Status report on CP violation with charge kaons

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The NA48/2 experiment at CERN performed a high precision study of direct CP-violation in charged kaon decays into three pions, using an upgraded NA48 setup and a novel design for simultaneous unseparated $K^{\pm}$ beams. The asymmetry in the Dalitz plot linear slopes $A_g = (g_+ - g_-)/(g_+ + g_-)$ is measured to be $A_g^c = (-1.3 \pm 2.3) \cdot 10^{-4}$ by studying $3.1 \cdot 10^9$ $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$ decays and $A_g^n = (2.1 \pm 1.9) \cdot 10^{-4}$ by studying $91 \cdot 10^6$ $K^{\pm} \to \pi^o\pi^o\pi^{\pm}$ decays. The unique $K^{\pm}$ simultaneuos beam system, the design of the detectors and the method of analysis provide good control of the instrumental charge asymmetries and allow to keep the precision of the result limited by statistics, reaching accuracy one order of magnitude better than in previous experiments. The large amount of charged kaon decays collected allow also precision measurements of several rare decay processes.

1. Introduction

More than 40 years after its discovery in the mixing of neutral kaons, the full under-standing of CP violation is far from being reached. Two recent breakthroughs spread light over this puzzling phenomenon: in the late 90s the experiments NA48 and KTeV confirmed the earlier indication from NA31 experiment for direct CP-violation in the neutral kaon system. Secondly the CP-violating processes were recently found in B mesons by the experiments Belle and Babar.

In order to explore possible non-Standard Model (SM) enhancements to heavy-quark loops which are at the core of direct CP-violating processes various systems must be studied. In kaons, besides the ϵ'/ϵ parameter in K^o decays, promising complementary observables are the rates of GIM-suppressed rare kaon decays proceeding through neutral currents, and an asymmetry between K + and K decays to three pions.

Direct CP violation in $K^{\pm}$ is expected to induce different decay amplitudes: $|A(K^+ \to (3\pi)^+)| \neq |A(K^- \to (3\pi)^-)|$. The three-body decay has a low Q value, which allows for the following parametrization in terms of the two Dalitz variables $u = (s_3 - s_0)/m_\pi^2$ (odd pion coordinate) and $v = (s_1 - s_2)/m_\pi^2$ (even pion coordinate): $|A(K \to (3\pi))| = a + b \times u + \mathcal{O}(u^2, v^2)$, where a and b are two $\Delta I = 1/2$ interfering amplitudes. If a and b have different weak and strong phases, the transitions to the two charge conjugate states $(3\pi)^{\pm}$ are not equally affected by the interference, resulting in different distributions of final state momentum for K^+ and K^- decays. If the matrix element is parametrized as $|M(u, v)|^2 \propto 1 + g \times u + \mathcal{O}(u^2, v^2)$, the asymmetry

$$A_g = \frac{g^+ - g^-}{g^+ + g^-} \neq 0$$

of the slope parameter g would be a signal of direct CP violation.

Theoretical predictions based on the Standard Model cover the range $\sim 10^{-6} - 10^{-3}$ for A_g^c [9,10], relative to the "charged 3π channel" $K^{\pm} \to \pi^+\pi^-\pi^{\pm}$. The asymmetry A_g^n for the "neutral 3π channel" $K^{\pm} \to \pi^o\pi^o\pi^{\pm}$, which is dominated by NLO counterterms in the chiral perturbation theory (χPT), is expected to be of the same order of magnitude of A_g, due to the suppression of the $\Delta I = 3/2$ transition observed in ϵ'/ϵ. Values of A_g above the level of 5×10^{-5} would imply physics beyond the standard model [3] and would strengthen the still open question about non-standard contributions to ϵ'/ϵ.

In the past no slope asymmetries were found at a level of 10^{-3}. The BNL experiment [6] studied A_g^c with a total of 3×10^6 decays and measured a slope asymmetry $A_g^c = (-7 \pm 5) \times 10^{-3}$ and a total decay rate asymmetry $\Delta\Gamma/2\Gamma = (5 \pm 7) \times 10^{-4}$. Recently HyperCP [5] at FNAL measured
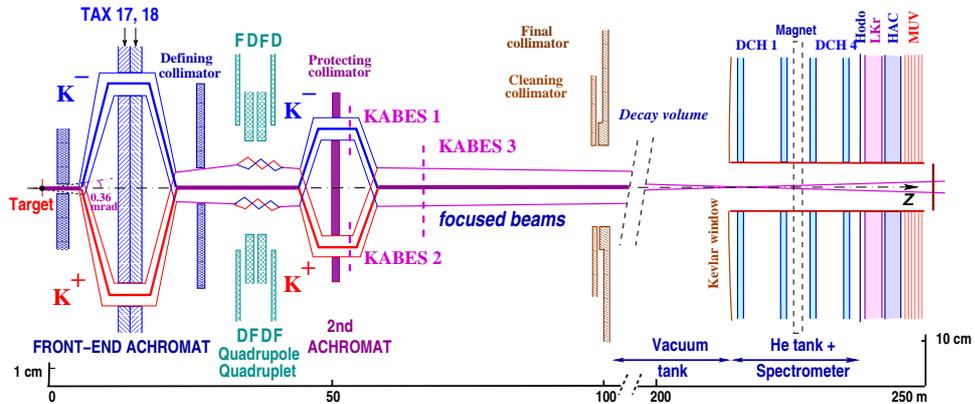
Figure 1. A view of NA48/2 beam line (TAX17,18: motorized beam dump selecting momentum of K^+/K^- beams; DFDF: focusing quadrupoles, KABES1–3: beam spectrometer) and detector (DCH1–4: drift chambers, Hodo: hodoscope, LKr: EM calorimeter, HAC: hadron calorimeter, MUV: muon veto). Vertical scale differs in two parts of the figure.

$A_g = (2.2 \pm 1.5 \pm 3.7) \times 10^{-3}$.

An experiment [7] at the CERN-PS measured a slope asymmetry at a level of $A_g^n = (0.2 \pm 1.2) \times 10^{-2}$ and $\Delta\Gamma/2\Gamma = (4 \pm 3) \times 10^{-4}$ in the "neutral channel". Recently experiment ISTRA+ [8] at TNF-IHEP found $A_g^b = (0.2 \pm 1.9) \times 10^{-3}$.

The aim of NA48/2 is to measure A_g^c and A_g^n with an accuracy of 10^{-4} (statistically dominated).

2. Beams and detectors

The novel design of the K12 beam line (Fig. 2) allows the transport simultaneously of positive and negative particles. A $400\,\mathrm{GeV}/c$ primary proton beam with an intensity of 7×10^{11} protons per spill impinge the Be target located $\sim 200\,\mathrm{m}$ upstream from the central detector. The particles of opposite charge produced at 0° are split, selected in a narrow momentum band ($p_K = 60 \pm 2.5\,\mathrm{GeV}/c$) and recombined by passing through an achromatic dipole magnet system. A quadruplet of quadrupoles focuses the beams so that they overlap with an accuracy of better than $1\,\mathrm{mm}$ at the beginning of the central detector. A second "achromat" houses a collimator to absorb neutrons, and two stations of Micromegas type TPC detector (KAon-BEam-Spectrometer). In combination with a third chamber, located downstream, the KABES chambers provide tag-

ging and momentum measurement of individual kaons. The particle rate at the KABES position is $\sim 40\,\mathrm{MHz}$. The final collimator, placed $\sim 100\,\mathrm{m}$ downstream of the target, is followed by a decay volume of $\sim 115\,\mathrm{m}$ length.

The NA48 central detector described elsewhere [2] had a new drift chamber read-out capable of withstanding high rates without introducing deadtime. The spectrometer magnet was operated to give a $p_T = 120\,\mathrm{MeV}/c$ kick, and the resolution in momentum (GeV/c) was $\sigma_p/p = 1.0\% + 0.044\%p$. The Liquid Krypton calorimeter, which has been very stable across years of running, provides an energy resolution of $\sigma_E/E = 3.2\%/\sqrt{E} + 9\%/E + 0.42\%$ where E is in GeV.

Kaon masses from three-pion decay are reconstructed with very good resolution (1.7 MeV for $K^\pm \to \pi^+\pi^-\pi^\pm$ decays and 0.9 MeV for $K^\pm \to \pi^o\pi^o\pi^\pm$ decays), allow for precise calibration and monitoring of the spectrometer performance.

The trigger is based on a low level (L1) fast pre-selection (hodoscope multiplicity and cluster number counting in the calorimeter) and a high level (L2) selection (on-line processing of the information from calorimeter and drift chambers). From an input rate of $1\,\mathrm{MHz}$, an output rate of $10\,\mathrm{kHz}$ triggers the read-out with negligible dead time.

The full on-line kinematics reconstruction at L2

and the narrow range of beam momenta allow for triggering on both three-track events and (two or) one-track events (with some π^o or photons in the LKr calorimeter) with adequate missing mass in order to reject the main background from $\pi^{\pm}\pi^o$.

Data were taken in the years 2003 and 2004 for a total of more than 100 days of effective running, providing more than 4 billion $K^{\pm} \rightarrow \pi^+\pi^-\pi^{\pm}$ and more than 100 million $K^{\pm} \rightarrow \pi^o\pi^o\pi^{\pm}$. In total 18×10^9 triggers were collected. In the following we report the preliminary analysis 2003 and 2004 data.

3. Experimental method

The asymmetry measurement method is based on comparing the reconstructed u spectra of K^+ and K^- decays $N^+(u)$ and $N^-(u)$. The possible presence of a direct CP violating difference between the linear slopes of K^+ and K^-, i.e. $\Delta g = g^+ - g^-$, can be extracted from a fit to the ratio:

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

where g and h are the actual of the Dalitz slope parameters. The measured asymmetry is then given by $A_g = \Delta g / 2g$.

Charge symmetrization of experimental conditions is to a large extent achieved by using simultaneous collinear K^+/K^- beams of similar momentum spectra. However, the presence of magnetic fields in both the beam line (achromats, quadrupoles) and the spectrometer, combined with some asymmetries in detector performance, introduces residual charge asymmetries. To equalize local effects on the acceptance, polarities of all the magnets in the beam line were reversed during the data taking on an approximately weekly basis (corresponding to the periodicity of SPS technical stops), while the polarity of the spectrometer magnet was alternated on a more frequent basis.

Data collected over a period with all the four possible setup configurations (i.e. combinations of beam line and spectrometer magnet polarities) spanning about two weeks of data taking repre-

sent a "supersample", which is treated as an independent self-consistent set of data for asymmetry measurement. Nine supersamples numbered 0 to 8 were collected in two years of running.

Each supersample contains eight distinct data samples corresponding to various combinations of setup configurations and kaon sign. In order to minimize the effects of beam and detector asymmetries, the following "quadruple ratio" involving the eight u spectra, composed as a product of four $R(u) = N^+(u)/N^-(u)$ ratios with opposite kaon sign, and deliberately chosen setup configurations in numerator and denominator, is considered:

$$R_4(u) = R_{US}(u) \cdot R_{UJ}(u) \cdot R_{DS}(u) \cdot R_{DJ}(u)$$

Here the indices U (D) denote beam line polarities corresponding to K^+ passing along the upper (lower) path in the achromats, and the indices S (J) represent spectrometer magnet polarities (opposite for K^+ and K^-) corresponding to the "even" pions deflection to negative (positive) x, i.e. towards the Salève (Jura) mountains. Fitting the ratio $R_4(u)$ with $f(u) = n \cdot (1 + \Delta g \cdot u)^4$ results in two parameters: the normalization n and the slope difference Δg.

The quadruple ratio technique completes the procedure of polarity reversals, and allows a three-fold cancellation of systematic biases: 1) beam line biases cancel between K^+/K^- samples with the beams following the same path; 2) local detector biases cancel between K^+/K^- samples with decay products illuminating the same parts of the detector; 3) due to simultaneous K^+/K^- beams, global time-variable biases and rate dependent effects cancel between K^+/K^- samples.

The method is independent of the K^+/K^- flux ratio and the relative sizes of the samples collected with different setup configurations. The result remains sensitive only to time variations of asymmetries in the experimental conditions with characteristic times smaller than corresponding field alternation period, and in principle should be free of systematic biases. In addition only charge-asymmetric effects dependent on u can bias the measurement.

With the above method, no Monte Carlo (MC) corrections to the acceptance are required. Nevertheless, a detailed GEANT-based MC simulation

was developed as a tool for systematic studies, including full geometry and material description, simulation of time variations of local DCH inefficiencies, beam geometry and DCH alignment. A large MC production was made, providing a sample of a size comparable to that of the data.

4. Evaluation of the CPV asymmetry in the "charge" mode

The absence of background in the $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ channel allows very simple online and off-line selection. Only information from the spectrometer and the hodoscope are used: tracks and vertex topology are reconstructed using the measured magnetic field map of the spectrometer analyzing magnet rescaled according to the recorded current and taking into account the stray magnetic fields in the decay volume.

The most relevant systematic effects that need carefull investigation are the following:

(i) time variations of the detector response, mainly due to variations of the transverse alignment of the chambers, which are measured to drift by small but relevant amounts (below $70\,\mu$m) and to trigger inefficiencies.

The right-left accuracy of the relative transverse DCH alignment is obtained by by imposing that K^+ and K^- three-pion decays have the same reconstructed invariant mass averaged over periods of ~ 1 hour. The sensitivity of m_K is $\sim 150\,\mathrm{keV}/c^2$ for 100 mm displacement along the horizontal direction. Also the absolute momentum scale is tuned so that the reconstructed invariant mass of $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ decays equals the PDG value for the kaon mass.

Concerning inefficiencies of trigger components, they are measured as functions of u using control data samples from low bias triggers collected along with the main triggers, which allows to account for their time variations, and propagate their statistical errors into the result. Among the different components only corrections for the L2 trigger were applied, as the others were stable in time and independent of u.

(ii) time variations of the K^+ vs K^- beam ge-

ometries: the systematic biases related to beam movements in short term (beam spill) and long term (hours) and to the imperfect overlap and coaxiality of the two beams are minimized by applying a the radial selection around the average measured beam position. In additon, being this selection azimuthally symmetric it also reduces also possible systematic biases due to the presence of stray permanent magnetic elds (Earth eld, vacuum tank magnetization).

In order to cross-check the effects from various systematics some "fake asymmetries" are studied, which should be zero from first principles, but can differ from zero due to detector/beam effects. For instance the slope asymmetries extracted from the ratios $R_J(u)/R_S(u)$ are good indicators of the degree of left-right symmetry of the setup after the above-mentioned analysis procedure.

With a total of 3.1×10^9 selected $K^\pm \rightarrow \pi^+\pi^-\pi^\pm$ events (collected in 2003 and 2004 years) the difference in Dalitz plot slope parameter is found to be:

$$\Delta g^c = g^{c+} - g^{c-} =$$

$$= (0.6 \pm 0.7_{stat.} \pm 0.4_{trig.(stat.)} \pm 0.6_{syst.}) \times 10^{-4}$$

leading to a CPV charge asymmetry of:

$$A_g^c = (-1.3 \pm 1.5_{stat.} \pm 0.9_{trig.(stat.)} \pm 1.4_{syst.}) \times 10^{-4} =$$

$$= (-1.3 \pm 2.3) \times 10^{-4}$$

5. Evaluation of the CPV asymmetry in the "neutral" mode

The event reconstruction in the "neutral" mode exploits only the spectrometer and the LKr calorimeter. The spectrometer inner radial selection is chosen according to the measured average beam position, as described before. The decay vertex is recostructed from the photon impact positions on the LKr,: by imposing for each π^o the relation $Z_{ij} = 1/m_{\pi^o}\sqrt{E_iE_jd_{ij}^2}$. This allows for the best resolution especially in the low u region, where the fit is most sensitive to the asymmetry.
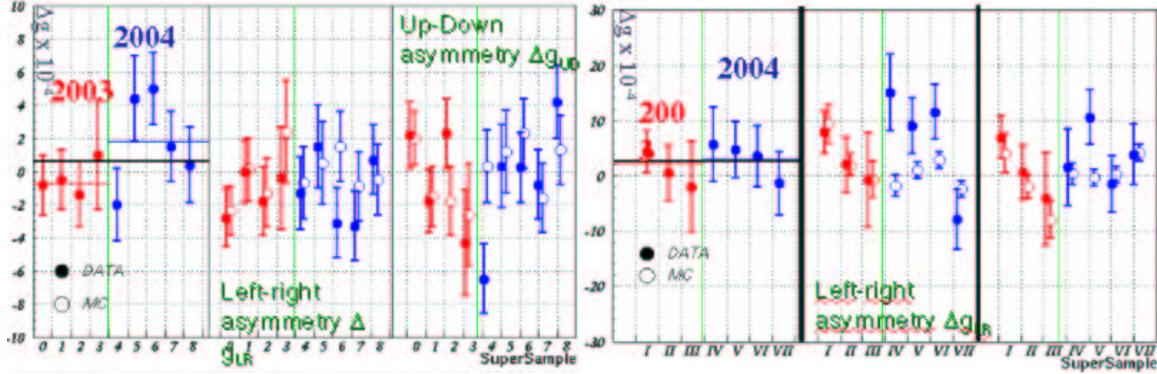
Figure 2. Time stability of the results ("charged" asymmetry on the left and 'neutral' asymmetry on the right) and "fake" L-R and U-D asymmetries.

The "neutral" mode is in general less sensitive to biases due to beam geometry and detector acceptance (DCH vs LKr) than the "charged" mode is. The most relevant potential source of systematic bias is the L1 component of the trigger generated by the number of x and y 1D projections of the clusters as they were counted on-line by the calorimeter (NTPEAK).

With a total of 91×10^6 selected $K^\pm \to \pi^o\pi^o\pi^\pm$ events (collected in 2003 and 2004 years) the difference in Dalitz plot slope parameter is found to be:

$$\Delta g^n = g^{n+} - g^{n-} =$$

$$= (2.7 \pm 2.0_{stat.} \pm 1.3_{syst.} \pm 0.3_{ext.}) \times 10^{-4}$$

where the uncertainty related to the trigger is included in the systematic error and the "external" error comes from the uncertainty on the g and h dalitz plot parameters[11] The resulting CPV charge asymmetry is:

$$A_g^n = (2.1 \pm 1.6_{stat.} \pm 1.0_{syst.} \pm 0.2_{ext.}) \times 10^{-4} =$$

$$= (2.1 \pm 1.9) \times 10^{-4}$$

The reason for a similar precision of the results given "neutral" and "charged" asymmetry measurements, despite a factor of 30 in the collected statistics, is the fact that the population density of the Dalitz plot is more favourable in the "neutral" mode.

6. Conclusions

The largest samples ever of $K^\pm \to \pi^+\pi^-\pi^\pm$ and $K^\pm \to \pi^o\pi^o\pi^\pm$ were recently analyzed by NA48/2 and null CP violating asymmetries were found. The results, respectively $A_g^c = (-1.3 \pm 2.3) \times 10^{-4}$ and $A_g^n = (2.1 \pm 1.9) \times 10^{-4}$ are one order of magnitude more precise than previous measurements and does not contradict the SM. Due to the high precision they can be used to constrain SM extensions predicting enhancements of the charge asymmetry.

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