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THE PHYSICS CASE FOR A DAΦNE UPGRADE

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Abstract

Possible physics programs relevant for an upgrade of the Frascati Φ Factory are briefly discussed. Particular attention is devoted to the kaon-physics program of a realistic high-luminosity option, yielding up to 100 fb^{-1} at the Φ peak.

1 Introduction: low-energy physics in the LHC era

An upgrade of the DAΦNE complex is likely to produce physics results in a time period where most of the attention of the particle-physics community will be focused on the first (hopefully exciting!) results of LHC. It is therefore natural to address the general question of which type of low-energy experiments could

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still be relevant/attractive in such time period. On general grounds, we can identify three basic categories:

I. *Search/measurements of forbidden/rare processes* sensitive to short-distance dynamics, such as rare K decays, $(g-2)_\mu$, CPT tests, etc... The ultimate goal of such measurements is similar to the one of LHC, namely searching/understanding physics beyond the SM. But the two programs are not in competition. On the contrary, there is full complementary between the high-energy and the high-intensity frontiers: one would benefit from the progress of the other. Improving the understanding of theoretically clean rare processes is therefore very useful also in the LHC era.

II. *Precision measurements of fundamental SM parameters*, such as CKM angles, quark masses and gauge couplings. Also in this case there is a some complementarity with the LHC program. Several parameters of the SM Lagrangian (particularly in the Yukawa sector) are likely to be determined (in terms of fewer couplings) by some unknown high-energy dynamics. Their precise knowledge, which can be obtained only at low energies, could help to shed slight on physics beyond the SM.

III. *Deeper understanding of QCD in the non-perturbative regime* by means of precise measurements of exotic hadronic systems, such as hadronic atoms, hypernuclei, multiquark states, etc... To a large extent, this physics program is orthogonal to the one of LHC and will not be influenced by the developments at the high-energy frontier.

The present set-up of the DAΦNE complex, with an accelerator running at the Φ peak and three different type of experiments (KLOE, FINUDA and DEAR) has allowed (and is still allowing) to make significant advancements in all the three directions.

It is quite clear that a change of the c.o.m. energy of the accelerator, reaching the 2–2.5 GeV region, would bring a significant benefit to the last category. By this upgrade it would be possible to study with high precision nucleon form factors and to address spectroscopy issues which are not accessible at the Φ peak –a detailed discussion about the interest of this physics program can be found in the talk by F. Iachello [2]– However, it is also quite clear that leaving the Φ peak, there is no hope to make significant progress concerning the first two categories. Less obvious is the question if there is still room to make significant progress in the first two categories, with a substantial but realistic increase of the luminosity at the Φ peak. In the rest of this talk we shall try to address this last question.

2 Dreams vs. realistic possibilities: the Alghero heritage

The possible upgrades of DAΦNE and their related physics program has been the subject of an entire workshop, held in Alghero in September 2003. [1] A few important conclusions of this workshop can be summarized as follows:

- Kaon physics offer an outstanding physics case belonging to the first category: the search and the measurement of the very rare decays $K \to \pi\nu\bar{\nu}$ [3] and $K_L \to \pi^0 \ell^+ \ell^-$. [4] Indeed, most of the future kaon programs at fixed-target colliders are focused on these rare decays modes. From the experimental point of view, a Φ factory would be an ideal environment to search for these rare decays. However, the tiny branching ratios (in the 10^{-10}–10^{-11} range) and the difficult experimental signature, calls for peak luminosities at the Φ peak around or above 10^{35} cm^{-2} s^{-1} (or integrated luminosities of at least 10^3 fb^{-1}). Such scenario does not appear to be feasible, at least in the short term.

- A realistic upgrade of the luminosity could yield at most 100 fb^{-1} at the Φ peak, or the production of $\approx 10^{11}$ $K\bar{K}$ pairs. Although the *golden* short-distance channels are not accessible with such statistics, the clean environment of the Φ factory would still allow a series of unique and fundamental measurements (categories I & II) in the kaon sector. [5] These includes CPT tests, neutral kaon interferometry, rare K_S decays, improved measurements of the Cabibbo angle and deeper studies of CHPT.

Similarly to the present set up, the Φ-peak option would also allow an intense hadron-physics program with hypernuclei, kaonic atoms, $\gamma\gamma$ spectroscopy, radiative Φ decays and hadronic cross-sections via radiative return. The possibility to perform these measurements without a serious conflict with the kaon program is certainly a positive aspect of the Φ-peak option. To our knowledge, the maximal luminosity is a less crucial issue for the hadronic of program. For this reason, in the following we shall discuss only a few kaon measurements which provide good motivations to reach luminosities above 10^{33} cm^{-2} s^{-1}.

3 The kaon-physics program with 10–100 fb^{-1}

3.1 CPT tests and interferometry

As is well known, the neutral kaon system offers a unique opportunity to search for possible violations of CPT invariance. Just to mention a famous example, CPT invariance predict equal masses and decay widths for particles and antiparticles: this prediction is currently probed at the 10^{-18} level of relative precision in the neutral kaon system.

CPT invariance necessary holds in any local Lorentz-invariant quantum field theory. Testing its validity is equivalent to probe some of the most fundamental hypothesis on which the present description of particle physics is based. Interestingly enough, these hypotheses are likely to be violated at scales where the quantum effects of gravitational interactions cannot be ignored. Unfortunately, since we still miss a consistent theory of quantum gravity, it is hard to predict at which level CPT-violating effects could become visible at low energies: the field is totally driven by experiments, with the most significant bounds setting the reference scale for future improvements.

A Φ factory could probe CPT in the neutral kaon system in several ways; an extensive discussion can be found in the *Second DAΦNE Physics Handbook*. [6] One of the cleanest probes is the comparison of the charge asymmetries ($\delta_{L,S}$) of K_L and K_S semileptonic decays ($K_{\ell 3}$). These two observables are *necessarily* equal in the limit of exact CPT invariance; assuming that CPT is violated only in the mass matrix, we can relate their difference to the K^0–$\bar{K}^0$ mass difference:

$$\frac{|m_{K^0} - m_{\bar{K}^0}|}{m_K} \approx 5 \times 10^{-15} \times |\delta_L - \delta_S| \ + \ O(\not{\text{CPT}} \text{ in } \Delta S = 1) \qquad (1)$$

The limiting factor of this CPT test is the error on δ_S, whose present best measurement is obtained by KLOE:

$$\delta_S = (-2 \pm 9 \pm 6) \times 10^{-3} \qquad (2)$$

(δ_L is known with an absolute error below 10^{-4}). With ≈ 100 fb^{-1} it should be possible to reach an absolute error on δ_S of $O(10^{-4})$ i.e. to probe the K^0–$\bar{K}^0$ mass difference below the 10^{-18} level.

The most powerful test of CPT invariance in the neutral kaon system is presently obtained by means of the Bell-Steinberger relation. [7] This relation make use of unitarity (or the conservation of probability) to connect a possible violation of CPT in the neutral kaon system to the CP-violating interference of K_L and K_S decays into the same final state f. Unitarity implies that K^0 and $\bar{K}^0$ decay widths can be expressed as

$$\begin{array}{rcl} \Gamma_{K^0} & = & \sum_f \mathcal{A}(K^0 \to f)\mathcal{A}(K^0 \to f)^* \\ \Gamma_{\bar{K}^0} & = & \sum_f \mathcal{A}(\bar{K}^0 \to f)\mathcal{A}(\bar{K}^0 \to f)^* \end{array} \tag{3}$$

In the limit of exact CPT invariance, these two expressions should coincide. More in general, parameterizing the amount of CPT violation in the K^0–$\bar{K}^0$ system as

$$\Delta = \frac{i(m_{K^0} - m_{\bar{K}^0}) + \frac{1}{2}(\Gamma_{K^0} - \Gamma_{\bar{K}^0})}{\Gamma_S - \Gamma_L} \cos\phi_{SW} e^{i\phi_{SW}} \tag{4}$$

where $\phi_{SW} = \arctan[2(m_L - m_S)/(\Gamma_L - \Gamma_S)]$, the unitarity decomposition implies

$$\begin{aligned} \left[\frac{\Gamma_L + \Gamma_S}{\Gamma_S - \Gamma_L}\right] \frac{\mathrm{Re}(\epsilon_M)}{1 + |\epsilon_M^2|} + \tan\phi_{SW}\mathrm{Im}(\Delta) &= \frac{1}{\Gamma_S - \Gamma_L} \sum_f \mathcal{A}_L(f)\mathcal{A}_S(f)^* \\ &= \frac{\Gamma_S}{\Gamma_S - \Gamma_L} \sum_f B(K_S \to f)\eta_f \end{aligned} \tag{5}$$

This relation is exact in the limit of CPT invariance: only the CPT-violating term $\mathrm{Im}(\Delta)$ has been treated as a small parameter and expanded to first non-trivial order. In Eq. (5) everything but the CPT-violating term is measurable [$\epsilon_M = (\epsilon_L + \epsilon_S)/2$], and one can use data on $B(K_S \to f)$ and η_f to extract stringent bounds $\mathrm{Im}(\Delta)$. A non-vanishing result could only be attributed to one of the following non-standard scenarios: i) violation of CPT; ii) violation of unitarity; iii) existence of exotic invisible final states which escape detection. Needless to say that each of this scenarios would imply major breakthrough in fundamental physics.

A Φ factory is an ideal machine to study the Bell-Steinberg relation for two main reasons: i) the perfectly tagged K_S sample can be used to measure/bounds the poorly known K_S branching ratios; ii) it is possible to have direct access to the K_L–K_S interference terms. The first advantage has already been exploited by KLOE to control the contribution of the $3\pi^0$ final state in the r.h.s. of Eq. (5). Till few years ago the $3\pi^0$ final state was the dominant source of uncertainty in the bounds on $\mathrm{Im}(\Delta)$; thanks to the recent KLOE [8]

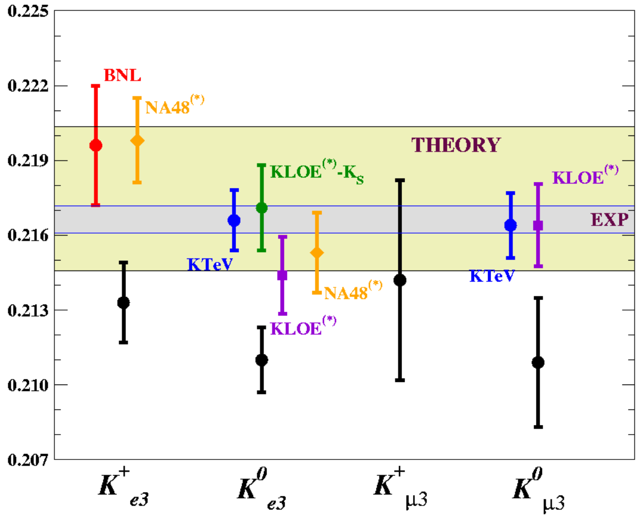

Figure 1: *Experimental results on* $|V_{us}| \cdot f_+(0)$. [12] *The gray band indicates the average of the new experimental results* ($|V_{us}| \cdot f_+(0) = 0.2166 \pm 0.0005$)*, as reported at the ICHEP '04 conference (the '*' indicates results which are still preliminary); the black points are the old PDG values; the yellow band represents the unitarity prediction combined with the recent Lattice* [11] *determination of the vector form factor* $[(1 - |V_{ud}|^2 - |V_{ub}|^2)^{1/2} \cdot f_+(0) = 0.2175 \pm 0.0029]$.

and NA48 [9] limits on $B(K_S \to 3\pi^0)$, this channel has become subleading in the final error, contributing only at $O(10^{-6})$ to $\sigma[\mathrm{Im}(\Delta)]$. Certainly much more could be done with higher statistics. In particular, with few$\times$10 fb^{-1} the interference measurements in the leading $2\pi(\gamma)$ channels should bring the *total error* on $\mathrm{Im}(\Delta)$, from the present level of few$\times 10^{-5}$ down to few$\times 10^{-6}$. Such a sensitivity is equivalent to a relative precision on the K^0–$\bar{K}^0$ mass difference below 10^{-19}.

3.2 V_{us}

The improved determination of V_{us} from $K \to \pi \ell \nu$ decays is one of the highlights of this conference. The new data [10] from BNL-E865, KTeV, NA48 and KLOE leads to a consistent picture, substantially different from the old results quoted in the PDG. When combined with the Leutwyler–Ross estimate of the $K \to \pi$ vector from factor at $q^2 = 0$ [$f_+(0)$] –whose validity has recently been reinforced by Lattice results [11]– these new data leads to an extraction $|V_{us}|$ (or the Cabibbo angle) in perfect agreement with the expectation of CKM unitarity (see Fig. 1).

Despite this important recent development, the field if far from being exhausted and there is still substantial room for improvements in the extraction of V_{us}. For instance, useful informations could still be extracted by precise measurements of the two $K_{\ell 3}$ form factors: their slopes provides important benchmarks to test and improve any method used in the (theoretical) evaluation of $f_+(0)$. Indeed, chiral perturbation theory let us to correlate unambiguously up to $O(p^6)$ the amount of $SU(3)$-breaking in $f_+(0)$ to slope and curvature of the scalar form factor $f_0(t)$. [14] To reduce the theoretical error on $f_+(0)$ below 1% requires a measurement of the slopes λ_0 and λ_0', defined by

$$f_0(t) = f_+(0)\left[1 + \lambda_0 \frac{t}{m_\pi^2} + \lambda_0' \frac{t^2}{m_\pi^4}\right] , \qquad t = (p_K - p_\pi)^2,$$

with absolute errors of 10^{-3} (λ_0) and 10^{-4} (λ_0'). This goal is well within the reach of a Φ factory with few$\times$10 fb^{-1}.

3.3 Rare K_S decays

As anticipated, the very rare K^+ and K_L short-distance dominated channels are not accessible with integrated luminosity below 10^4 fb^{-1}. Nonetheless, a Φ factory with $\approx$ 100 fb^{-1} could still play a significant role in this field: it would allow to perform a series of *auxiliary measurements*, which would help to reduce the theoretical uncertainties of some of the golden channels. The most representative examples of this type of measurements are the rates of the two $K_S \to \pi^0 \ell^+ \ell^-$ modes. These transitions, dominated by long-distance dynamics, contribute to a sizable (30 − 50%) fraction of the total $K_L \to \pi^0 \ell^+ \ell^-$ rate via K_L–K_S mixing. The size of this indirect-CP-violating pollution of the K_L channels (which have a sizable short-distance amplitude) can be computed with good accuracy in terms of the corresponding K_S rates. As a result, the knowledge of $B(K_S \to \pi^0 \ell^+ \ell^-)$ determines the precision on which we are able to extract the interesting short-distance info from $B(K_L \to \pi^0 \ell^+ \ell^-)$.

The two $K_S \to \pi^0 \ell^+ \ell^-$ transitions have recently been observed by the

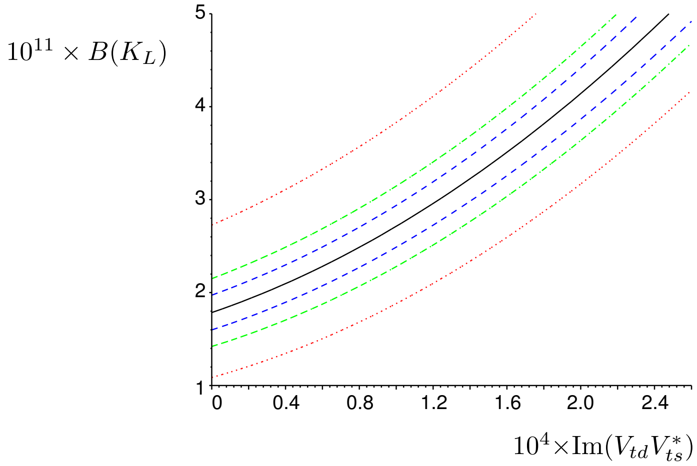

Figure 2: *SM Prediction for $B(K_L \to \pi^0 e^+ e^-)$ as a function of the CKM combination Im$(V_{td}V_{ts}^*)$, which rules the strength of the short-distance amplitude within the SM.* [4] *The three bands correspond to an error on $B(K_S \to \pi^0 e^+ e^-)$ of* 10% *(dashed blue lines);* 20% *(dashed green lines); present experimental uncertainty* [15] *(red dotted lines).*

NA48/1 experiment, but the present errors are still very large [15]

$$B(K_S \to \pi^0 e^+ e^-)_{m_{ee} > 165 \text{ MeV}} = \left(3.0^{+1.5}_{-1.2} \pm 0.2\right) \times 10^{-9} \ , \quad (6)$$

$$B(K_S \to \pi^0 \mu^+ \mu^-) = \left(2.9^{+1.4}_{-1.2} \pm 0.2\right) \times 10^{-9} \ . \quad (7)$$

As shown in Fig. 2, with these large errors, the corresponding uncertainty on the K_L modes is $\approx 100\%$. A high-luminosity Φ factory is the ideal machine to improve these measurements: with ≈ 100 fb^{-1} we could reach $\sigma[B(K_S \to \pi^0 \ell^+ \ell^-)] \approx 10\%$. At this level of precision, the corresponding uncertainty on the K_L mode would also drop at the 10% level, allowing to perform a new very significant test of short-distance dynamics. [4] It is worth to stress that this test is unique and, in particular, is *not equivalent* to the one which could be performed in the $K \to \pi \nu \bar{\nu}$ system.

4 Conclusions

We concluded the Introduction with the following question: *is there is still room to make significant progress in fundamental physics* (searches of new phenomena and measurements of basic SM couplings) *with a substantial but realistic increase of the luminosity at the* Φ *peak*? We believe that the few examples of key measurements we have discussed (CPT tests & interferometry, $|V_{us}|$ and rare K_S decays) already provides a positive answer to this question. But of course this is only the top of the iceberg. As mentioned in the Introduction (and as discussed in more detail in Ref. 1), there are several other interesting measurements (both within and beyond the kaon sector) which could enlarge the physics program of this option.

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