A new $K_S \to \pi e \nu$ branching fraction measurement from KLOE-2

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Abstract. The KLOE-2 Collaboration continues the KLOE long-standing tradition of flavour physics precision measurements in the kaon sector with a new $K_S \to \pi e \nu$ branching fraction measurement with 1.63 fb^{-1} KLOE data acquired at the DAΦNE Frascati ϕ-factory. The strategy to achieve this new result has been presented together with the combination with our previous BR($K_S \to \pi e \nu$) measurement, based on an independent data sample, which allows the total precision to be improved by almost a factor of two, and a new derivation of $f_+(0)|V_{us}|$.

1. Introduction

The KLOE experiment integrated 2.5 fb^{-1} running at the DAΦNE ϕ-factory of INFN Laboratori Nazionali di Frascati [1] and pursued several achievements in both precision kaon and hadron physics [2] playing a leading role in testing the CKM matrix unitarity measuring V$_{us}$ from both semileptonic $K_{S,L}(l3)$ and leptonic $K^+_{\mu 2}$ decays.

Branching fraction measurements for semileptonic decays of charged and neutral kaons together with their lifetimes are used to determine the $|V_{us}|$ Cabibbo–Kobayashi–Maskawa quark mixing matrix element [4, 5, 6]. The relation $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ among the matrix elements of the first row provides the most stringent test of the CKM matrix unitarity. Lately an apparent 3.2σ violation of the first-row CKM unitarity condition has been reported, using the most recent inputs from theory and experiment to extract the V_{us} value from $K_{\ell 3}$ decays and the V_{ud} value from superallowed nuclear beta decays [3]. Given the lack of pure high-intensity K_S meson beams, $K_S \to \pi l \nu$ decays provide the least precise determination of $|V_{us}|$ compared to K$^{\pm}$ and K_L mesons [5], with the first direct measurement ever of the branching fraction $\mathcal{B}(K_S \to \pi \mu \nu)$ recently published by the KLOE-2 collaboration[7].

At DAΦNE K_S (K_L) mesons are identified (*tagged*) with high efficiency and purity by the presence of a K_L (K_S) in the opposite hemisphere. Exploiting this unique capability of selecting pure K_S beams, a sample of 300 million K_S mesons produced in $\phi \to K_L K_S$ decays and recorded by the KLOE experiment has been analyzed to improve the precision on the $K_S \to \pi e \nu$ branching fraction measurement [8].

2. Measurement Strategy

KLOE is a general purpose detector composed of one of the biggest drift chambers (DC) ever built [9] surrounded by a lead-scintillating fiber Electromagnetic Calorimeter (EMC) among the best ones for energy and timing performance at low energies [10]. The $K_S \to \pi e \nu$ signal selection exploits a boosted decision tree (BDT) classifier built with kinematic variables measured with

DC only together with time-of-flight measurements from EMC. The signal yield is provided by the fit to the reconstructed electron mass distribution which is then normalised to $K_S \to \pi^+\pi^-$ decays in the same data set. $K_L \to \pi e\nu$ data control samples are used to evaluate signal selection efficiencies. The master formula for the evaluation of the $K_S \to \pi e\nu$ branching fraction is:

$$\mathcal{B}(K_S \to \pi e\nu) = \frac{N_{\pi e\nu}}{\epsilon_{\pi e\nu}} \times \frac{\epsilon_{\pi\pi}}{N_{\pi\pi}} \times R_\epsilon \times \mathcal{B}(K_S \to \pi^+\pi^-), \quad (1)$$

with $N_{\pi e\nu}$ and $N_{\pi\pi}$ the numbers of selected $K_S \to \pi e\nu$ and $K_S \to \pi^+\pi^-$ events, $\epsilon_{\pi e\nu}$ and $\epsilon_{\pi\pi}$ the selection efficiencies, and $R_\epsilon = (\epsilon_{\pi\pi}/\epsilon_{\pi e\nu})_{\rm com}$ the ratio of common efficiencies for the trigger, on-line filter, event classification and preselection that can be different for the two decays.

2.1. Sample selection

First K_S mesons are tagged by K_L interactions in the calorimeter (K_L–crash) with a clear signature of a delayed cluster in EMC not associated to tracks. The K_L–crash is identified as one cluster not associated to tracks, with energy $E_{\rm clu} > 100$ MeV, polar angle $15^\circ < \theta_{\rm clu} < 165^\circ$ and velocity in the ϕ-meson reference system of the K_L candidate $0.17 < \beta^* < 0.28$. Then signal and $K_S \to \pi^+\pi^-$ normalization candidates are pre-selected requiring two tracks with opposite curvature forming a vertex inside the cylinder with $\rho_{\rm vtx} = \sqrt{x_{\rm vtx}^2 + y_{\rm vtx}^2} < 5$ cm and $|z_{\rm vtx}| < 10$ cm. The $K_S \to \pi^+\pi^-$ normalization sample is selected applying an additional cut on the two charged secondaries momentum $140 < p < 280$ MeV.

The signal selection is performed in two steps based on uncorrelated information: the event kinematics based on DC tracking information only and the time-of-flight (TOF) measured with EMC.

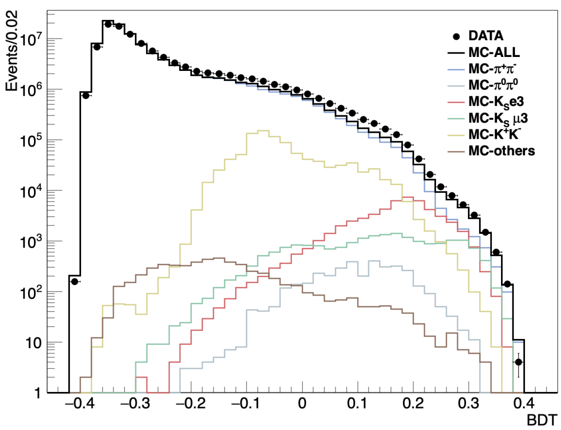

Figure 1. Distribution of the BDT classifier output for data and simulated signal and background events.

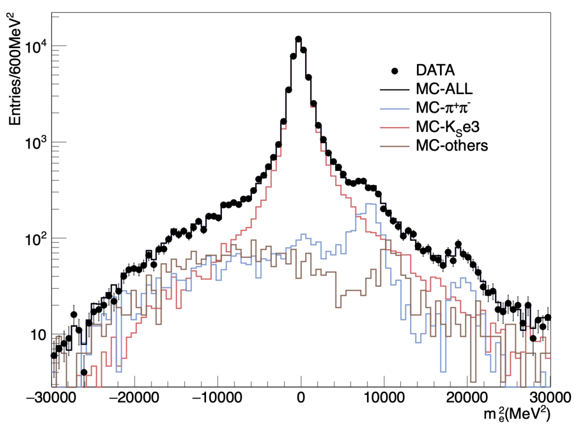

Figure 2. The m_e^2 distribution for data, MC signal and background compared with the fit result.

Five kinematic variables with satisfactory data-MC agreement in the signal region and good discriminating power against background are selected, to build a boosted decision tree (BDT) classifier and perform a multivariate analysis. Tracks momenta and their angle in the K_S reference frame are among these variables together with the angle between the total momentum and the K_L–crash direction, the difference between the total momentum and the K_S momentum, as determined from the ϕ-meson and the K_L momenta, and the two-track invariant mass in the pion mass hypothesis. Fig.1 shows the distribution of the BDT classifier output for data and simulated signal and background events, mainly from $K_S \to \pi^+\pi^-$ and $\phi \to K^+K^-$ decays. Events with BDT output > 0.15 are retained.

The electron-pion pair in the signal final state is identified with the time-of-flight measurement which requires a track-to-cluster association (TCA) for both charged secondary tracks. The associated clusters must have energy $E_{\rm clu} > 20$ MeV and $15^\circ < \theta_{\rm clu} < 165^\circ$ and cluster centroid within 30 cm of the track extrapolation on EMC. For each TCA, the difference δt between the time-of-flight measured by the calorimeter and the flight time measured along the particle trajectory is evaluated, the value depending on the charged secondary mass assignment. To reduce the uncertainty, the difference $\delta t_{1,2} = \delta t_1 - \delta t_2$ between the time differences evaluated for each track is used. Background suppression is performed testing the pion-pion mass hypothesis and retaining events with 2.5 ns $< |\delta t_{\pi\pi}| <$ 10 ns. Then the electron-pion hypothesis is tested based on the comparison of the two quantities $\delta t_{\pi,e} = |\delta t_{1,\pi} - \delta t_{2,e}|$ and $\delta t_{e,\pi} = |\delta t_{1,e} - \delta t_{2,\pi}|$. The lowest value of δ_t provides the correct mass assignment to charged secondary tracks and then the signal is selected with $|\delta t_e| < 1$ ns.

The signal count is extracted from the fit to the mass of the charged secondary identified as the electron $m_e^2 = (E_{K_S} - E_\pi - p_{\rm miss})^2 - p_e^2$ with $p^2_{\rm miss} = (\vec{p}_{K_S} - \vec{p}_\pi - \vec{p}_e)^2$, E_{K_S} and $\vec{p}_{K_S}$ the energy and momentum reconstructed using the tagging K_L, and $\vec{p}_\pi$ and $\vec{p}_e$ the pion and electron momenta. MC shapes of the three components $K_S \to \pi e\nu$, $K_S \to \pi^+\pi^-$ and the sum of all other backgrounds are used to fit the m_e^2 distribution. Fig. 2 shows the m_e^2 distribution for data and simulated events compared with the fit output. The number of signal events is $N_{\pi e\nu} = 49647 \pm 316$ with $\chi^2/\text{ndf} = 76/96$.

2.2. Efficiency evaluation

A data control sample of $K_L \to \pi e\nu$ decays, tagged by the detection of $K_S \to \pi^+\pi^-$ decays, is used to evaluate the signal selection efficiency. The efficiency of the first step of the signal selection, based on kinematic variables and BDT cuts, is measured on a 97% purity control sample selected using TOF variables. Similarly the efficiency on the TCA and TOF signal selection is measured with a 95% purity control sample selected using kinematic variables only. A good comparison between control and signal samples has been shown in MC for both BDT and $|\delta t_e|$ distribution. The signal selection efficiency is about 20%. The selection efficiency of the $K_S \to \pi^+\pi^-$ normalization sample is about 97%, evaluated with the preselected data sample.

3. The Result

The branching fraction is evaluated using Eq. (1) with $N_{\pi e\nu} = 49647 \pm 316$ events, $\epsilon_{\pi e\nu} = (19.38 \pm 0.10)$, $N_{\pi\pi}/\epsilon_{\pi\pi} = (292.08 \pm 0.27) \times 10^6$, $R_\epsilon = 1.1882 \pm 0.0059$ and $\mathcal{B}(K_S \to \pi^+\pi^-) = 0.69196 \pm 0.00051$ measured by KLOE [11]:

$$\mathcal{B}(K_S \to \pi e\nu) = (7.211 \pm 0.046_{\rm stat} \pm 0.052_{\rm syst}) \times 10^{-4} = (7.211 \pm 0.069) \times 10^{-4}.$$

The combination with the previous measurement from KLOE based on a 0.41 fb^{-1} independent data sample $\mathcal{B}(K_S \to \pi e\nu) = (7.046 \pm 0.076_{\rm stat} \pm 0.049_{\rm syst}) \times 10^{-4}$ [12] is:

$$\mathcal{B}(K_S \to \pi e\nu) = (7.153 \pm 0.037_{\rm stat} \pm 0.043_{\rm syst}) \times 10^{-4} = (7.153 \pm 0.057) \times 10^{-4}.$$

The corresponding new derivation of the $f_+(0)|V_{us}|$ value is done with the equation:

$$\mathcal{B}(K_S \to \pi\ell\nu) = \frac{G^2(f_+(0)|V_{us}|)^2}{192\pi^3}\tau_S m_K^5 I_K^\ell S_{\rm EW}(1 + \delta_{\rm EM}^{K\ell}),$$

with I_K^ℓ the phase-space integral including the semileptonic form factors, $S_{\rm EW}$ the short-distance electro-weak correction, $\delta_{\rm EM}^{K\ell}$ the mode-dependent long-distance radiative correction, and $f_+(0)$ the form factor at zero momentum transfer for the $\ell\nu$ system. With the values $S_{\rm EW} = 1.0232 \pm 0.0003$ [13], $I^e_K = 0.15470 \pm 0.00015$ and $\delta^{Ke}_{\rm EM} = (1.16 \pm 0.03)\ 10^{-2}$ from Ref. [3], and the world average values for the K_S mass and lifetime [6] we have:

$$f_+(0)|V_{us}| = 0.2170 \pm 0.0009.$$

4. Conclusions

The KLOE-2 Collaboration has performed a new measurement of the $K_S \to \pi e \nu$ branching ratio based on a 1.63 fb^{-1} data sample with an overall uncertainty below 1%. The combination with the previous KLOE measurement yields a new determination of $\mathcal{B}(K_S \to \pi e \nu)$ with 0.8% precision and a sizable reduction of the new derivation of $f_+(0)|V_{us}|$, from 0.6% to 0.4%.

In addition to this the KLOE-2 experiment, the continuation of KLOE at the upgraded DAΦNE collider [14], collected 5 fb^{-1} at the center of mass energy of the ϕ-meson with an upgraded detector which included a state-of-the-art cylindrical GEM detector used for the first time in HEP experiments, the Inner Tracker [15], LET [16] and HET [17] taggers for $\gamma\gamma$ physics, and the CCALT and QCALT detectors [18], crystal and tile calorimeters positioned near the interaction point and along the beam-pipe respectively.

Together with the data set of its predecessor KLOE, the total acquired data sample of 8 fb^{-1} corresponds to 2.4×10^{10} ϕ-meson produced and represents the largest sample ever collected at the $\phi(1020)$ at e^+e^- colliders. This will allow a very rich physics program with kaon interferometry, test of discrete symmetries, and the search for physics beyond the Standard Model including also Dark photon hunting to be pursued [19].

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