Tests of Chiral Perturbation Theory with K_{e4} decays at CERN NA48/2 experiment [*]

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The NA48/2 collaboration has accumulated the largest samples to date of semi-leptonic charged kaon decays in the K_{e4}^{+-} ($K^{\pm} \to \pi^+\pi^- e^{\pm}\nu$) and K_{e4}^{00} ($K^{\pm} \to \pi^0\pi^0 e^{\pm}\nu$) modes. From 1.1 million K_{e4}^{+-} decays, form factors in the S- and P-wave have been extensively studied. Branching ratio and form factors have been measured at unprecedented precision. From $\sim$ 66000 K_{e4}^{00} decays, preliminary values of the Branching ratio and form factor have been obtained at a percent level precision. The comparison of Branching ratio and form factor values in both K_{e4} modes sheds new light on isospin symmetry breaking effects. Form factor measurements are major inputs to the study of low energy QCD and are powerful tests of Chiral Perturbation Theory predictions.

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1. The K$_{e4}$ decay formalism

Four-body final state decays are described by five kinematic variables, namely for K$_{e4}$ decays, the Cabibbo-Maksymowicz variables [1]: two invariant masses $S_\pi = M_{\pi\pi}^2$ and $S_e = M_{e\nu}^2$ and three angles ϑ_π, ϑ_e and φ. The hadronic current is described by form factors which can be developed in a partial wave expansion as suggested in [2]. Limiting the expansion to S- and P-waves and considering a unique phase δ_p for all P-wave form factors, two axial (F, G) and one vector (H) complex form factors contribute to the transition amplitude: $F = F_s \, e^{i\delta_s} + \, F_p \, e^{i\delta_p} cos\theta_\pi$, $G = G_p \, e^{i\delta_p}$, $H = H_p \, e^{i\delta_p}$. From the differential rate study in the 5-dimensional space, four real form factors (F_s, F_p, G_p and H_p) and a single phase difference ($\delta = \delta_s - \delta_p$) are then measured, together with their energy variation with S_π and S_e. In the neutral pion mode K$_{e4}^{00}$, the variables ϑ_π and φ are irrelevant and the form factors reduce to the single F_s value due to Bose statistics.

2. Beam and detector setup

Two simultaneous K$^\pm$ beams were produced by 400 GeV/c protons from the CERN/SPS impinging on a beryllium target. Opposite charge particles with a central momentum of (60 ± 3) GeV/c were selected and focused ~ 200 m downstream at the first spectrometer chamber. A magnetic spectrometer (a dipole magnet surrounded by two sets of drift chambers) measured the momentum (p) of charged decay products with a relative precision of $\sim 1\%$ for 10 GeV/c momentum tracks. It was followed by a scintillator hodoscope consisting of two planes segmented into horizontal and vertical strips achieving a very good ~ 150 ps time resolution. A liquid krypton calorimeter (LKr), 27 radiation length thick, was used to measure electromagnetic deposits (E) and to identify electrons through their E/p ratio (the energy and transverse position resolutions were $\sim 1\%$ and ~ 1.5 mm (resp.) for 10 GeV showers). A two-level trigger logic selected and flagged events with a high efficiency for both K$_{e4}$ topologies. A detailed description is available in [3].

3. Event reconstruction, analysis procedure and results

Event reconstruction and selection follow similar paths for both signal modes: the K$_{e4}^{+-}$ (K$_{e4}^{00}$) candidates are reconstructed from three charged tracks (one track and four photons forming two π^0s) pointing to the same decay vertex. The abundant K$_{3\pi}$ decay modes (K$^\pm \to \pi^+\pi^-\pi^\pm$ and K$^\pm \to \pi^0\pi^0\pi^\pm$) are considered as normalization modes. They are recorded concurrently with the same trigger logic and subjected to the same reconstruction as the signal events. Kinematic separation of signal and normalization candidates is obtained by requiring (or not) missing mass and missing transverse momentum in the K$_{3\pi}$ hypothesis. Extra requirements of electron identification ($0.9 < E/p < 1.1$ and properties of LKr associated shower consistent with the electron hypothesis) ensure a low background contamination of order $\sim 1\%$ relative. The remaining background is mainly due to K$_{3\pi}$ decays with a $\pi^\pm$ faking an electron response in LKr or followed by the rare $\pi \to e\nu$ decay, while accidental coincidence with another track/photon is one order of magnitude lower. Most background contributions are measured from control data samples. Geometrical acceptances for the four decay modes are obtained from a MC simulation including detector geometry, material description and local imperfections. They are typically $\sim 18 - 20\%$ in the K$_{e4}^{+-}$ and K$_{3\pi}^{+-}$ modes and 2% (4%) in the K$_{e4}^{00}$ (K$_{3\pi}^{00}$) modes.

Form factors values are obtained by adjusting the differential distributions of simulated signal candidates to those of data candidates in small boxes of the multi-dimensional kinematical space. Branching ratios (BR) are obtained as:

$$\mathrm{BR}(\mathrm{K}_{e4}) = (N_s - N_b)/N_n \cdot (A_n\,\varepsilon_n)/(A_s\,\varepsilon_s) \cdot \mathrm{BR}(\mathrm{K}_{3\pi}),$$

where N_s is the number of signal candidates (1.1×10^6 K$_{e4}^{+-}$, 6.6×10^4 K$_{e4}^{00}$), N_b the background contribution (10552 for K$_{e4}^{+-}$, 708 for K$_{e4}^{00}$) and N_n the number of normalization events (19×10^8 K$_{3\pi}^{+-}$, 94×10^6 K$_{3\pi}^{00}$). $A_s(A_n)$ are the geometrical acceptances described above and $\varepsilon_s(\varepsilon_n)$ are the trigger efficiencies, well above 95% and similar for signal and normalization modes. BR(K$_{3\pi}$) are the normalization Branching ratios. The detailed K$_{e4}^{+-}$ form factor and BR measurements are already available in [4] while the corresponding K$_{e4}^{00}$ measurements are preliminary.

Branching ratios, inclusive of K$_{e4\gamma}$ decays, are obtained at improved precision:

$$\mathrm{BR}(\mathrm{K}_{e4}^{+-}) = (4.257 \pm 0.004_{\mathrm{stat}} \pm 0.016_{\mathrm{syst}} \pm 0.031_{\mathrm{ext}}) \times 10^{-5}, \text{ PDG value} = (4.09 \pm 0.10) \times 10^{-5},$$

$$\mathrm{BR}(\mathrm{K}_{e4}^{00}) = (2.585 \pm 0.010_{\mathrm{stat}} \pm 0.010_{\mathrm{syst}} \pm 0.032_{\mathrm{ext}}) \times 10^{-5}, \text{ PDG value} = (2.2 \pm 0.4) \times 10^{-5},$$

where systematic errors include uncertainties on acceptance, resolution, beam geometry, particle identification, trigger efficiencies and radiative corrections. External errors stem from the normalization mode BR uncertainties and are now the dominant errors. The F_s form factor variations with $q^2 (= S_\pi/4m_{\pi^+}^2 - 1)$ are displayed in Fig.1. The same quadratic behavior is present in both modes for ($q^2 > 0$) and a deficit of events is observed below the $2m_{\pi^+}$ threshold ($q^2 = 0$) in the K$_{e4}^{00}$ mode as observed in the K$_{3\pi}^{00}$ mode [5]. It can be explained by final state charge exchange scattering ($\pi^+\pi^- \to \pi^0\pi^0$). The absolute form factors have also been obtained as:

$$F_s(\mathrm{K}_{e4}^{+-}) = 5.705 \pm 0.003_{\mathrm{stat}} \pm 0.017_{\mathrm{syst}} \pm 0.031_{\mathrm{ext}},$$
$$F_s(\mathrm{K}_{e4}^{00}) = 6.092 \pm 0.012_{\mathrm{stat}} \pm 0.017_{\mathrm{syst}} \pm 0.045_{\mathrm{ext}}.$$

The observed tension between $F_s(\mathrm{K}_{e4}^{+-})$ and $F_s(\mathrm{K}_{e4}^{00})$ as well as between BR(K$_{e4}^{+-}$) and 2 BR(K$_{e4}^{00}$) points to possible isospin symmetry breaking, radiative or other effects to be investigated.
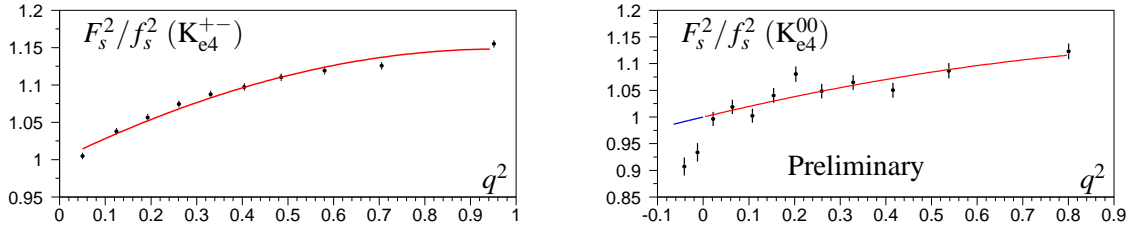
Figure 1: Relative F_s^2/f_s^2 form factor measurements function of q^2 in the K$_{e4}^{+-}$ (**Left**) and the K$_{e4}^{00}$ (**Right**) mode. By construction $F_s^2/f_s^2(q^2 = 0) = 1$. Red lines are degree-2 polynomial fits to the data (stat. errors only) for $q^2 > 0$ while the blue line is the extrapolation to negative values.

References

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