Test of Chiral Perturbation Theory with K_{e4} Decays at CERN NA48/2 Experiment

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Abstract. The NA48/2 collaboration has accumulated ~45,000 semileptonic charged kaon decays to $\pi^0\pi^0 e^\pm \nu$ (K_{e4}^{00}), increasing the world available statistics by more than two orders of magnitude. Low background contamination and very good π^0 reconstruction bring the first precise measurement of the Branching Fraction and decay Form Factor at the percent level. Concurrently, more than one million charged K decays to $\pi^+\pi^- e^\pm \nu$ (K_{e4}^{+-}) have been analyzed, leading to an improved determination of the Branching Fraction by a factor of 3 and detailed Form Factor studies. Comparison of both K_{e4} modes decay properties allows a test of chiral symmetry relations and ChPT predictions at unprecedented level.

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INTRODUCTION

The analysis of the strong interaction dynamics at low energy is one of the main issues studied using kaon decays. Semileptonic four-body decays are rare but of particular interest theoretically because of the small number of hadrons in the final state and are traditionally used to study $\pi\pi$ scattering. At low energy (~1 GeV) QCD cannot be used because far from perturbative regime. Chiral Perturbation Theory (ChPT) is an effective theory which circumvents this problem by making use of the chiral symmetry of the theory in the limit of vanishing quark masses. Over the past 40 years calculations at leading order and two subsequent orders have converged towards very precise values of the underlying constants of the theory. ChPT predictions for the K_{e4} decay[1] have reached a competitive precision level but the experimental input for K_{e4} dates mid 70's and has a $\sim 5\%$ error which propagates to all predictions. So far relations between rates and BRs are verified within experimental errors but new measurements from high statistic samples collected concurrently by NA48/2 in several modes will provide a stronger test of ChPT.

EXPERIMENTAL SETUP

NA48 experiment at CERN has measured the direct CP violation in the neutral kaon system and more recently NA48/2 has been looking for CP violating charge asymmetry in the $K^\pm \to \pi^\pm\pi\pi$ decays. Thanks to the very high statistics achieved both in K^+ and K^- decays, many other interesting measurements have been performed with unprecedented precision. In particular, results obtained in $\pi\pi$ scattering length measurements, using two different approaches with similar precision (K_{e4} decays and *cusp* effect in the decay $K^\pm \to \pi^\pm\pi^0\pi^0$), have been published by NA48/2[2][3] and their combination provides one of the most stringent test of ChPT.

A schematic view of the beam line can be found in [2] and a detailed description of the NA48/2 detector in [4]. Two simultaneous K^+ and K^- beams are produced by 400 GeV/c protons impinging on a beryllium target. Particles with a central momentum of (60 ± 3) GeV/c are selected in a charge-symmetric way by a system of dipoles magnets forming a so-called *achromat* with zero total deflection, followed by a set of focusing quadrupoles, muon sweepers and collimators. The beams are steered to be collinear within ~1 mm in the entire decay volume (114m). The charged decay products are measured by a magnetic spectrometer consisting of a dipole magnet surrounded by two sets of drift chambers and providing a momentum resolution of $\sim 1\%$ for 10 GeV/c tracks. It is followed by a scintillator hodoscope providing a fast trigger and achieving a very good time resolution, ~150 ps. Photons and electrons energy

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is measured by a liquid krypton electromagnetic calorimeter (LKr), a quasi-homogeneous ionisation chamber with an active volume of $10m^3$, segmented transversally in 13,248 cells ($2 \times 2cm^2$ each and 27 electromagnetic radiation lengths long). The LKr calorimeter was designed to give a very good $\pi^0 \to \gamma\gamma$ reconstruction and is used also to identify electrons through their E/p ratio. The energy and position resolutions are $\sim 1\%$ and $\sim$1.5 mm for 10 GeV showers. A two-level trigger logic selects and flags events with a high efficiency for both K_{e4} topologies

K_{e4} KINEMATICS AND K_{e4} BRANCHING RATIO MEASUREMENTS

The analysis is carried out in the five independent Cabibbo-Maksymowicz variables: the squared invariant dipion and dilepton masses $S_\pi = M^2_{\pi\pi}$ and $S_e = M^2_{e\nu}$, the angles θ_π and θ_e of π^+ and e^+ directions in the $\pi\pi$ and $e\nu$ rest frames, respectively, and the angle ϕ between the $\pi\pi$ and $e\nu$ decay planes. Form factors can be developed in a partial wave expansion. Limiting the expansion to S and P wave, four real form factors (F_S, F_P, G_P and H_P) and a single phase ($\delta = \delta_S - \delta_P$) are measured, including their energy variation. In the neutral mode, the variables θ_π and ϕ are irrelevant and the form factors reduce, due to Bose statistics, to the single F_S value. In addition, if $\Delta I = 1$ holds, F_S values should be equal in the charged and neutral K_{e4} modes.

The K_{e4} branching ratios (BR) are measured relative to abundant and topologically similar normalization modes that are recorded concurrently by the same trigger logic[2]: $BR(K_{e4}) = (N_{sign} - N_{bkg})/N_{norm} \times A_{norm}/A_{sign} \times \varepsilon_{norm}/\varepsilon_{sign} \times BR(norm)$ where N_{sign}, N_{bkg}, N_{norm} are the numbers of signal, background and normalization candidates, A_{sign} (A_{norm}) and ε_{sign} (ε_{norm}) are the geometrical acceptance and trigger efficiency for the signal (normalization) sample.

Charged K_{e4} ($K^\pm \to \pi^+\pi^-e^\pm\nu$) measurements

The charged K^{+-}_{e4} BR is measured relative to the abundant $K^\pm \to \pi^+\pi^-\pi^\pm$ normalization mode ($BR(norm) = (5.59 \pm 0.04)\%$). NA48/2 recently has analyzed the very large sample of 1.13 million charged K_{e4} decays to measure $\pi\pi$ scattering lengths with a few percent precision and has obtained a precise measurement of the relative form factors of K^{+-}_{e4} decays (normalised to a single overall factor f_S). In order to access the absolute form factors with high precision, NA48/2 is performing a new measurement of the decay probability (which is proportional to f_S^2).

Out of $\sim 2.3 \times 10^{10}$ total recorded triggers, $\sim 1.11 \times 10^6$ K_{e4} candidates are selected, with a very small contamination of 10,545 background events and 1.9×10^9 normalization candidates. The geometrical acceptances, based on a GEANT3 simulation that makes use of our best knowledge of the signal and normalization matrix elements [2][5], have large and similar values: $18.22\%(K_{e4})$ and $24.18\%(K_{3\pi})$. Trigger efficiencies are measured using minimum bias control triggers[3] and they have high similar values: $98.3\%(K_{e4})$ and $97.5\%(K_{3\pi})$. The analysis has been performed independently for each kaon charge (K^-_{e4} mode has never been measured before). The preliminary results (including radiative K_{e4} decays) are: $BR(K^+_{e4}) = (4.277 \pm 0.009_{stat+trig})10^{-5}$ and $BR(K^-_{e4}) = (4.283 \pm 0.012_{stat+trig})10^{-5}$ that can be statistically combined into $BR(K_{e4}) = (4.279 \pm 0.004_{stat} \pm 0.005_{trig(stat)} \pm 0.015_{sys} \pm 0.031_{ext})10^{-5}$.

The total error $\pm 0.035 \times 10^{-5}$(0.8% relative) is dominated by the external error (0.7% relative). This measurement brings a factor of three improvement with respect to the world average $(4.09 \pm 0.10)10^{-5}$ and a factor of more than five on the relative decay rate to $K_{3\pi}$: $\Gamma(K_{e4})/\Gamma(K_{3\pi}) = (7.654 \pm 0.030_{exp})10^{-4}$ while the world average is $(7.31 \pm 0.16)10^{-4}$. Absolute form factors estimation, using the new branching fraction measurement, is in progress.

Neutral K_{e4} ($K^\pm \to \pi^0\pi^0e^\pm\nu$) measurements

The neutral K^{00}_{e4} BR is measured relative to the $K^\pm \to \pi^\pm\pi^0\pi^0$ normalization mode ($BR(norm) = (1.761 \pm 0.022)\%$), extensively studied by NA48/2 [3][6]. The event selection and reconstruction follow very closely those developed for the detailed analysis of the normalization mode [3]. Normalization events are required to cluster at low transverse momentum relative to the beamline (p_t) and to reconstruct the $\pi^\pm\pi^0\pi^0$ mass close to the kaon mass when m_{π^+} is assigned to the charged particle; signal events instead are required to reconstruct the $\pi^\pm\pi^0\pi^0$ mass away from

[2] This allows to minimise various systematic effects.
[3] Because of downscaling, control samples have limited statistics.

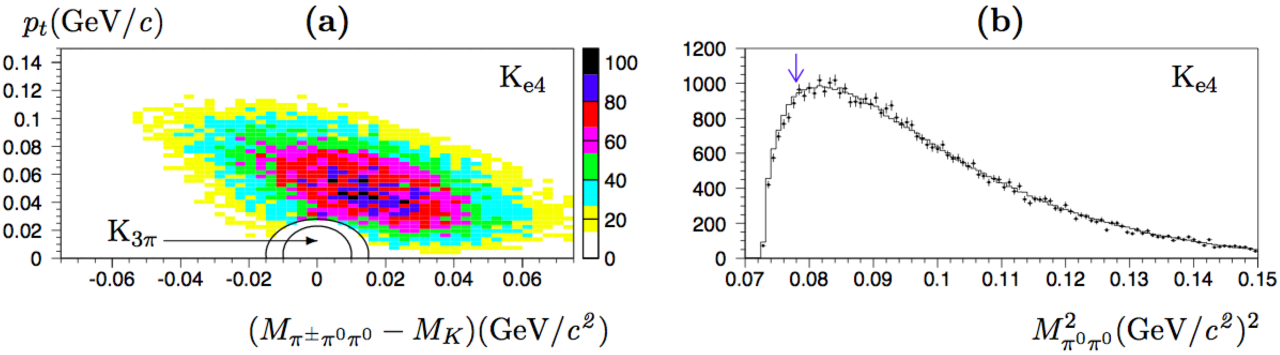

FIGURE 1. (a) Distribution of selected K_{e4} events in the variables $((M_{\pi^\pm\pi^0\pi^0} - M_K)$, $p_t)$ plane. $K_{3\pi}$ normalization events are not displayed but would cluster inside the tight cut contour. (b) Distribution of $M_{\pi^0\pi^0}$ for data (dots) and simulation (histogram) . The arrow indicates the $(2m_{\pi^+})^2$ threshold.

the kaon mass together with a sizable p_t (Figure 1a). Additional requirements on the LKr energy associated to the charged track (E/p $\simeq$1 and shower properties) ensure electron identification. The dominant background comes from $K_{3\pi}$ events with misidentification of the charged pion as an electron. Its contribution can be measured in the two modes from control regions. The background from $K_{3\pi}$ events with a subsequent $\pi^\pm \to e^\pm\nu$ decay has been studied from simulation and contributes one order of magnitude lower. The total background is estimated to be $\sim 1.3\%$ relative to the signal. Geometrical acceptances have been computed using GEANT3-based simulations, including our best knowledge of the normalization mode which describes accurately the observed *cusp* effect and uses the charged K_{e4} measured F_S value[2] for the signal simulation. They amount to 4.11% (sign) and 1.77% (norm)[4].

The analysis selects 44,909 K_{e4} candidates, 598 background events and 71×10^6 normalization events. Trigger efficiencies have been measured from minimum bias control triggers. They vary with data taking conditions between 92 and 98% but the ratio $\varepsilon_{norm}/\varepsilon_{sign}$ is stable and close to unity. Preliminary systematic uncertainties have been quoted conservatively[5]. A preliminary branching ratio value (including radiative K_{e4} decays) for the combined $K^\pm$ mode is obtained as: $BR(K_{e4}) = (2.595 \pm 0.012_{stat} \pm 0.024_{sys} \pm 0.032_{ext})10^{-5}$. The total error $\pm 0.042 \times 10^{-5}$(1.6% relative) is dominated by the external error (1.25% relative). This measurement brings a factor of ten improvement on the total error with respect to the world average $(2.2 \pm 0.4)10^{-5}$. The agreement between data and simulation over the whole range of the $M^2_{\pi^0\pi^0}$ variable is shown in Figure 1b.

A first approach to the K^{00}_{e4} F_S form factor analysis shows consistency with K^{+-}_{e4} but we observe a deficit of events interpreted as charge exchange scattering ($\pi^+\pi^- \to \pi^0\pi^0$), with negative interference below $(2m_{\pi^+})^2$ threshold. The final form factor analysis will include such a *cusp* correction. This study will complete the overall picture of K_{e4} decays and will bring precise measurements to be compared with the most elaborate predictions from ChPT.

In the future we plan to look for $K_{\mu 4}$ decays where several thousand events are expected in NA48/2 data while very little is known (7 events observed in the $K^{+-}_{\mu 4}$ mode measured in late 60s, none in the $K^{00}_{\mu 4}$ mode).

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[4] One should note that about 45% of the signal events are discarded at trigger level by the anti $K^\pm \to \pi^\pm\pi^0$ cut, due to the light mass of the electron, while the $K_{3\pi}$ events are unaffected by the cut.

[5] Trigger efficiency related uncertainties will be reduced by a statistical treatment of sub-samples recorded in stable trigger conditions.