PROCEEDINGS OF SCIENCE

Rare lepton and K-meson decays

Alessandro Massimo Baldini*
INFN Sezione di Pisa
E-mail: alessandro.baldini@pi.infn.it

Ultra rare K-meson and lepton decays are very sensitive probles for exploring New Physics beyond the Standard Model. In this report I review the status and the progress of experiments which are running or about to start running in this field of particle physics

35th International Conference of High Energy Physics - ICHEP2010,
July 22-28, 2010
Paris France

*Speaker.

PoS(ICHEP 2010)528

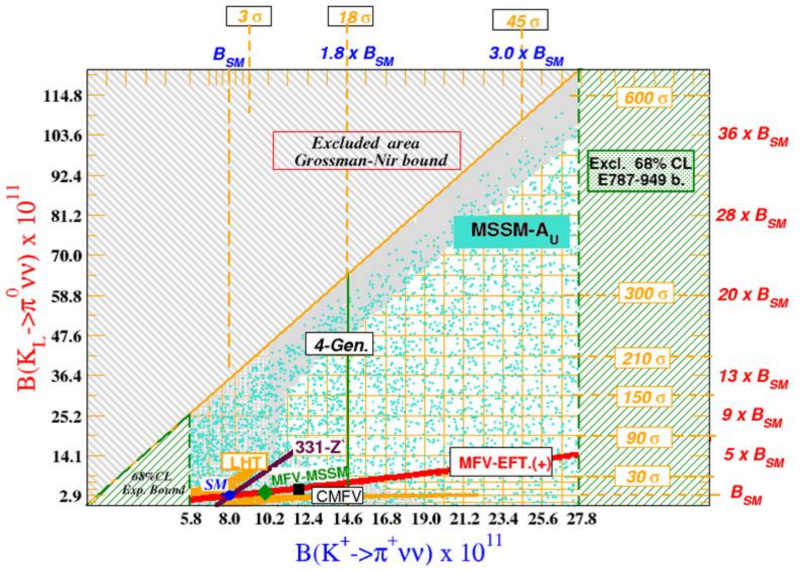

Figure 1: Sensitivity of the $K \to \pi\nu\bar{\nu}$ search to different NP models. The vertical dashed green lines indicate the 68% CL limits given by the E787/949 series of experiments.

The study of ultra-rare decays in the Kaon and lepton sectors is very attractive because these processes have theoretical contributions due to the Standard Model (SM) which are strongly suppressed and at the sime time calculable with excellent precision, therefore New Physics (NP) effects could give relatively relevant and thus measurable contributions. In this report I concentrate only on few of the possible experimentally viable decays treating only running or about to run experiments or cases in which new results were recently released. The decays on which experimental effort is currently being put in the K case are the $K \to \pi\nu\bar{\nu}$ decay, for both charged and neutral initial states, and the study of the $K_{e2}/K_{\mu 2}$ ratio while in the lepton sector results have been presented at this Conference by the Belle[1] and MEG[2] experiments for $\tau \to l\ x$ and $\mu \to e\gamma$ respectively.

$K \to \pi\nu\bar{\nu}$ rate can be calculated to be $< 10^{-10}$ in the SM with a precision at the percent level (see next section) while it was recentlly pointed out[3] that the ratio $K_{e2}/K_{\mu 2}$, which is calculated[4] to be $(2.477 \pm 0.001) \times 10^{-5}$ in the SM, might receive contributions from NP processes at the percent level. In the case of leptonic decays SM predictions for flavour non conserving processes are completely negligible from an experimental point of vew, therefore any observation of these decays would constitute a clear signal of New Physics[5].

1. Ultra rare K-meson decays experiments

The sensitivity to NP of the search for $K \to \pi\nu\bar{\nu}$ is usually illustrated by referring to Fig.1, taken from[6], where the expectations for several models of the neutral versus the charged mode branching ratios are shown. It can for instance be seen that even a measurement with 10% accuracy would be sensitive to a very large number of these models.

The $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio was measured to be $(1.73^{+1.5}_{-1.05}) \times 10^{-10}$ by the BNL E787 - E949 experiment[7] on the basis of 7 observed events and is compatible within the experimental

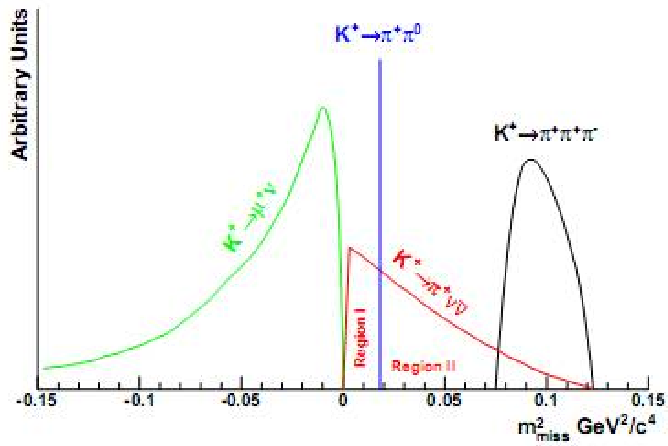

Figure 2: Squared missing mass distribution of signal and backgrounds for the NA62 experiment.

errors with the SM prediction: $(0.85 \pm 0.07) \times 10^{-10}$. The P996 proposal at Fermilab plans to use the same techninque of the BNL experiments. By using the Tevatron as a stretcher, by increasing the detector acceptance, the number of kaons stopped per hour and the number of hours per year the number of events corresponding to the SM predictions could be ≈ 200 per year which should make possible to have an accuracy of 5% in the measurement of this decay in 5 years of sata taking.

At CERN the NA62 experiment, currently in a mixed construction - R&D phase, plans to use a new technique for measuring the $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio. In this case an unseparated (from protons and pions) beam of 75 GeV/c momentum is used and K^+ decays in flight are studied by distinguishing the desired channel from background on the basis of kinematics as can be seen from Figure 2 where the squared the missing mass distribution of signal and background is shown and the regions to be used for selecting the desired decays are indicated as Region I and II.

The NA62 experiment will take great advantage from using the existing infrastructures and part of the existing detectors of a previous experiment (NA48). In order to perform a good event kinematical reconstruction and a good separation from background a new very fast tracking device ($\sigma_t \approx 150$ ps) called Gigatracker, which will measure the momentum of the incoming beam and provide a tight coincidence of incoming kaons with downstream detected pions, is critical.

The number of expected $K^+ \to \pi^+ \nu \bar{\nu}$ decays in the NA62 experiment is 55 per year with a $\approx 15\%$ background mainly due to misidentified $K^+ \to \pi^+ \pi^0$ decays.

Meanwhile, in evolving from NA48 to NA62, the NA62 collaboration used the NA48 experiment to take data for precisely measuring $R_K = K_{e2}/K_{\mu 2}$ [8]: four months of data were taken in 2007 and a special run of two weeks in 2008 for allowing reduction of systematic uncertainties. The magnetic spectrometer, the scintillator hodoscope and the liquid kripton electromagnetic calorimeter of the NA48 experiment were used for this measurement. The two different K decays are separated by using the kinematical reconstruction and by exploiting particle identification in the liquid kripton calorimeter. Below 25 GeV/c the kinematical reconstruction allows a complete separation of the two categories of events but above this momentum $K_{\mu 2}$ starts being the major

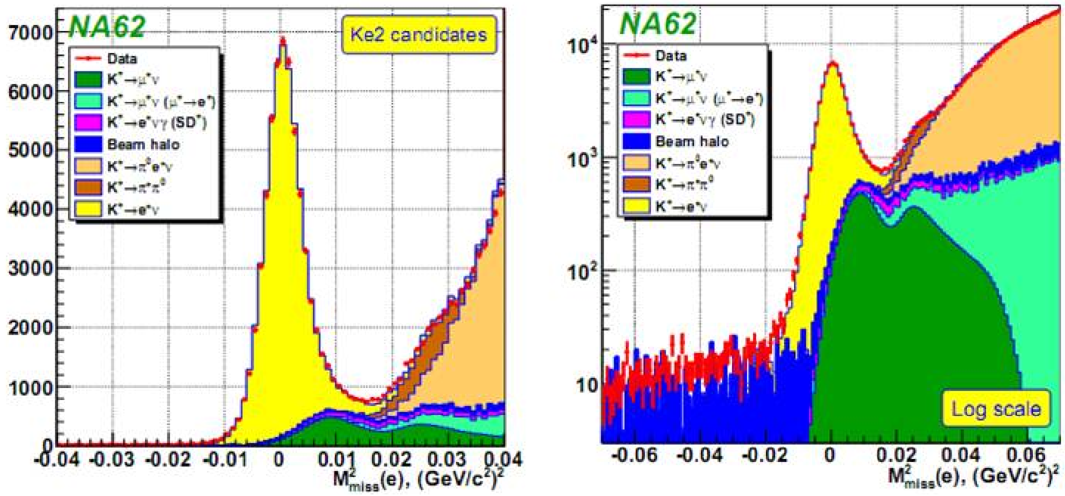

Figure 3: Squared missing mass distribution of K_{e2} and $K_{\mu 2}$ events with the estimated backgrounds superimposed.

background in the K_{e2} sample and it has to be accurately determined in order to reach a high accuracy in the measurement of R_K. It was therefore necessary to accurately measure the probability of misidentification of a muon as an electron by placing a lead wall in front of the liquid kripton calorimeter.

The distributions of the K_{e2} and $K_{\mu 2}$ candidates as a function of the squared missing mass are shown in Figure 3. The final result based on 40% of the NA62 K_{e2} sample is:

$$R_K = (2.486 \pm 0.013) \times 10^{-5}$$

consisting in a 0.5% accuracy measurement in agreement with the value predicted by the SM. With the full data sample an overall uncertainty of 0.4% will be reached. NA62 phase II and KLOE-2[9] aim in future at reaching an accuracy for this measurement of 0.2% and 0.4% respectively.

Coming back to the $K \to \pi \nu \bar{\nu}$ decay, the present best measurement of the neutral decay channel $K_L \to \pi^0 \nu \bar{\nu}$ consists in the upper limit given by the E391a experiment at KEK which established an experimental method that will be used in a following experiment at JPARC, named KOTO[10], where a sensitivity to the SM branching ratio prediction for this decay is expected to be reached. The E391a technique consists in a hermetic detector with high γ detection efficiency, in order to reduce the background due to $K_L \to \pi^0 \pi^0$ decays where one of the π^0 is lost , combined with a pencil K_L beam, which enables to reconstruct the decay vertex and compute the outgoing π^0 transverse momentum. These two variables are used at the analysis stage for minimizing the background. The KOTO collaboration has measured the K_L yield at JPARC[11] to be 2.3 times the yield expected in the proposal by measuring the $K_L \to \pi^+ \pi^- \pi^0$ decays.

2. Charged lepton flavour violating decays

In recent years interesting results on $\tau \to l\,x$ were produced at B-factories which are also τ-factories since for $\sqrt{S} \approx M_\Upsilon$ one has $\sigma_{\tau\tau} \approx 0.8 \sigma_{bb}$. The Belle experiment updated its results on

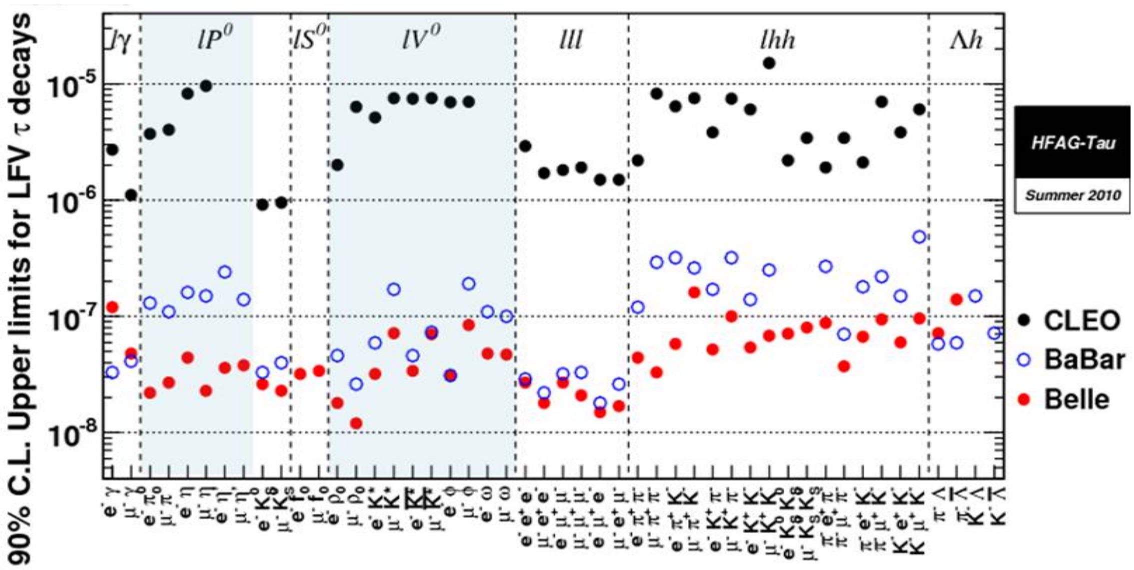

Figure 4: 90% Confidence Level upper limits on $\tau \to$ l x decays from the Belle experiment compared with BaBar and Cleo results

$\tau \to$ l x decay upper limits at this Conference[1].

The analysis strategy for the $\tau \to$ l x search is to look for the production of two particles, one of which is tagged as a τ, thanks to its decay into one charged particle plus missing energy, while the other is required to decay into one lepton (l) plus the relevant decay mode of the other particle (x) considered. The invariant mass $\mathrm{M_{lx}}$ and the missing energy $\Delta\mathrm{E} = \mathrm{E^{CM}_{lx}} - \mathrm{E^{CM}_{beam}}$ of the lx pair can be computed. A blind box analysis method is used, in which the region (box) in the $(\mathrm{M_{lx}}, \Delta\mathrm{E})$ parameter space centered at $(\mathrm{M}_\tau, 0\ )$ which, within the experimental errors, should contain the events searched is made non accessible (blind box) in a first analysis step. The other regions of the $(\mathrm{M_{lx}}, \Delta\mathrm{E})$ parameter space (side bands) are used to compute the expected number of background events in the blind box. In a secon step the box is opened and the result is obtained by comparing the expected with the observed number of events in the box.

The 90% C.L. upper limits on $\tau \to$ l x decays presented by the Belle collaboration are shown in Figure 4 together with BaBar and Cleo results. Future SuperB factories should be able to improve the sensitivity to these decays by one order of magnitude.

The MEG experiment[12] searches for the more conventional $\mu \to \mathrm{e}\gamma$ decay at PSI, where the most intense continuous muon beam is available.

Positive muons (to avoid nuclear captures in the stopping target), coming from decay of π^+ produced in proton interactions on a graphite target, are brought to stop and decay at rest in a very thin target. The signature of $\mu \to \mathrm{e}\gamma$ is therefore the simple simultaneous emission of a γ and a e^+ (both monochromatic: $E_{\mathrm{e}^+} = E_\gamma = m_\mu/2 = 52.83$ MeV neglecting the positron mass) in back-to-back directions. Two kinds of background can mime the signal, due the finite experimental resolution : a *physical* background, due to the radiative muon decay (RMD): $\mu^+ \to \mathrm{e}^+ \bar{\nu}_\mu \nu_\mathrm{e} \gamma$ and an *accidental* one due to the accidental coincidence, within the experimental resolutions, of an e^+ coming from the usual muon decay and a γ coming from al the possible processes (RMD, positron

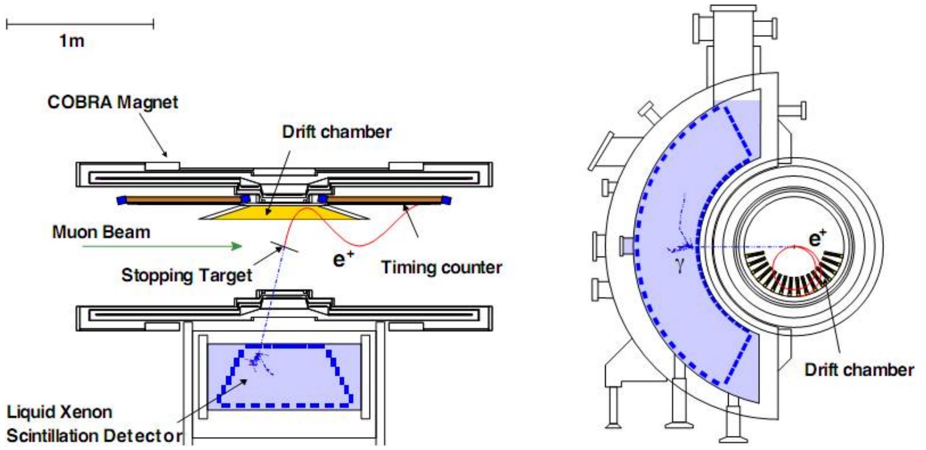

Figure 5: Sketch of the MEG experiment

annihilation in flight or bremstrahlung) able to produce γ's with an energy of about 52.8 MeV. In MEG the accidental background dominates the physical one by roughly one order of magnitude.

A sketch of the MEG experiment is shown in Figure 5. A 3×10^7 μ^+/s beam is stopped in a 205 μm slanted polyethylene target. Positron momentum is measured by a magnetic spectrometer consisting in a set of sixteen ultra-thin drift chambers (DC) operating in an almost solenoidal magnet with an axial gradient field. Positrons timing is measured at the end of their path by a timing counter made of two identical arrays of plastic scintillators read by fine mesh photomultuipliers (PMTs). The γ energy, direction and timing is measured in a ≈ 800 l volume liquid xenon (LXe) scintillation detector. Xenon was chosen as scintillating medium because of its large light yield (60% of NaI), although in the VUV region ($\lambda \approx 178$ nm), its homogeneity and the fast decay time of its scintillation light (≈ 45 ns for γ's and ≈ 22 ns for α's) [14]. The LXe volume is viewed by 846 2$''$ PMTs, sensitive to UV light and designed to operate at cryogenic temperatures in a high rate environment. Xenon impurities can be removed by circulating liquid xenon through a purification system.

Several calibration tools for PMT gain monitoring (LEDs, point-like α sources deposited on wires [15] inside the LXe detector) and for light yield monitoring (a Cockroft-Walton (CW) accelerator, Am-Be sources, 55 MeV and 83 MeV γ's from the charge exchange reaction $\pi^- p \rightarrow \pi^0 n$...) are frequently used to optimise the detector performances and to monitor its time stability.

During the first physics run in 2008 the experiment suffeerd from instabilites due to the DCs HVdistribution system and liquid xenon impurities. The DCs problem resulted in a net loss of efficiency while Xe lightyield changes could be precisely measured at a level of accuracy better than 1% by means of the CW system by using the 17.6 MeV γ line produced by the Li(p,γ)Be reaction.

Data are analysed with a combination of blind and likelihood strategy. Events are pre-selected on the basis of loose cuts, requiring the presence of a track and $|T_{e\gamma}| < 4$ ns. Preselected data are processed several times with improving calibrations and algorithms and events falling within a tight window (blinding box, BB) in the (E_γ, $T_{e\gamma}$) plane are hidden. The remaining pre-selected events fall in "sideband" regions and are used to optimize the analysis parameters, study the background

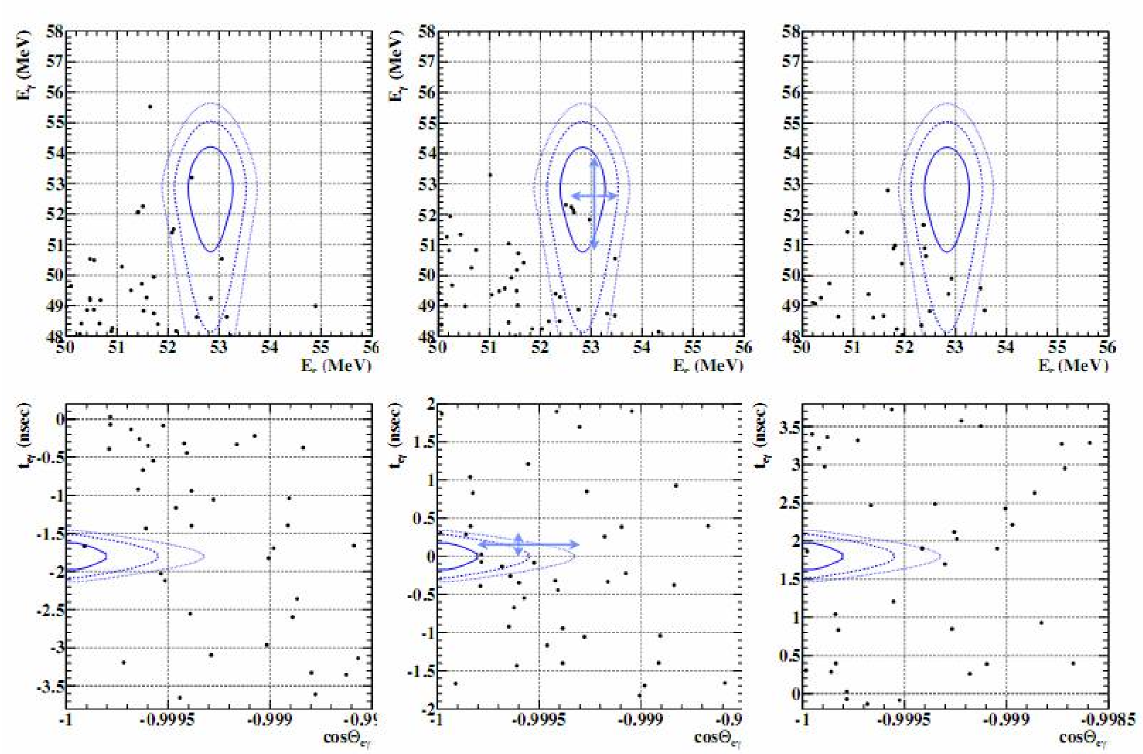

Figure 6: Events disributions in the BB (center) and two sidebands (lateral plots) . See the text for a description.

and evaluate the experimental sensitivity under the zero signal hypothesis. When the optimization procedure is completed, the BB is opened and a maximum likelihood fit is performed to the distributions of five kinematical variables (E_{e^+}, E_γ, $T_{e\gamma}$, $\theta_{e\gamma}$ and $\phi_{e\gamma}$), in order to extract the number of signal (S), RMD (R) and accidental background (B) events. Probability distribution functions (PDFs) are determined by using calibration measurements and Montecarlo simulation (MC) for S, theoretical formulae folded with experimental resolution for R and sideband events for B. Michel positrons are used to calculate the normalization factor needed to convert an upper limit on S into an upper limit on $BR(\mu \to e\gamma)$. The fit is performed by several independent likelyhood analysis tools in order to check possible systematics effects.

This analysis procedure was applied for the first time to the data collected in 2008, with reduced statistics and not optimal apparatus performances, and a first result was published [16]: the sensitivity computed from MC and estimated fom sidebands was 1.3×10^{-11} while the result obtained from the likelyhood analysis in the BB turned out to be $BR(\mu \to e\gamma) \leq 2.8 \times 10^{-11}$ at 90 % C.L..

In 2009 a larger and better quality data sample was collected and the analysis procedure was repeated. The estimated sensitivity of this sample is 6.1×10^{-12}. In Figure 6 the events contained in the BB (center) and in two sidebands in which $T_{e\gamma}$ is not centered at zero (left and right) are shown in E_γ vs E_e (upper) and $T_{e\gamma}$ vs $\cos(\theta_{e\gamma})$ (lower) plots (to be considered preliminarry). The contour lines represent the 1, 1.64 and 2 σ regions for each of the two variables of each individual plot. The lines with arrows in the central plots corespond the 1 σ values of each variable, to be used as a guide for the eye.

The (preliminary) best fit result gives S = 3.0 (but S=0 is still contained in the 90% C.L. region) corresponding to a 90% C.L. upper limit $BR(\mu \to e\gamma) \leq 1.5 \times 10^{-11}$.

The experiment is constantly improving its performances by means of hardware improvements, better calibration devices (a monochromatic positron beam to test positron tracking was implemented in 2010), noise reduction attempts and refinements in the analysis.

In three more years of data taking (2010 - 2012) it is expected that the experiment will reach a sensitivity of the order of 10^{-13} .

3. Summary

Rare decay experiment are complementary to LHC in search of new physics. New experiments in this field of physics are about starting data taking. MEG should soon clarify the situation in its BB since it is now starting a long term data taking period.. Future experiments like COMET at JPARC[17] or Mu2e at Fermilab[18] which I could not describe in this talk will maybe be able to discriminate among different theoretical models.

References

[1] K. Hayasaka's Contribution, these proceedings.

[2] R. Sawada's contribution, these proceedings.

[3] A. Masiero, P. Paradisi, R. Petronzio, Phys. Rev. D 74 (2006) 011701.

[4] V. Cirigliano, I. Rossell, JHEP 0710:005 (2007).

[5] See G. Isidori's contribution, these proceedings.

[6] F. Mescia and C. Smith, http://www.lnf.infn.it/wg/vus/content/Krare.html

[7] J. Lewis, poster presented at this Conference.

[8] See A. Winhart's contribution, these proceedings.

[9] F. Archilli, poster presented at this Conference.

[10] See H. Watanabe's contribution, these proceedings.

[11] K. Shimo, poster presented at this conference.

[12] T. Iwamoto's contribution, these proceedings.

[13] M. Ahmed et al., Phys. Rev. D65 (2002) 112002.

[14] A. Baldini et al., Nucl. Instr. and Meth. A545 (2005) 753.

[15] A. Baldini et al., Nucl. Instr. and Meth. A565 (2006) 589.

[16] The MEG Collaboration, Nucl. Phys. B834 (2010) 1.

[17] Y. Kuno, poster presented at this Conference.

[18] Y. Kolomensky, poster presented at this Conference.