx 0.5\ \% \oplus 0.009\ p\ \%$ (p in GeV/c), which corresponds to a resolution of 0.95% for a particle with a momentum of 50 GeV/c. The spectrometer is followed by a hodoscope which provides an

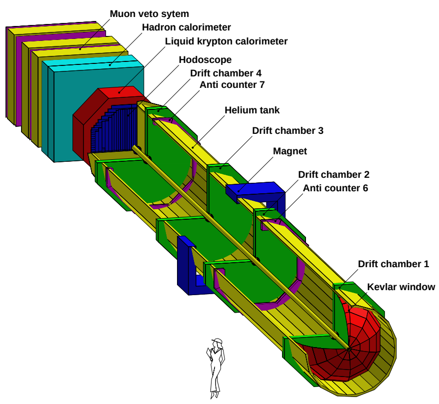

Figure 1. The NA48 detector.

excellent time measurement and which is used for the low level trigger for charged particles.

The energy measurement is done with a liquid krypton calorimeter (LKr) and a hadron calorimeter. The LKr has a length along the beam line of 1.27 m. It consists of $\approx$ 13500 cells stretching along the whole detector with an area of 2×2 cm^2 facing the beam. The resulting energy resolution is $\sigma(E)/E \approx 3.2\ \%/\sqrt{E} \oplus 9\ \%/E \oplus 0.42\ \%$ (E in GeV). The spacial resolution in the transversal plane is $\sigma_x = \sigma_y = (0.42/\sqrt{E} \oplus 0.06)$ cm. A hodoscope inside the LKr is again used as an input to the low level trigger.

The hadron calorimeter consists of 42 t of iron with layers of scintillators inside. It is followed by a muon veto system with three layers of an iron and a scintillator wall each.

1.2. The NA48/2 experiment

After the NA48/1 experiment took data of K_S and hyperon decays in 2002, the NA48/2 experiment followed to acquire data using simultaneous, high intensity K^+ and K^- beams. The data taking period of the NA48/2 experiment covered about 50 days in 2003 and 60 days in 2004.

The major change towards NA48/2 was of course the beam line. Using the same target position as for the production of K_L, it then had two sets of achromats to select charged particles with a momentum of 60 ± 3 GeV/c. These achromats consisted of sets of dipole magnets to deflect charged particles both up and down and lead them through collimators, thus selecting the momentum, before joining the two beams of different charge again. The second achromat had two microstrip drift chambers at the two points of maximum amplitude of the charged beams, respectively, and with a third chamber after the beam reunion. These three chambers formed the KAon BEam Spectrometer (KABES) which allowed for a measurement of the kaon momentum.

The magnet current was reduced to take into account the lower average momentum of the decay products. Thus a momentum resolution of $\sigma(p)/p \approx 1.02\ \% \oplus 0.044\ p\ \%$ (p in GeV/c) was achieved.

2. Results from NA48

Both results from NA48 on which we report here were obtained from data taken during a three day minimum bias run with K_L decays only. The charged decays were triggered by a two-level trigger system. The first level asked for two particles in the hodoscope for charged particles whilst the second level required a vertex of two tracks of opposite charge using information from the spectrometer. As a control trigger to measure the efficiency of the second trigger level a down-scaled version of the first trigger level was used.

2.1. $K_L \to \pi^+\pi^-$

Recent measurements from KTeV and KLOE show results on the ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi^\pm e^\mp \nu)$, denoted as $\Gamma_{K2\pi}/\Gamma_{Ke3}$, as well as on $BR(K_L \to \pi^+\pi^-)$ and $|\eta_+ -|$, which all disagree by several percent with the averages quoted in PDG 2004 [2]. Based on our measurement of $BR(K_{e3})$ [3] the goal of the analysis presented here is to measure the ratio $\Gamma_{K2\pi}/\Gamma_{Ke3}$ with a total relative uncertainty of less than one percent.

The data sample used in this analysis consists of events selected in three days of data taking in 1999. The trigger used is described above. Monte Carlo studies were carried out using the GEANT-based NA48 simulation in the version NASIM032. To account for radiative effects we used the PHOTOS program package [4] to simulate inner bremsstrahlung (IB) in the $K_L \to \pi^+\pi^-$ decay mode. For K_{e3} decays, IB was simulated using the event generator KLOR [5], a program which includes both real photon emission and virtual photon exchange.

2.1.1. Data analysis

Event selection

The majority of the event selection was common to the decays $K_{2\pi}$ and K_{e3}. After passing the trigger the events had to have two tracks of opposite charge. The decay position was defined by the point of closest approach of the two tracks. A set of general geometrical cuts was passed by $\approx$ 20 million events.

To select $K_{2\pi}$ events from the basic 2-track sample further cuts were applied. Kinematical cuts on the two-track invariant mass and the transverse momentum removed background coming from hadronic and semileptonic channels, respectively. Further suppression of K_{e3} decays involved a cut in the ratio of the energy deposited in the electromagnetic calorimeter to the associated track momentum (E/p). $K_{\mu 3}$ decays were removed from the data sample by rejecting any matching hit in the muon veto system.

Being the only relevant K_L decay channel with an electron in the final state, K_{e3} events can be selected only by applying the E/p criterion.

A final cut for both decay channels was the requirement that the kaon momentum had to be between 70 GeV/c and 140 GeV/c to ensure a good description by the MC simulation. Due to the neutrino the kaon momentum for the K_{e3} decay channel can only be calculated up to a quadratic ambiguity. In this case, both solutions had to lie within the limits.

The detector acceptance was $A(K_{2\pi}) = 0.5929 \pm 0.0012$ and $A(K_{e3}) = 0.1843 \pm 0.0002$ for the two decay modes, respectively.

Corrections and systematic uncertainties

A correction to the rejection of events with hits in the muon veto system (MUV) had to be applied as pions penetrating the whole detector or decaying after having entered the electromagnetic calorimeter were not simulated in the MC.

As described at the beginning of this section, a down-scaled version of the first level trigger (i.e. two tracks) was recorded to provide a sample for evaluating the efficiency of the second trigger level which was then used as a correction.

As showers could not be simulated to the required precision, the E/p criterion was not applied to simulated events. Thus, a correction to the ratio $\Gamma_{K2\pi}/\Gamma_{Ke3}$ had to be evaluated from data.

A final correction was applied to account for background contributions in the $K_{2\pi}$ and K_{e3} samples. The main contributions to the $K_{2\pi}$ sample originated from K_{e3} and $K_{\mu 3}$ events, whereas background in the K_{e3} sample came mainly from $K_{\mu 3}$ events with a minor contribution from $K_{2\pi}$ events. The overall correction was evaluated to $(-0.46 \pm 0.03)\%$.

The total systematic uncertainty was estimated as the quadrature sum of the uncertainties of the corrections as well as influences due to the choice of using the lower kaon energy solution in K_{e3} events and due to an uncertainty in the radiative corrections.

2.1.2. Results

The ratio $\Gamma_{K2\pi}/\Gamma_{Ke3}$

Applying the corrections which yield a total correction of only -0.1% we obtained

$$\frac{\Gamma(K_{2\pi})}{\Gamma(K_{e3})} = (4.835 \pm 0.026_{stat} \pm 0.027_{syst}) \times 10^{-3} = (4.835 \pm 0.038) \times 10^{-3} \quad (1)$$

The branching ratio $BR(K_L \to \pi^+\pi^-)$

To calculate the branching ratio we chose to exclude the CP-conserving contribution from $K_L \to \pi^+\pi^-\gamma$ decays with the gamma coming from direct emission (DE), keeping only those coming from inner bremsstrahlung (IB). As photons were neither required nor rejected in the event selection, the remaining contribution of the DE decay had to be evaluated. Using the E731 and KTeV measurements for the DE fraction in $K_{2\pi}$ decays [6–8] and correcting for the different acceptances, we obtained a remaining fraction of $(0.180 \pm 0.009)\%$ which had to be subtracted from the result for $\Gamma_{K2\pi}/\Gamma_{Ke3}$ presented above. Using furthermore the NA48 measurement [3] for $BR(K_{e3}) = 0.4022 \pm 0.0031$, which had been corrected for updated results on $BR(K_{3\pi^0})$, we achieved the following result

$$BR(K_L \to \pi^+\pi^- + \pi^+\pi^-\gamma(IB)) = (1.941 \pm 0.021) \times 10^{-3} \quad (2)$$

The CP-violation parameter $|\eta_{+-}|$

Finally, using our result for $BR(K_L \to \pi^+\pi^-)$ we determined the CP-violation parameter

$$|\eta_{+-}| = \sqrt{\frac{BR(K_L \to \pi^+\pi^-)}{BR(K_S \to \pi^+\pi^-)} \cdot \frac{\tau_{KS}}{\tau_{KL}}} = (2.223 \pm 0.013) \times 10^{-3} \quad (3)$$

using NA48 [9] and KLOE [10,11] measurements for τ_{KS}, τ_{KL} and $BR(K_S \to \pi^+\pi^-)$, respectively.

Comparison of results

In figure 2 we show the comparison of our results with those from KTeV [12] and KLOE [13] as well as with the PDG 2004 values [2]. For all three measurements the recently obtained values commonly contradict the older measurements summarised in PDG 2004.

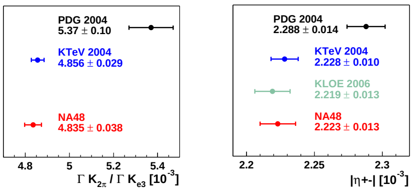

Figure 2. Comparison of results for $\Gamma_{K2\pi}/\Gamma_{Ke3}$ (left) and $|\eta_{+-}|$ (right). The date represents the year of publication.

2.2. $K_L \to \pi^\pm \mu^\mp \nu$

K_{l3} decays allow for the determination of $f_+(0)|V_{us}|$. $f_+(0)$ is the vector form factor at zero momentum transfer which has to be determined by theory. As recent calculations [14] show, $f_+(0)$ could be constrained by measurements of slope and curvature of the scalar form factor f_0 of the $K_{\mu 3}$ decay in particular. Furthermore, it has been suggested by M. Oertel at this conference that a precise measurement of $K_{\mu 3}$ decays would be sensitive to right-handed charged quark currents.

Here, we present preliminary results of a precise measurement of the $K_{\mu 3}$ form factors.

2.2.1. Data analysis

Based on the same data sample as the above analysis, in the selection of $K_{\mu 3}$ events similar geometrical requirements to any reconstructed two track vertex as the selection described in the previous chapter were applied. After a loose momentum cut on the track, another kinematical variable $P_0'^2$ was introduced. A positive value for this variable indicated a $K_{3\pi}$ decay, whereas a negative value identified a K_{l3} decay which was required here. For both tracks the above described E/p value had to be below 0.9 and the muon track was identified by a spatially coinciding hit in the muon veto system. The two solutions for the kaon momentum (due to the ambiguity caused by the undetected neutrino) both had to give larger values than 70 GeV/c. Finally, a cut on the minimum reconstructed neutrino momentum was applied to ensure a good description by the MC simulation. After starting with 10^8 events, 2.3×10^6 were successfully reconstructed as $K_{\mu 3}$ decays.

The program used for MC simulations was the same as described in the above analysis using the KLOR package for radiative corrections. The major sources of background were K_{e3} and $K_{3\pi}$ decays. The remaining contribution from K_{e3} events was estimated to be $(6.59 \pm 0.09) \times 10^{-4}$. After suppressing events that could be successfully reconstructed as $K_{3\pi}$ decays, the remaining contamination from $K_{3\pi}$ events was estimated to $(5.74 \pm 0.15) \times 10^{-4}$. A contamination from $K_{2\pi}$ events was estimated to be below the level of 10^{-4}.

As only the vector current contributes to the matrix element of $K_{\mu 3}$ decays this can be written as

$$\mathcal{M} = \frac{G}{\sqrt{2}} V_{us} [f_+(t)(P_K + P_\pi)^\mu \overline{u}_l \gamma_\mu (1+\gamma_5) u_\nu + f_-(t) m_l \overline{u}_l (1+\gamma_5) u_\nu] \quad (4)$$

using the dimensionless form factors $f_\pm$. In this analysis the determination of the form factors is based on a study of the Dalitz plot density which can be parametrized [15] as

$$\rho(E_\mu^*, E_\pi^*) = \frac{dN^2(E_\mu^*, E_\pi^*)}{dE_\mu^* dE_\pi^*} \propto A f_+^2(t) + B f_+ f_- + C f_-^2(t) \quad (5)$$

with A, B and C being functions of kinematical variables. Alternatively, the form factor $f_0(t)$ can be defined as

$$f_0(t) = f_+(t) + \frac{t}{(m_K^2 - m_\pi^2)} f_-(t) \quad (6)$$

where f_+ and f_0 relate to the vector (1^-) and scalar (0^+) exchange to the lepton system, respectively. With the assumption that the form factors are linear in $t = (P_K - P_\pi)^2$ one gets

$$f_{\pm 0}(t) = f_{\pm 0}(0)(1 + \lambda_{\pm 0} t / m_\pi^2) \quad (7)$$

where this assumption implies $\lambda_- = 0$ and $f_+(0) = f_0(0)$.

2.2.2. Fit and results

To perform the actual form factor fit on the Dalitz plot the solution with the lower kaon momentum was chosen (see fig 3). According to MC studies, this choice was the correct one in over 60% of the cases and moreover it introduced less migration to neighbouring cells in the Dalitz plot which was divided into cells of 5×5 MeV^2. The content of each cell was corrected for acceptance and radiative effects. To avoid a bias in the acceptance calculation the MC samples were generated with form factor values close to the fitted ones.

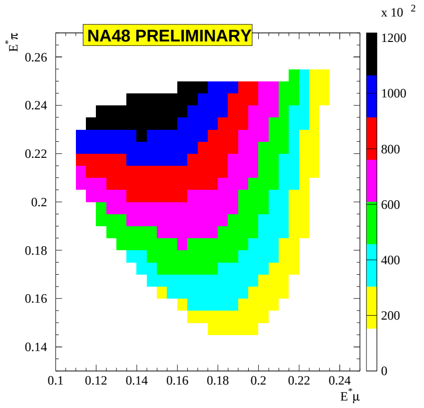

Figure 3. Dalitz plot distribution for $K_{\mu 3}$ events.

The results were then determined using the MINUIT [16] package to fit the Dalitz plot according to the parametrisation given in equation 5. The major sources of systematic uncertainty were the acceptance calculation and the description of the lateral expansion of showers in the electromagnetic calorimter.

The preliminary result is

$$\begin{aligned}\lambda_+ &= (26.1 \pm 0.6_{stat} \pm 0.8_{syst}) \times 10^{-3} \\ \lambda_0 &= (12.6 \pm 0.7_{stat} \pm 1.0_{syst}) \times 10^{-3} \end{aligned} \quad (8)$$

with a correlation of 0.43 between the two parameters and $\chi^2/ndf = 405.0/406$.

In comparison with the recent KTeV measurement [17] the result for λ_+ is compatible while that for λ_0 is shifted to a lower value.

3. Results from NA48/2

3.1. $K^\pm \to \pi^\pm \pi^0 \gamma$

The chiral anomaly plays a crucial role in Chiral Pertubation Theory (ChPT). In the charged kaon sector it can be accessed via the decay $K^\pm \to \pi^\pm \pi^0 \gamma$.

The origin of the photon in this decay can be either final state radiation of the π^+, Inner Bremsstrahlung (IB), or the decay process itself, Direct Emission (DE). While IB dominates the decay DE is rather difficult to observe. Two processes contribute to DE: magnetic and electric transitions. Only the magnetic component has a contribution from the chiral anomaly which can be calculated. The electric component cannot be predicted by ChPT at all. Yet, the electric component of DE interferes with IB, thus it can be distinguished from the magnetic component. In general, IB, INT, and DE can be distinguished kinematically using the variable W which is defined as

$$W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)}{(m_K m_\pi)^2} \quad (9)$$

with P_x^* the 4-momentum of particle x. Apart from W the decay rate depends only on the pion energy in the kaon system T_π^*. Integrating over T_π^* yields

$$\begin{aligned}\frac{d\Gamma^\pm}{dW} &\approx \left(\frac{d\Gamma^\pm}{dW}\right)_{IB} [1 + \\ &+ 2\left(\frac{m_\pi}{m_K}\right)^2 W^2 |E| \cos((\delta_1 - \delta_0) \pm \phi) \\ &+ \left(\frac{m_\pi}{m_K}\right)^4 W^4 (|E|^2 + |M|^2)] \end{aligned} \quad (10)$$

where the first term represents IB, the second INT, and the third stands for DE.

3.1.1. Data analysis

We present a high statistics analysis of the decay $K^\pm \to \pi^\pm \pi^0 \gamma$ based on data taken by the NA48/2 experiment. The data sample used in this analysis is a part of that acquired in the year 2003. The trigger to extract the events used here was selecting multiple signals in the electromagnetic calorimeter at the first trigger level and a one track trigger which implemented a kinematical cut against $K^\pm \to \pi^\pm \pi^0$ decays at the second trigger level. The selection is based on matching a single track (from the π^+) with two photons coming from the π^0 decay. With the single photon added the invariant mass of the sum of all decay products then has to give the mass of the charged kaon.

To suppress background coming from $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays it is sufficient to use a cut against fused gamma events and a narrow cut around the kaon mass (10 MeV/c^2) which is feasible due to the excellent resolution in the reconstructed invariant mass. The second possible source of background are $K^{\pm} \to \pi^{\pm}\pi^{0}$ decays which are already suppressed at trigger level. To avoid effects occuring at the trigger threshold all events have to fulfil the requirement $T^*_\pi < 80$ MeV.

3.1.2. Fit and results

Experiments were thus far restricted to the region 55 MeV $< T^*_\pi <$ 90 MeV to get a background free data sample. With our experiment the lower cut was no longer necessary thus giving access to a larger kinematic region and better possibilities to probe INT.

The fit method to retrieve the relative contributions of IB, INT and DE was utilising a maximum likelihood technique to fit the measured W distribution to a weighted sum of MC simulated W distributions for IB, INT and DE. The biggest systematic uncertainty is caused by the measurement of the trigger efficiencies involved.

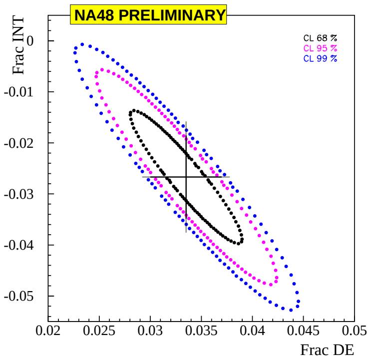

Figure 4. Fit results for INT and DE in the decay $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$.

The fit was performed in a W range of 0.2 to 0.9 thus using a smaple of ≈ 124000 fully reconstructed events. The preliminary results for the measured fractions for the region 0 MeV $< T^*_\pi <$ 80 MeV are (see fig. 4)

$$Frac(DE) = (3.35 \pm 0.35_{stat} \pm 0.25_{syst})\%$$
$$Frac(INT) = (-2.67 \pm 0.81_{stat} \pm 0.73_{syst})\% \quad (11)$$

This is the first measurement of a non-vanishing interference term in the $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$ decay.

4. Summary

Precise results on $\Gamma_{K2\pi}/\Gamma_{Ke3}$ have been presented confirming results recently obtained by other experiments. Preliminary results on the measurement of the linear form factors of the decay $K_{\mu3}$ have been shown. We have reported on the first measurement of a non-vanishing interference term in the decay $K^{\pm} \to \pi^{\pm}\pi^{0}\gamma$.

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