The Kaon Physics Programme at CERN

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Abstract

The Standard Model was largely built by studying the properties of the strange particles and at CERN there has been a long tradition of experimentation on the subject. After a short reminder about the highlights from the latest round of CERN kaon experiments, I will describe the plans towards high sensitivity rare kaon decay studies at the SPS.

The Standard Model (SM) was largely built by studying the properties of strange particles: the $\theta - \tau$ puzzle and the fall of parity conservation; the concept of strangeness and flavour conservation in strong interactions; the universality of weak interactions; the GIM explanation of the absence of Flavour Changing Neutral Currents (FCNC); the discovery of CP-violation and its comprehension withing the mixing of three families of elementary fermions are just some of the pillars of our understanding of Nature uncovered studying the properties of kaons and hyperons.

There are currently three main directions in elementary particle physics. On the one side experiments are made at the highest possible energies searching for the origin of electroweak symmetry breaking and direct evidence of New Physics (NP); a second line of attack aims to study the properties of the neutrinos, both of accelerator and cosmic origin, and of other astro-particle messengers. The third strategy is to explore the precision frontier looking for deviations from the SM predictions in rare or forbidden processes. At the precision frontier the sensitivity to NP originates from the virtual fluctuations that can involve all discovered and not yet discovered particles in higher order quantum loops and therefore can address, indirectly, energy scales beyond those reachable at colliders. The most interesting rare decays are those FCNC that can be predicted with small hadronic uncertainty in the SM. Some of these decays are decisive probes of the short distance interactions between quarks. To study precisely these processes is particularly important now that the Cabibbo-Kobayashi-Maskawa model for quark missing and CP-Violation has been generally confirmed. Very few observables exist where sensitivity to NP and predictability within SM coexist. A very prominent example is given by the $K \to \pi\nu\bar{\nu}$ decays and it is precisely on this subject that the future CERN kaon physics strategy is being developed.

Recent physics results on radiative and hyperon decays from CERN were presented at this conference by N. Molokanova. In this paper I will set the framework by recalling some highlights from the CERN kaon programme (NA48) and I will summarise the status of the new initiative (NA62) planning to study ultra-rare decays at the CERN-SPS. To complete the kaon world picture the reader should also refer to the presentations by V. Duk and M. Doroshenko at this conference.

The CERN proton complex is unique. The Super Proton Synchrotron (SPS) will remain in operation for the foreseeable future as LHC injector. This injector task should occupy only a few hours per day leaving the SPS available to send 400 GeV/c primary protons to fixed target experiments for the rest of the time. In the NA48 experiment the kaons are made striking the

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primary proton beam on a 40 cm long Be target placed about 120 m before the beginning of a 90 meter long evacuated tube that form the decay region. The NA48 main detectors are placed at the end of the decay region and consist of a state-of-the-art electromagnetic calorimeter based on liquid krypton (LKR) and a very thin magnetic spectrometer formed by four large planar drift chambers and a dipole magnet. Details about the NA48 detectors can be found in [1].

The NA48 experiment was commissioned in 1996 and took data from 1997 until 2001 to establish direct CP-violation in neutral kaon decays into two pions by measuring the $\Re\ \epsilon'/\epsilon$ parameter. A new experiment (NA48/1) took data in 2000 and 2002 to study K^0_S kaon rare decays and neutral hyperons. The next experiment (NA48/2) was devoted to the study of CP-violation in charged kaon decays. It took data in 2003 and 2004 to search for direct CP-violation by comparing the Dalitz plot slopes for positive and negative kaons collected simultaneously. While preparing the new setup to address very rare decays, the new Collaboration (NA62) has accumulated data in 2007 over five months to perform a precise study of lepton universality in kaon leptonic decays.

Two of the most important questions in particle physics are concerned with the apparently purposeless replication of fermion generations (leptons and quarks) and to the study the origin of the matter-antimatter asymmetry [2]. The interactions between quark generations are governed by the weak force and deeply interwoven with the origin of CP-violation, one of the three essential "Sakharov Conditions" [3] that allow the development of an unbalance between matter and anti-matter in the Universe. By extending the Cabibbo theory [4] of quark mixing to three generations, Kobayashi and Maskawa [5] showed that CP-violation could be incorporated in the framework of the weak interactions.

The first verification of this assumption was the discovery of direct CP-violation in the neutral kaon decays into two pions. The original indication obtained at CERN by the experiment NA31 [6] was not confirmed at FNAL [7] and a new round of experiments, NA48 at CERN [8] and KTeV [9] at FNAL were built to settle the issue. In Fig. 1 the sequence of $\mathcal{R}\ \epsilon'/\epsilon$ measurements is shown as a function of time. By now direct CP-violation is firmly established and the average including the latest updates gives:

$$\mathcal{R}\ \epsilon'/\epsilon = 1.68 \pm 0.14 \times 10^{-3} \tag{1}$$

This value is typically larger than the predictions inspired to lattice QCD calculations but agrees with phenomenological estimates within the framework of the Standard Model (SM) [11, 12, 13, 14]. A subsequent experiment at CERN (NA48/2) looked for CP-asymmetries in the Dalitz plot slopes in $K \to 3\pi$ decays. These asymmetries (A_g) are predicted to be very small in the SM and therefore a non-zero value of $A_g \geq 10^{-5}$ would unambiguously signal physics beyond SM. The experiment was performed using a narrow-band 60 GeV/c achromatic secondary beam to collect concurrently K^+ and K^- decays. In Fig. 2 and Fig. 3 the Dalitz plot distributions for the NA48/2 final samples of $K \to 3\pi$ are shown. The number of events used in the analysis are dazzling: 3.1 $\times 10^9 K^\pm \to \pi^\pm\pi^+\pi^-$ and 9.1 $\times 10^7 K^\pm \to \pi^\pm\pi^0\pi^0$! The final results are reported below [15] for $K^\pm \to \pi^\pm\pi^+\pi^-$ and $K^\pm \to \pi^\pm\pi^0\pi^0$ respectively:

$$A^c_g = (-1.5 \pm 2.2) \times 10^{-4} \tag{2}$$

$$A^n_g = (-1.8 \pm 1.8) \times 10^{-4}. \tag{3}$$

To summarise the current status of the understanding of CP-violation and quark-mixing, it can be said that NA48/2 has closed another window of opportunity. The current manifestations of CP-Violation in K and B decays and mixing confirm that the main source of CP-violation is due to the complex phase in the CKM matrix. Precise experimental probes are required to detect possible deviations from the SM. As it will be described later in this article, the study of ultra-rare kaon decays provide a promising road.

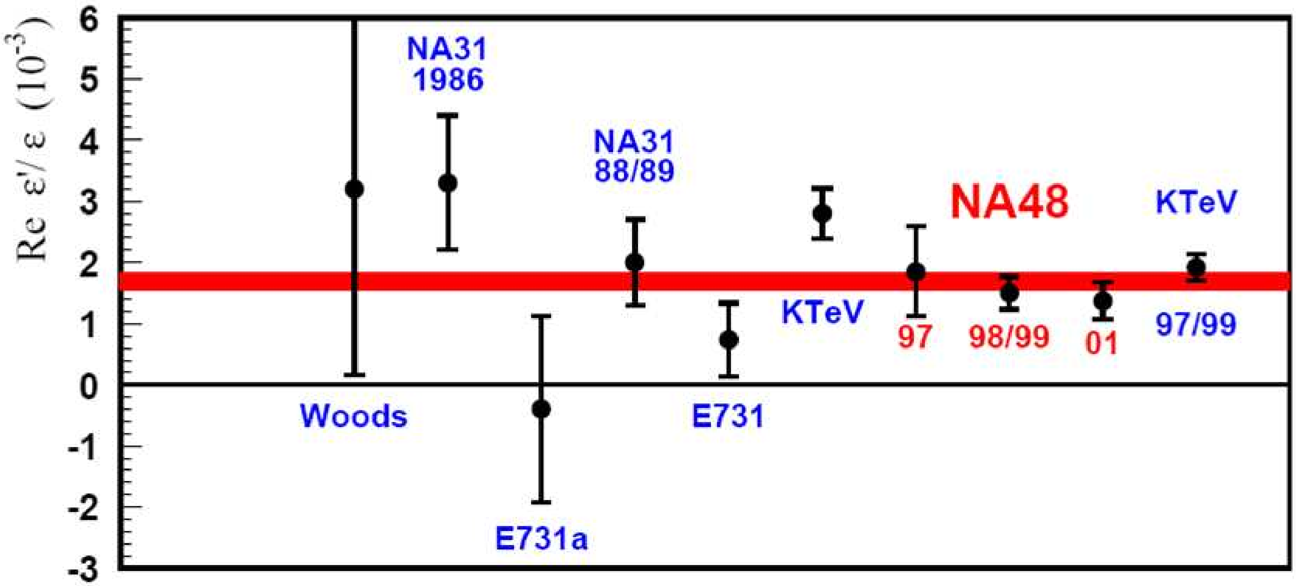

Figure 1: Measurements of $\Re\ \epsilon'/\epsilon$.

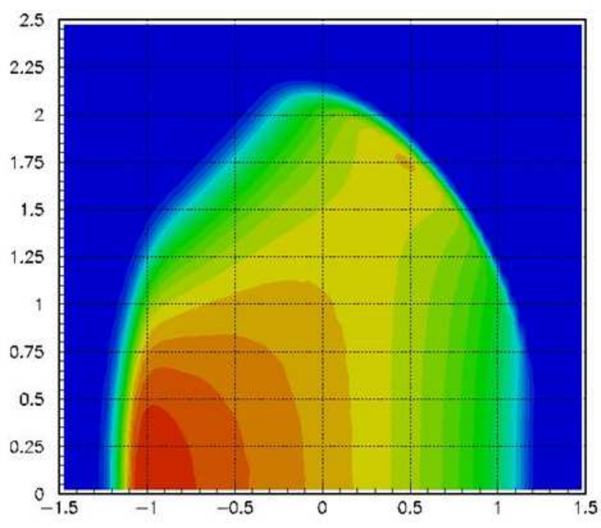

Figure 2: Dalitz plot distribution ($|v|$ vs. u) for the $K^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays accumulated by NA48/2.

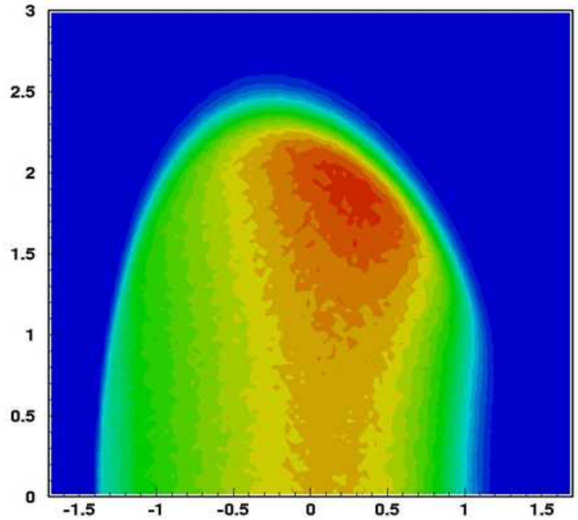

Figure 3: Dalitz plot distribution ($|v|$ vs. u) for the $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays accumulated by NA48/2.

An important by-product of the study of CP-violation performed by NA48/2 is the study of $\pi\pi$ scattering. This process is important because:

- it is the simplest non-trivial hadron scattering process;
- it is an ideal laboratory to test low energy QCD;
- it is very attractive theoretically because the complication of spin is not present.

From an experimental point of view progress is hampered by the lack of real pion targets! In NA48/2 there are two methods to study pion pion scattering:

1. Study of the $\pi\pi$ phase-shift in $K^{\pm} \to \pi^{+}\pi^{-}e^{\pm}\nu$ decays (Ke4);
2. Study of cusp-like interference in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays.

The description of how the $\pi\pi$ scattering length is measured from Ke4 data is beyond the scope of this paper and to appreciate the quality of the NA48/2 data the reader is referred to a recently published paper [16]. What I wish to point out here instead is that the NA48/2 discovery [17] of the cusp-like structure in $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$, which led to an completely independent method [18] to measure the pion pion scattering length, was totally unexpected. This situation is not unusual in experimental physics, it underlines the importantance to keep state-of-the-art experimental facilities available and an open mind towards Nature. In Fig. 4 the invariant mass of the $\pi^{0}\pi^{0}$ for $K^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ decays is displayed and the cusp-like structure is striking.

I will turn now to the future describing the plans to study very rare kaon decays at the CERN SPS. To be interesting in order to probe high energy scales, a rare decay has to be:

- strongly suppressed in the Standard Model;
- dominated by short-distance dynamics;
- sensitive to new degrees of freedom.

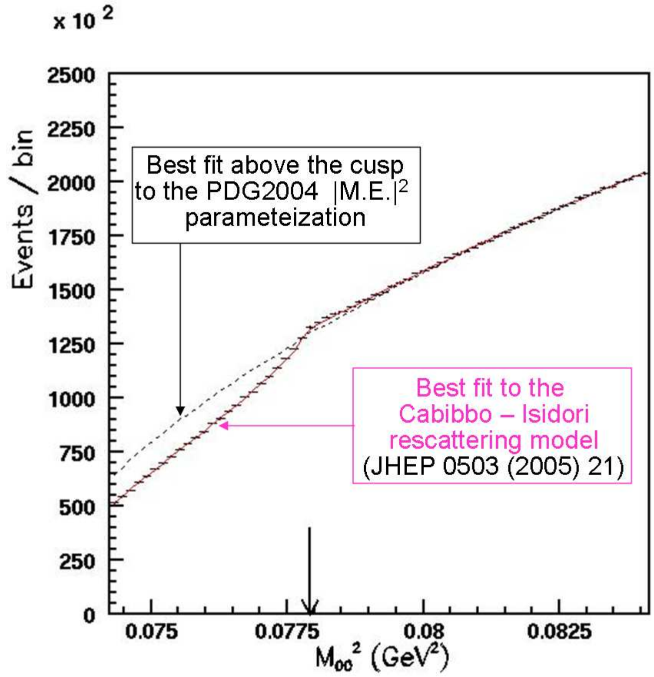

Figure 4: $\pi^0\pi^0$ Invariant mass of the $K^\pm \to \pi^\pm\pi^0\pi^0$ decays accumulated by NA48/2. The presence of the cusp-like structure at $4m^2_{\pi^\pm}$ (the $\pi^+\pi^-$ threshold) is striking.

The following rare kaon decays are particularly important to study CP-Violation and quark-mixing:

$$K^+ \to \pi^+\nu\bar{\nu} \tag{4}$$

$$K_L^0 \to \pi^0\nu\bar{\nu} \tag{5}$$

$$K_{S,L}^0 \to \pi^0 e^+e^- \tag{6}$$

$$K_{S,L}^0 \to \pi^0 \mu^+\mu^- \tag{7}$$

The best limits concerning the CP-Violating decays of the decays with charged leptons in the final states were obtained at FNAl by the KTeV Collaboration [19, 20]. Experimental progress to control the long distance effects due to CP-violation effects in the neutral kaon mixing in the reactions with charged leptons in the final states was made by the experiment NA48/1 at CERN by measuring $K_S^0 \to \pi^0 e^+e^-$ [21] and $K_S^0 \to \pi^0\mu^+\mu^-$ [22].

The decays with a pion and a neutrino-antineutrino pair in the final state are the most important because they are precisely calculable in the Standard Model. The uncertainty of the prediction is dominated by the limited knowledge of the CKM matrix elements and not by lack of knowledge of the hadronic theory which in most cases renders unreliable the predictions of meson decay rates. The reason why the hadronic uncertainty is small is that the hadronic matrix element can be measured from the corresponding Cabibbo-favored semi-leptonic tree decay by using isospin rotation.

The purely CP-violating process $K_L^0 \to \pi^0\nu\bar{\nu}$ can be predicted in the SM with the smallest theoretical error because there is no contribution from charm quark exchange. The uncertainty of the prediction [23]:

$$\mathcal{B}(K_L^0 \to \pi^0\nu\bar{\nu}) = (3.0 \pm 0.6) \times 10^{-11}, \tag{8}$$

is purely parametric. Significant progress was reported at this conference by Doroshenko, who also described the prospects to continue the investigations at the newly built J-PARC complex in Japan. The study $K_L^0 \to \pi^0\nu\bar{\nu}$ was pioneered at FNAL by the KTeV Collaboration [24] and further pursued at KEK [25]. These initiatives were based on the exploitation of a so-called "pencil beam" were the only kinematical constraint is given by the presumed line of flight of the neutral kaon. The Protvino U70 accelerator seems also a good place to address this technique [27]. The idea to constrain more the initial state by determining the momentum of the incoming neutral kaon by time-of-flight was worked out by the KOPIO Collaboration [28]: the necessary R&D was carried out but, after long consideration, the experiment was not funded and these ideas are still left at the level of concept.

For $K^+ \to \pi^+\nu\bar{\nu}$, the master formula can be written as:

$$\mathcal{B}\left(K^+ \to \pi^+\nu\bar{\nu}\right) = \kappa_+ \left[\left(\frac{\Im V_{ts}^* V_{td}}{\lambda^5} X(x_t)\right)^2 + \left(\frac{\Re V_{ts}^* V_{td}}{\lambda^5} X(x_t) + \frac{\Re V_{cs}^* V_{cd}}{\lambda}\left(P_c + \delta P_{c,u}\right)\right)^2\right] \quad (9)$$

where, $\lambda = \sin\theta_C$, θ_C is the Cabibbo angle,

$$\kappa_+ = r_{K^+} \frac{3\alpha^2 \mathcal{B}\left(K^+ \to \pi^0 e^+ \nu\right)}{2\pi sin^4\theta_w} \lambda^8 \quad (10)$$

and r_{K^+} is the isospin breaking correction. A recent NNLO QCD calculation [29] has reduced considerably the theoretical error and the prediction uncertainty is now dominated by the knowledge of the CKM parameters:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (8.0 \pm 1.1) \times 10^{-11}. \quad (11)$$

Over the past years we have witnessed decisive progress on the study of the charged kaon decay $K^+ \to \pi^+\nu\bar{\nu}$. The experiment was carried out at Brookhaven National Lab (BNL) by employing stopped kaons. It took data in the '90s (E787) and in the year 2002 (E949). The latest published result gives [30]:

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-1.1}) \times 10^{-10}. \quad (12)$$

The mean value, although consistent with the SM prediction given the large error, entices new experiments to achieve much better precision. A proposal to study this decay in flight with a separated kaon beam was approved at FNAL [31]. Unfortunately the experiment was terminated before the construction could start.

A new proposal to study $K^+ \to \pi^+\nu\bar{\nu}$ in flight at the SPS was submitted to the CERN SPS Committee [32] and is now completing the R&D phase. It is based on the idea that the high energy secondary beams available from the SPS can give an advantage in the suppression of potential background sources. The advantage of the decay-in-flight experiment with respect to the stopped kaon technique is that it does not suffer from the scattering introduced by the stopping target material and that the geometrical acceptance can be kept large.

The limitation of employing high energy secondary beams (75 GeV/c) is that the kaons cannot be separated from the unwanted particles (mostly charged pions and protons) in the beam. Therefore all beam particles have to be tracked on event by event basis even if only about 6.6 % of these are useful kaons. In additions, only a fraction ($\approx$ 20%) of these kaons decay usefully in the fiducial volume.

The experiment is based on the consideration that the most troublesome background, consisting of $K^+ \to \pi^+\pi^0$ decays where the photons are not detected and the two-body kinematics is not correctly reconstructed, can be addressed by restricting the acceptance to pions decaying backward in the kaon center of mass with respect to the kaon direction in the laboratory frame. Under this hypothesis, the π^0 is boosted forward in the laboratory and deposits a very large amount of the kaon energy in the calorimeter or in the photon vetoes surrounding the decay tank so that the photons can hardly be missed. In addition, a pion from $K^+ \to \pi^+\nu\bar{\nu}$ decaying backward in the kaon center of mass has the correct momentum range to be distinguished

Decay Mode	Events/year
Signal (flux 4.8 $\times 10^{12}$)	55
$K^+ \to \pi^+\pi^0$	2.4
$K^+ \to \mu^+\nu$	1.2
$K^+ \to e^+\pi^+\pi^-\nu$	$\leq$ 1.6
Other 3-track decays	$\leq$ 0.8
$K^+ \to \pi^+\pi^0\gamma$	1.1
$K^+ \to \mu^+\nu\gamma$	0.4
$K^+ \to e^+(\mu^+)\pi^0\nu$, others	-
Total Expected Backgrounds	$\leq$7.5

Table 1: Signal and background events expected for one year data taking.

from a muon by means of a RICH detector based on atmospheric Neon and spherical mirrors. Combining the RICH performance with a Muon Veto Detector (MUV), the other potentially dangerous background ($K^+ \to \mu^+\nu$ decays where the muon is mistaken for a pion and the kinematics is not correctly reconstructed) can also be controlled. The number of expected signal and background events for one year of data taking is given in Table 1. One of the most important aspects of the proposal is related to the photon rejection. For a high-energy, in-flight experiment the photon detectors represent one of the driving costs because of the large volume that one has to equip to provide hermetic coverage. For this reason since 2006 the R&D has focused on cost effective solutions for these detectors. To cover the forward region, the NA48 LKR will be re-used. In 2006 its performance as photon veto was validated using $K^+ \to \pi^+\pi^0$ data kinematically selected. The charged pion and one of the two photons was used to predict the position of the other photon in the calorimeter. The predicted photon was not found with a probability of less than one time in 10^5, which fully satisfies the specifications. As far as the larger angle vetoes are concerned, after evaluating several technical solutions, it was realised that the lead glass employed by the OPAL experiment at LEP was still available and perfectly suitable for the experiment. A few blocks were exposed to radiation doses similar to those expected during the experiment lifetime and no radiation damage was found. An engineering study was performed for the integration of the lead glass in the experiment and this solution was adopted as base line for the large angle photon veto. Later this year a prototype module equipped with about 20 OPAL crystals will be installed in the vacuum tank and exposed to photons from kaon decays.

Another challenge is represented by the tracking detectors. I have already mentioned the importance of the beam tracker that has to track every single beam particle. The beam rate is almost 1 GHz hence the name "Gigatracker" by which the detector is known. The proposed tracker will be formed by three stations of silicon micropixels (pitch 300 $\times$ 300 μm) with a time resolution of about 200 ps per station. The time resolution is essential to correlate the correct beam track with the daughter particle reconstructed in the downstream detectors. The main innovations in the Gigatracker are related to the read-out electronics. It is planned to test a fully fledged sub-matrix in the beam early in 2009. Concerning the downstream tracker, it is planned to operate inside the vacuum tank to reduce to a minimum the multiple scattering. A prototype straw tracker was tested in the vacuum tank in 2007. It is based on a new technology developed in JINR (Dubna) were metalised mylar are folded and welded by ultrasound to form a tube. Last but not least, a prototype muon detector developed by INR-Protvino will be beam tested in September-October 2008. The fast muon detectors is crucial to veto $K^+ \to \mu^+\nu$ decays at the level 0 trigger because two thirds of all kaon decays involve a muon and have to be veto as fast as possible. The status of P-326 NA62 can be summarised as follows:

- The R&D phase is approaching completion

- Some funding Agencies, and notably the Italian INFN, have already approved the construction programme
- The construction is foreseen to take place from 2009 until 2011, to be followed by first data taking for $K^+ \to \pi^+ \nu\bar{\nu}$ in 2011-2012
- The new Collaboration is growing
- In 2007 the new Collaboration – NA62– has collected five months of proton data at the SPS to study lepton universality in kaon leptonic decays

The decay width of mesons into leptons can be precisely calculated in the SM. Angular momentum conservation implies that the electron modes are helicity suppressed with respect to the muonic ones. It was pointed out [33] that variations of the order of a % from the SM prediction could be expected in the ratio

$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} \tag{13}$$

due to lepton non-universality in some SUSY scenarios. The most recent SM prediction [34] gives: $R_K(SM) = 2.477 \pm 0.001) \times 10^{-5}$ NA62 has accumulated more than 100 k $K \to e\nu$ events in 2007 to push the experimental error on R_K from about 2% to 0.3%. A subset of the data accumulated by NA62 in 2007 is shown in Fig. 5.

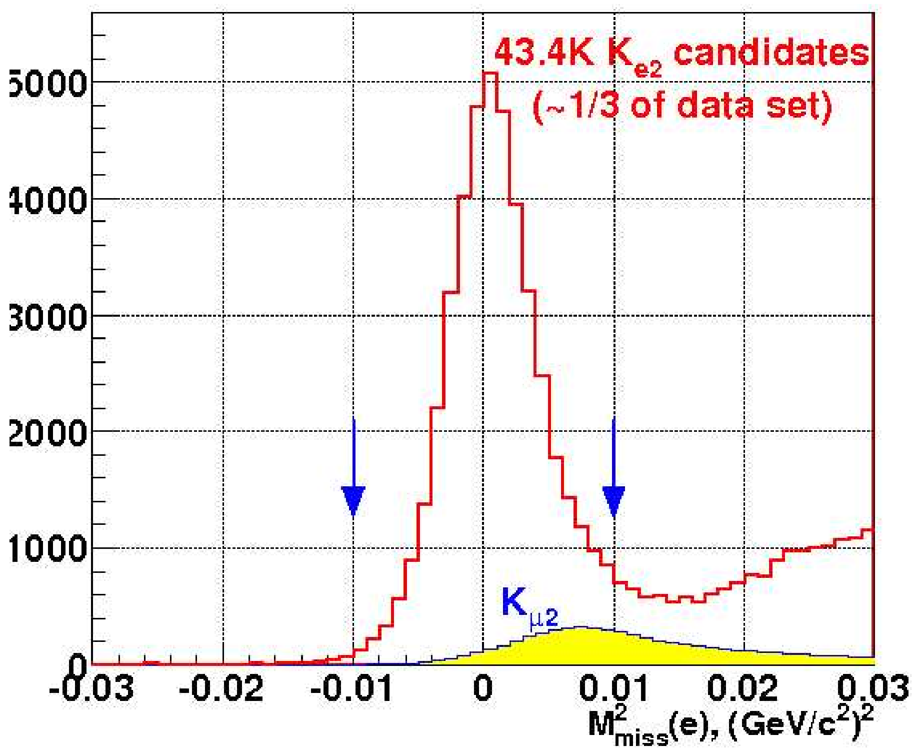

Figure 5: The squared missing mass recoiling against the charged particle assumed to be a positron (NA62, fraction of the 2007 data).

In conclusion, I hope to have convinced you that we can be optimistic: owing to the unique proton complex, kaon studies at CERN not only had a glorious past but, most importantly, are poised for a bright future. And maybe, thanks to the high sensitivity of the new setup, the physics programme could be extended and some new particles like the sgoldstinos [35] or νMSM[36] will be discovered!

I wish to thank the organizers of the Quarks 2008 seminar for an excellent programme and for the choice of a very inspiring and hospital venue.

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