Precision Standard Model Tests with Kaons

R. Wanke
Institut für Physik, Universtät Mainz, D-55099 Mainz, Germany

In kaon physics, several new precision measurements on flavour variables and $\mathcal{CP}$ violation have performed in the recent years. Presented are a new precise determination of the CKM parameter $|V_{us}|$, which combines the results of all experiments together with recent theoretical progress, and new measurements of the ratio $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$, which is sensitive to contributions of a possible charged Higgs in the SUSY framework. Also, final results of a precision search for direct $\mathcal{CP}$ violation in charged kaon decays are presented.

1. Introduction

In the recent years, kaon physics has celebrated a huge revival, with many new experiments recording data of several billion kaon decays. These new data samples allow to study flavour physics and $\mathcal{CP}$ violation with even greater precision than in B or D decays, as well as to explore many rare and extremely rare decays in the search for new physics.

In the following, a new precise determination of the CKM parameter $|V_{us}|$, new measurements of the ratio $R_K = \Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$, and results of a precision search for direct $\mathcal{CP}$ violation in charged kaon decays are reported.

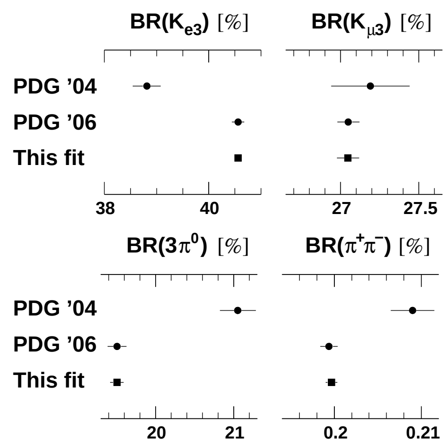

Figure 1: Main K_L branching fractions [6].

2. Precision Measurement of $|V_{us}|$

The measurement of the parameter V_{us} of the Cabibbo-Kobayashi-Maskawa mixing matrix of weak eigenstates has undergone a large improvement with respect to one or two year ago, due to both more precise measurements of the main kaon decays and better computations for the theoretical inputs.

The kaon semileptonic decay width is given by [1]

$$\Gamma(K_{l3(\gamma)}) = \frac{G_F^2 m_K^5}{192\pi^3}\, C_K^2\, S_{EW} \times |V_{us}|^2\, |f_+(0)|^2 I_K^l (1 + 2\delta^l_{SU(2)} + 2\delta^l_{EM}), \quad (1)$$

with $C_K^2 = 1$ ($\frac{1}{2}$) for K^0 ($K^\pm$), the short distance electro-weak correction $S_{EW} = 1.0232$, the hadronic matrix element $f_+(0)$ at $q^2 = 0$, the integral I_K^l of the form factors over the phase space, and the form factor corrections $\delta^l_{SU(2)}$ and δ^l_{EM} for isospin symmetry breaking and long-distance electro-magnetic interactions, respectively.

The decay width is provided by experiment by measurements of the lifetimes and semileptonic branching fractions of charged and neutral kaons and the integrals I_K^l are determined by measurements of the form factor slope parameters. In particular, the KLOE collaboration has recently provided a complete set of new absolute branching fraction measurements [3], but also the NA48/2 and ISTRA+ experiments published new precise measurements of the semileptonic $K^\pm$ branching fractions with respect to the $\pi^\pm\pi^0$ decay [4, 5].

The Flavianet Kaon Working Group [2] has performed a global fit to all kaon branching fractions, lifetimes, and form factor slopes [6]. In this fit, about 50 measurements of all published and preliminary results of most former and all recent experiments were taken into account. The sum of branching fractions of each K meson was constrained to be 1. The fit results of the main K_L and $K^\pm$ branching ratios are shown in Figs. 1 and 2. They are substantially more precise than the current PDG averages [7], and, in case of the charged kaon, shifted with respect to the PDG values, mainly because of the new KLOE measurement of $\mathrm{Br}(K^\pm \to \pi^\pm\pi^0)$.

The fit results for the semileptonic kaon branching fractions are given in the first column of Table I. For determining $|V_{us}| \times f_+(0)$, the corrections $\delta^l_{SU(2)}$ and δ^l_{EM}, which are of order 1%, are taken from [8]. The final values of $|V_{us}| \times f_+(0)$, summarized in the second column of Table I, agree well within the single decay channels (Fig. 3). Averaging the results with

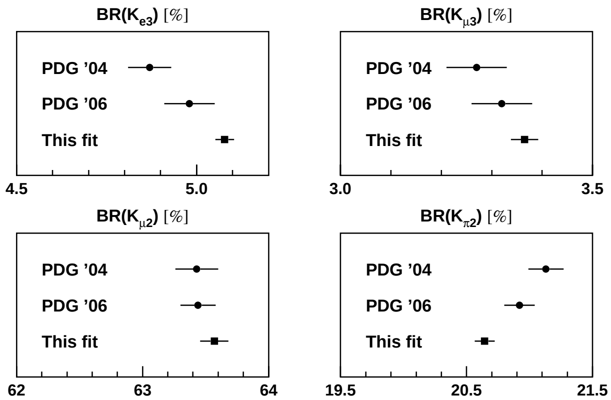

Figure 2: Main $K^{\pm}$ branching fractions [6].

	BR [%]	$\mathbf{\|V_{us}\| \times f_+(0)}$	% err	% error from BR	τ	Δ
$\mathbf{K_Le3}$	**40.58(9)**	**0.21625(60)**	**0.28**	0.09	0.19	0.15
$\mathbf{K_L\mu3}$	**27.06(6)**	**0.21675(66)**	**0.31**	0.10	0.18	0.15
$\mathbf{K_Se3}$	**0.0705(9)**	**0.21542(134)**	**0.67**	0.65	0.03	0.15
$\mathbf{K^{\pm}e3}$	**5.078(25)**	**0.21728(84)**	**0.39**	0.26	0.09	0.26
$\mathbf{K^{\pm}\mu3}$	**3.365(27)**	**0.21758(111)**	**0.51**	0.40	0.09	0.26
Average		**0.21661(47)**				

Table I World average branching fractions of semileptonic kaon decays and determination of $|V_{us}| \times f_+(0)$ [6].

correlations taken into account, gives

$$|V_{us}| \times f_+(0) = 0.21661 \pm 0.00047, \tag{2}$$

where about equal parts of the uncertainty comes from experiment (BR's, lifetimes) and theory (mainly δ^l_{EM}).

For the final determination of $|V_{us}|$, the currently most precise value of $f_+(0) = 0.964 \pm 0.005$ from the UKQCD/RBC collaboration [9] is taken. This yields

$$|V_{us}| = 0.2246 \pm 0.0012. \tag{3}$$

Another possibility for the determination of $|V_{us}|$ is the comparison of the leptonic charged kaon and pion decay widths. The KLOE collaboration has recently presented a new precise measurement of $\mathrm{Br}(K^{\pm} \to \mu^{\pm}\nu) = 0.6366 \pm 0.0017$ [10], which leads to a new world average of [6]

$$\mathrm{Br}(K^{\pm} \to \mu^{\pm}\nu) = 0.6357 \pm 0.0011. \tag{4}$$

Using $\tau_{K^{\pm}}$ from the global fit to all available kaon data [6] and $\Gamma(\pi_{\mu2}) = 38.408(7)\ \mu s^{-1}$ [7], results in $(|V_{us}|/|V_{ud}|)/(f_K/f_\pi) = 0.2760 \pm 0.0006$. The currently best computation of the ratio of decay constants was performed by the MILC-HPQCD collaboration [11], giving $f_K/f_\pi = 1.189(7)$. This results

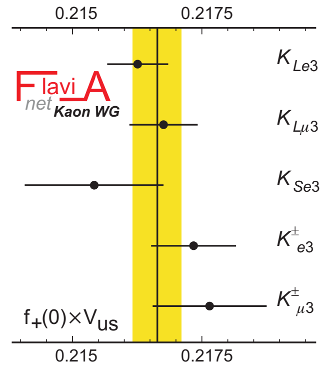

Figure 3: Measurements of $|V_{us}| \times f_+(0)$ [6].

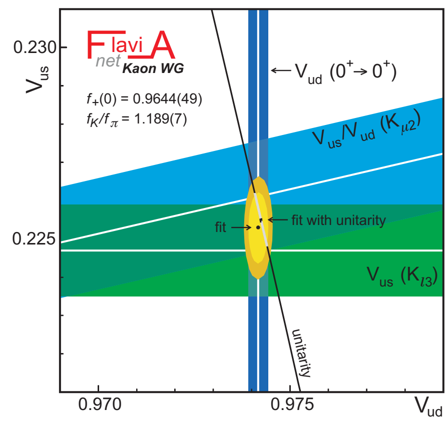

Figure 4: Measurements of $|V_{us}|$ versus $|V_{ud}|$ [6]. The black line is the SM prediction from unitarity of the CKM matrix.

in

$$|V_{us}|/|V_{ud}| = 0.2321 \pm 0.0015, \tag{5}$$

with the error being dominated by f_K/f_π.

Figure 4 [6] shows the measurements of $|V_{us}|$ and $|V_{us}|/|V_{ud}|$ together with the $|V_{ud}|$ value from $0^+ \to 0^+$ nuclear transitions and the SM prediction. The data are in excellent agreement with CKM unitarity.

Finally, the precise measurement of $\mathrm{Br}(K_{\mu2})$ can be used to set a stringent limit on the mass of a possible charged Higgs boson. In the Standard Model, the ratio

$$R_{l23} \equiv \left| \frac{V_{us}(K_{\mu2})}{V_{us}(K_{l3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\mu2})} \right| \tag{6}$$

has to be equal to 1. In e.g. Super Symmetry, however, the leptonic kaon and pion decay widths may be altered by exchange of a charged Higgs boson in addition to W exchange, yielding [12]

$$R_{l23} = \left| 1 - \frac{m^2_{K^+}}{m^2_{H^+}} \left(1 - \frac{m^2_{\pi^+}}{m^2_{K^+}} \right) \frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta} \right|. \tag{7}$$

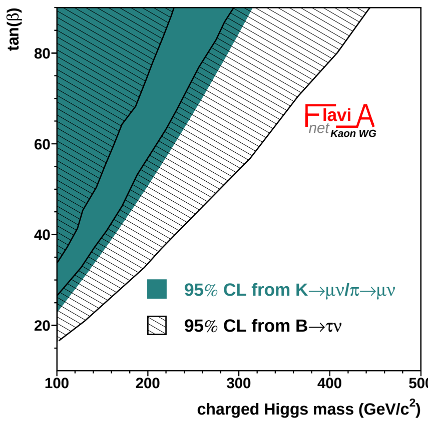

Figure 5: Exclusion limits on a SUSY charged Higgs mass and $\tan\beta$ from $K_{\mu 2}$ decays [6]. Shown are also the corresponding limits from $B \to \tau\nu$ decays [13].

From experimental data, using CKM unitarity for K_{l3}, and with $\frac{f_K}{f_\pi}/f_+(0)$ from the lattice [6],

$$R_{l23} = 1.004 \pm 0.007, \tag{8}$$

in perfect agreement with the SM prediction. The corresponding exclusion limits on the charged Higgs mass and $\tan\beta$ are competitive to the limits from $B \to \tau\nu$ decays (Fig. 5).

3. New Measurements of $\Gamma(K_{e2})/\Gamma(K_{\mu 2})$

The ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ can be precisely calculated within the Standard Model. Neglecting radiative corrections, it is given by

$$R_K^{(0)} = \frac{m_e^2}{m_\mu^2} \frac{(m_K^2 - m_e^2)^2}{(m_K^2 - m_\mu^2)^2} = 2.569 \times 10^{-5}, \tag{9}$$

and reflects the strong helicity suppression of the electronic channel. Radiative corrections have been computed within the model of vector meson dominance [14], yielding a corrected ratio of

$$\begin{aligned} R_K &= R_K^{(0)}(1 + \delta R_K^{\text{rad.corr.}}) \\ &= 2.569 \times 10^{-5} \times (0.9622 \pm 0.0004) \\ &= (2.477 \pm 0.001) \times 10^{-5}. \end{aligned} \tag{10}$$

Because of the helicity suppression of K_{e2} in the SM, the decay amplitude is a prominent candidate for possible sizeable contributions from new physics beyond the SM. Moreover, when normalizing to $K_{\mu 2}$ decays, it is one of the few kaon decays for which the SM-rate is predicted with very high accuracy. Any significant experimental deviation from the prediction would immediately be evidence for new physics. However, this new physics would need to violate lepton universality to be visible in the ratio $K_{e2}/K_{\mu 2}$.

	$\Gamma(K_{e2})/\Gamma(K_{\mu 2})$ $[10^{-5}]$
PDG 2006 [7]	2.45 ± 0.11
NA48/2 prel. ('03) [16]	$2.416 \pm 0.043 \pm 0.024$
NA48/2 prel. ('04) [17]	$2.455 \pm 0.045 \pm 0.041$
KLOE prel. [18]	$2.55 \pm 0.05 \pm 0.05$
SM prediction	2.472 ± 0.001

Table II Results and prediction for $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$.

Recently it has been pointed out, that in a SUSY framework sizeable violations of lepton universality can be expected in K_{l2} decays [15]. At tree level, lepton flavour violating terms are forbidden in the MSSM. Loop diagrams, however, should induce lepton flavour violating Yukawa couplings as $H^+ \to l\nu_\tau$ to the charged Higgs boson H^+. Making use of this Yukawa coupling, the dominant non-SM contribution to R_K modifies the ratio to

$$R_K^{\text{LFV}} \approx R_K^{\text{SM}} \left[1 + \left(\frac{m_K^4}{M_{H^\pm}^4} \right) \left(\frac{m_\tau^2}{M_e^2} \right) |\Delta_{13}|^2 \tan^6\beta \right]. \tag{11}$$

The lepton flavour violating term Δ_{13} should be of the order of $10^{-4} - 10^{-3}$, as expected from neutrino mixing. For moderately large $\tan\beta$ and $M_{H^\pm}$, SUSY contributions may therefore enhance R_K by up to a few percent. Since the additional term in Eqn. 11 goes with the forth power of the meson mass, no similar effect is expected in π_{l2} decays.

Experimental knowledge of $K_{e2}/K_{\mu 2}$ has been poor so far. The current world average of $R_K = (2.45 \pm 0.11) \times 10^{-5}$ dates back to three experiments of the 1970s [7] and has a precision of less than 4%. However, now three new preliminary measurements have been reported by NA48/2 and KLOE (Tab. II). A preliminary result of NA48/2, based on about 4000 K_{e2} events from the 2003 data set, was presented in 2005 [16]. Another preliminary result, based on also about 4000 events, recorded in a minimum bias run period in 2004, was shown in 2007 [17]. Both results have independent statistics and are also independent in the systematic uncertainties, as the systematics are either of statistical nature (as e.g. trigger efficiencies) or determined in an independent way. Another preliminary result, based on about 8000 K_{e2} events, was presented in 2007 by the KLOE collaboration [18]. Combining these new results with the current PDG value yields a current world average of

$$R_K = (2.457 \pm 0.032) \times 10^{-5}, \tag{12}$$

in very good agreement with the SM expectation and, with a relative error of 1.3%, a factor three more precise than the previous world average (Fig. 6).

In the SUSY framework discussed above, this result gives strong constraints for $\tan\beta$ and $M_{H^\pm}$ (Fig. 7).

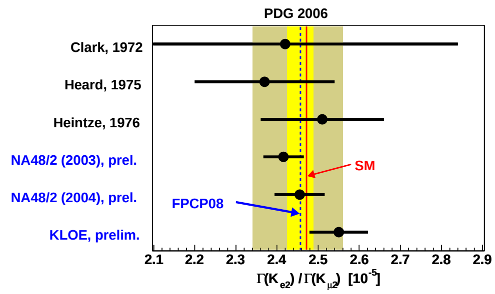

Figure 6: Results on $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$. Indicated are the current PDG average (brown), the average of all measurements (blue/yellow), and the SM prediction (red).

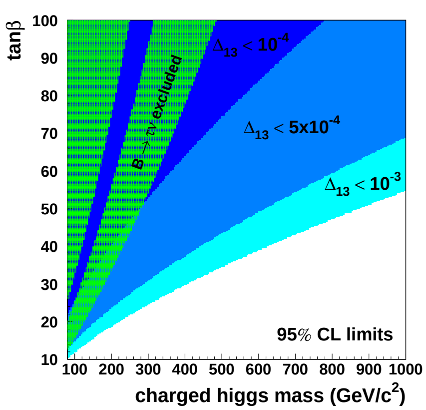

Figure 7: Exclusion limits at 95% CL on $\tan\beta$ and the charged Higgs mass $M_{H^\pm}$ from $K_{e2}/K_{\mu 2}$ for different values of Δ_{13}. Values $M_{H^\pm} < 80$ GeV/c^2 are excluded by direct searches. Indicated are also the exclusion limits from $B \to \tau\nu_\tau$ decays [13].

For a moderate value of $\Delta_{13} \approx 5 \times 10^{-4}$, $\tan\beta > 50$ is excluded for charged Higgs masses up to 1000 GeV/c^2 at 95% CL. These exclusion limits can be compared with SUSY limits obtained from $B \to \tau\nu$ decays. The exclusion limits on $\tan\beta$ and $M_{H^\pm}$, obtained from the current BELLE and BaBar average of $\mathrm{Br}(B \to \tau\nu) = (1.42 \pm 0.44) \times 10^{-4}$ [13], are superposed in Fig. 7. In general, the limit obtained from $K_{e2}/K_{\mu 2}$ is stronger than those from $B \to \tau\nu_\tau$. However, as the latter are lepton flavour conserving, they do not need an assumption on the value Δ_{13}.

In the near future, further improvements in the knowledge of R_K are expected. The preliminary KLOE measurement [18] is statistically dominated by MC statistics and has a conservative estimate of the systematic uncertainty. Improving both these items, adding the remaining KLOE statistics, and also adding events with an additional reconstruction method, should reduce the overall relative uncertainty down to 1%.

An improvement of a further factor of three is the goal of the NA62 collaboration at CERN. NA62, successor of NA48, plans to measure the very rare decay $K^+ \to \pi^+\nu\bar{\nu}$ in the mid-term future [19]. In a first phase, about four months of data taking for the measurement of $K_{e2}/K_{\mu 2}$ took place in 2007, with about 150000 K_{e2} decays being recorded in total. Preliminary results from this measurement are expected in the near future.

4. Search for Direct $\mathcal{CP}$ Violation in $K^\pm$ Decays

The violation of CP symmetry has always been of great interest in particle physics, not only because of its cosmological implications, but also for its potential for the discovery of new physics beyond the Standard Model. In particular, $\mathcal{CP}$ violation in decays (direct $\mathcal{CP}$ violation, as opposed to indirect $\mathcal{CP}$ violation and mixing induced $\mathcal{CP}$ violation) is sensitive to contributions of possible new physics.

For the decay of charged kaons into three pions, the obvious manifestation of direct $\mathcal{CP}$ violation would be an asymmetry in the partial rates. However, measuring rate differences is experimentally almost impossible, as the total fluxes would have to be known to sub per mille precision. Instead, experiments search for differences in the Dalitz plot slopes between K^+ and K^- decays.

The $K^\pm \to 3\pi$ matrix element squared is conventionally parametrized as [7]

$$|M(u,v)|^2 \sim 1 + gu + hu^2 + kv^2 + \cdots, \qquad (13)$$

where g, h, and k are the so-called linear and quadratic Dalitz plot slope parameters (with $|h|, |k| \ll |g|$), and the two kinematic variables $u = (s_3 - s_0)/m^2_{\pi^+}$ and $u = (s_2 - s_1)/m^2_{\pi^+}$ with $s_i = (p_K - p_{\pi_i})^2$ and $s_0 = (s_1 + s_2 + s_3)/3$, and the index $i = 3$ belonging to the "odd"-charged pion. Direct $\mathcal{CP}$ violation would manifest itself in a difference between the linear slope parameters g^+ and g^- for K^+ and K^- decays, respectively, which is usually expressed in a corresponding slope asymmetry

$$A_g = \frac{g^+ - g^-}{g^+ + g^-} = \frac{\Delta g}{2g}, \qquad (14)$$

where g is the average linear slope. The SM prediction for the size of A_g is of $\mathcal{O}(10^{-6}) - \mathcal{O}(10^{-5})$ [20], while new scenarios beyond the SM may enhance $\mathcal{CP}$ violation up to a few 10^{-4} [21].

The NA48/2 experiment was specifically designed to measure the Dalitz plot asymmetries between K^+ and K^- decays [22]. K^+ and K^- beams were produced together by proton collisions on a single beryllium target and selected by an achromat system to

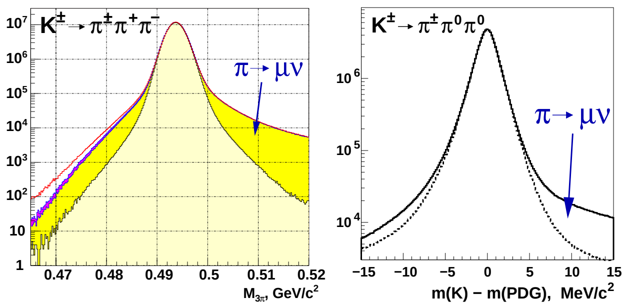

Figure 8: Reconstructed invariant 3π mass of $K^\pm \to \pi^\pm\pi^+\pi^-$ (left) and $K^\pm \to \pi^\pm\pi^0\pi^0$ (right) decays.

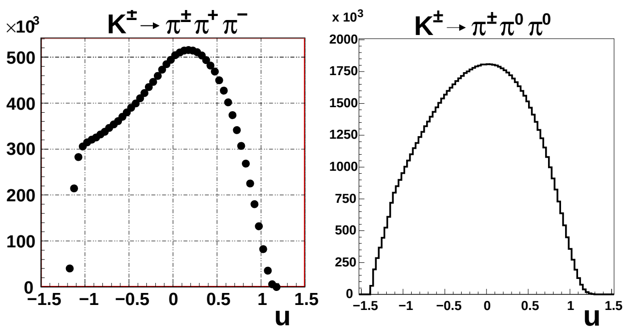

Figure 9: Distributions of the Dalitz plot parameter $u = (s_3 - s_0)/m_\pi^2$ for $K^\pm \to \pi^\pm\pi^+\pi^-$ (left) and $K^\pm \to \pi^\pm\pi^0\pi^0$ (right) decays.

have momenta of $p_{K^\pm} = (60 \pm 3)$ GeV/c. Superimposed on each other, the two beams entered the decay region, where K^+ and K^- decays were recorded simultaneously. To further symmetrize the set-up, regular changes of the beam-line achromat and the detector spectrometer polarities were performed during the data taking periods. In total, 3.1×10^9 $K^\pm \to \pi^\pm\pi^+\pi^-$ events and 9.1×10^7 $K^\pm \to \pi^\pm\pi^0\pi^0$ events were reconstructed from the final NA48/2 data set. Both decays were selected practically background-free. The invariant 3π mass distributions are shown in Fig. 8. The corresponding distributions of the Dalitz plot variable u are shown in Fig. 9.

To cancel possible systematic biases due to achromat and spectrometer polarity reversals, four single ratios $R_{UJ}(u)$, $R_{US}(u)$, $R_{DJ}(u)$, and $R_{DS}(u)$ between the K^+ and K^- u-spectra were built, where in each ratio only data were considered with both kaons either going through the upper (U) or lower (D) achromat path and being deflected by the spectrometer either to the left (Jura, J) or to the right (Salève, S) side. Finally, a quadruple ratio

$$\begin{aligned} R_4(u) &= R_{UJ}(u) \cdot R_{US}(u) \cdot R_{DJ}(u) \cdot R_{DS}(u) \\ &\propto \left(\frac{\Delta g\, u}{1 + g\, u + h\, u^2}\right)^4 \end{aligned} \tag{15}$$

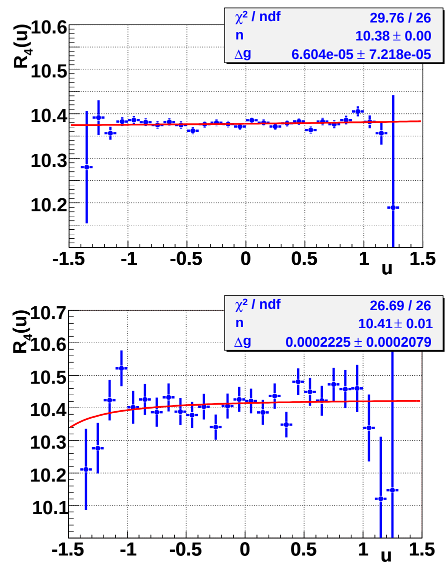

Figure 10: Distributions of the quadruple ratio $R_4(u)$ for $K^\pm \to \pi^\pm\pi^+\pi^-$ (top) and $K^\pm \to \pi^\pm\pi^0\pi^0$ (bottom) data together with the best fit.

was evaluated in the fit. In this ratio, in contrast to the single ratios, also possible time variation of run and detector conditions cancel. The $R_4(u)$ distributions for both modes are shown in Fig. 10. The fit resulted in asymmetries of [22]

$$\begin{aligned} A_g^{\pi^\pm\pi^+\pi^-} &= (-1.5 \pm 1.5_{\rm stat} \pm 0.9_{\rm trig} \pm 1.3_{\rm syst}) \cdot 10^{-3}, \\ A_g^{\pi^\pm\pi^0\pi^0} &= (1.8 \pm 1.7_{\rm stat} \pm 0.6_{\rm syst}) \cdot 10^{-3}, \end{aligned} \tag{16}$$

where the trigger uncertainty is of purely statistical nature. For both results, the statistical uncertainties dominate. They are an order of magnitude more precise than previous measurements and give no indication of possible non-SM $\mathcal{CP}$-violating amplitudes in these channels.

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