

THE PHYSICS CASE OF DAFNE-2*

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We present the physics case of DAFNE-2, an e^+e^- collider expected to deliver $20 - 50 \text{ fb}^{-1}$ at the $\phi(1020)$ peak, and $\sim 5 \text{ fb}^{-1}$ in the energy region between 1 and 2.5 GeV.

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1. Introduction

In the last decade a wide experimental program has been carried on at DAΦNE, the e^+e^- collider of the INFN Frascati National Laboratories running at a center of mass energy of 1020 MeV, the ϕ meson mass. Three experiments have run at DAΦNE: KLOE, dedicated to kaon and hadronic physics, FINUDA, dedicated to the study of hypernuclei and DEAR, designed to study the production of kaonic atoms.

In the last years a possible continuation of a low energy e^+e^- program has been considered. Two options emerged: (i) a continuation of the program at the ϕ peak with a luminosity significantly higher than the present one (DAΦNE best peak luminosity was of $1.5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to about 2 fb^{-1} per year) and (ii) an increase of the DAΦNE energy up to at least 2.5 GeV. In the following we call DAFNE-2 the program based on both options. While the second option seems technologically feasible, the first one is particularly challenging. A new machine scheme (“Crabbed Waist”) aiming to increase the luminosity towards $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ has been recently proposed by Raimondi, the Head of the Frascati Accelerator Division [1]. This scheme will be tested at DAΦNE in the next months and it will be used during the run of SIDDHARTA, an upgraded version of DEAR experiment aiming to collect data in the first months of 2008. The result of this machine test is very important in view also of higher energy programs like the SuperB project.

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2. DAFNE-2 physics program

Three Expressions of Interest (KLOE-2, AMADEUS, and DANTE) have been presented for DAFNE-2, with the following objectives:

- **KLOE-2:** to continue the KLOE physics program, including tests of Quantum Mechanics and CPT with kaon interferometry, measurement of the rare K_S decays, test of lepton universality (as in the ratio $K_{e2}/K_{\mu2}$), test of χPT in the radiative decays of the ϕ . In addition, by using an electron tagger, precise measurements of $\gamma\gamma$ -physics can be performed. The high energy program (from 1 to 2.5 GeV) will allow a precise measurement of the hadronic cross sections, and vector meson spectroscopy;
- **AMADEUS:** to study the deeply bound kaonic nuclear states by using gaseous targets around the interaction region;
- **DANTE:** to measure time-like form factors of nucleons and lower mass hyperons.

In the following we will discuss three arguments from the KLOE-2 EoI: *(i)* CPT tests with kaon interferometry; *(ii)* the measurement of the hadronic cross section (R -measurement) in the 1–2.5 GeV energy region¹; *(iii)* $\gamma\gamma$ -physics. For the whole DAFNE-2 program we refer the reader to [2, 3].

2.1. Kaon interferometry and CPT tests

CPT invariance is a fundamental theorem in quantum field theory. In several quantum gravity (QG) models, however, CPT can be violated via some mechanism which can also violate standard Quantum Mechanics (QM). In this respect the entangled neutral kaon pairs produced at DAΦNE play a unique role in precision tests of the CPT symmetry [4]. As an example of this incredible precision reachable with neutral kaons, let us consider the model by Ellis, Hagelin, Nanopoulos and Srednicki (EHNS) which introduces three CPT and QM-violating real parameters α , β and γ [5]. On phenomenological grounds, they are expected to be $O(m_K^2/M_{Pl}) \sim 2 \times 10^{-20}$ GeV at most, since $M_{Pl} \sim 10^{19}$ GeV, the Planck mass. Interestingly enough, this model gives rise to observable effects in the behaviour of entangled neutral meson systems, as shown also in [6], that can be experimentally tested. KLOE has already published competitive results on these issues, based on a statistics of $\sim 400 \text{ pb}^{-1}$ [7]. The analysis makes use of correlated $K_L^0 - K_S^0$ pairs, by measuring the relative distance of their decay point into two charged pions. The decay region most sensitive to the EHNS parameters is the one close to the IP.

¹ This topic is also considered in DANTE EoI.

Fig. 1 shows the potential limits that can be obtained by KLOE on α , β , and γ as a function of the integrated luminosity, both with and without the insertion of an inner tracker (see Sect. 3) with vertex resolution of $0.25 \tau_S$ (to be compared with the present KLOE vertex resolution, $0.9 \tau_S$). In the figure also are given the results from CPLEAR [8]. Without entering too much in details, it is clear that with a reasonable integrated luminosity, KLOE-2 can set the best limits on these parameters.

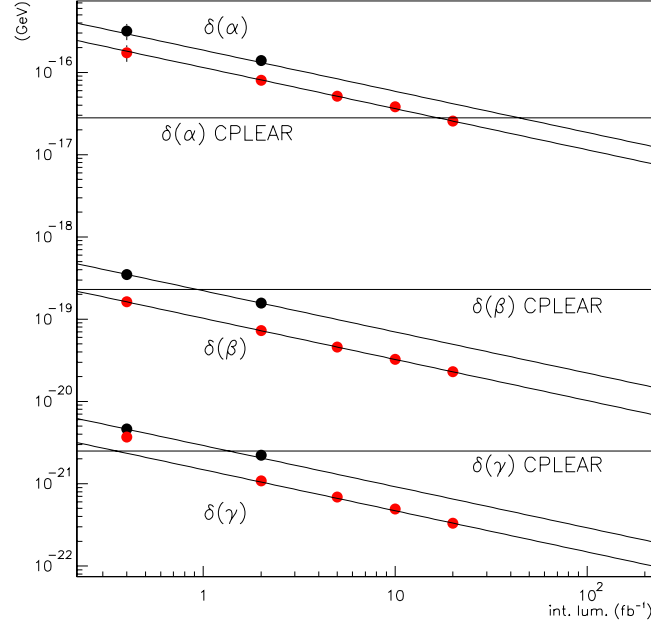


Fig. 1. Limits on the CPT violating parameters α , β , and γ obtainable by KLOE-2 as a function of the integrated luminosity. Results are presented for a detector both with and without the insertion of an inner tracker with vertex resolution of $0.25 \tau_S$ (to be compared with the present KLOE vertex resolution, $0.9 \tau_S$). In the figure also are given results from CPLEAR.

2.2. Measurement of R in the 1–2.5 GeV energy region.

The ratio $R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$ is poorly known in the region [1–2.5 GeV], where the uncertainty is $\sim 15\%$. This region contributes to about 40% to the total error of the dispersion integral for $\Delta_{\text{had}}^{(5)}(m_Z^2)$ [3]. It also provides most of the contribution to a_μ^{HLO} above 1 GeV [3, 9]. Recently [10] a new approach has been proposed to evaluate $\Delta_{\text{had}}^{(5)}(m_Z^2)$. Based on the evaluation of the so called Adler function, it allows to use safely pQCD down to 2.5 GeV

plus experimental data up to that threshold. In this approach DAFNE-2 can play a substantial role, and a measurement of R at 1% level below 2.5 GeV can considerably improve the accuracy on $\Delta_{\text{had}}^{(5)}(m_Z^2)$ [10]. As an example of the statistical accuracy that can be reached in this region we will consider the process $e^+e^- \rightarrow 3$ and 4 hadrons.

BaBar has already published results on these channels, obtained with an integrated luminosity of 89 fb^{-1} , and it is expected to reach 1 ab^{-1} by the end of the data taking. However, due to the ISR photon emission at the $\Upsilon(4s)$ resonance, the effective luminosity for tagged photon ($\theta_\gamma > 20^\circ$) for energies below 2.5 GeV, will be of the order of few pb^{-1} at full statistics [3]. Fig. 2 shows the statistical error for the channels $\pi^+\pi^-\pi^0$, $2\pi^+2\pi^-$ and $\pi^+\pi^-K^+K^-$, which can be achieved by an energy scan at DAFNE-2 with 20 pb^{-1} per point, compared with BaBar with published (89 fb^{-1}), and expected full (890 fb^{-1}) statistics. As it can be seen, an energy scan allows to reach a statistical accuracy of the order of 1% on these channels.

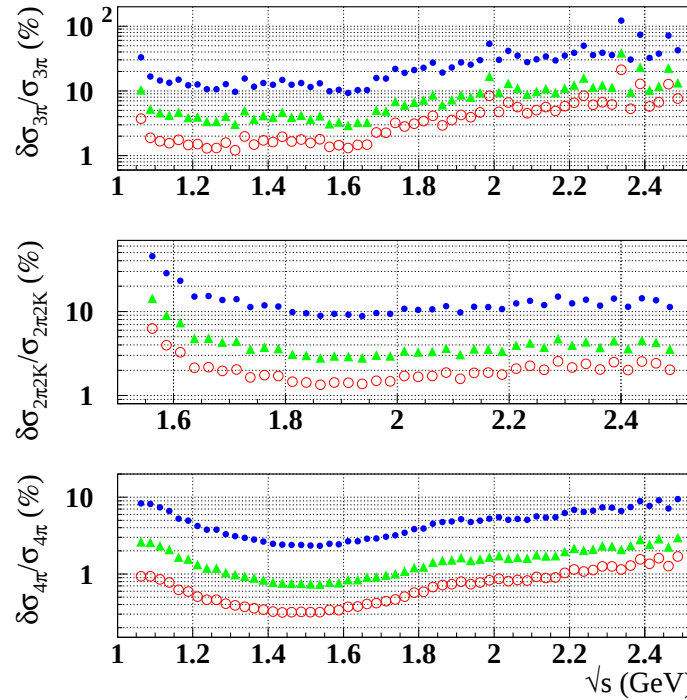


Fig. 2. Comparison of the statistical accuracy in the cross-section among DAFNE-2 with an energy scan with 20 pb^{-1} per point ($\circ$); published BaBar results ($\bullet$); BaBar with full statistics ($\blacktriangle$); for $\pi^+\pi^-\pi^0$ (top), $\pi^+\pi^-K^+K^-$ (middle) and $2\pi^+2\pi^-$ (down) channels. An energy step of 25 MeV is assumed.

2.3. $\gamma\gamma$ -physics

The term “ $\gamma\gamma$ -physics” (or “two-photon-physics”) stands for the study of the reaction:

$$e^+e^- \rightarrow e^+e^- \gamma^* \gamma^* \rightarrow e^+e^- + X,$$

where X is some arbitrary final state allowed by conservations laws.

The number of $e^+e^- \rightarrow e^+e^- X$ events per unit of invariant mass $W_{\gamma\gamma}$, as a function of $W_{\gamma\gamma}$ itself, is:

$$N \left(\frac{\text{evts}}{\text{MeV}} \right) = L_{\text{int}}(\text{nb}^{-1}) \frac{dF(W_{\gamma\gamma}, \sqrt{s})}{dW_{\gamma\gamma}} (\text{MeV}^{-1}) \times \sigma(\gamma\gamma \rightarrow X)(\text{nb}),$$

where L_{int} is the e^+e^- integrated luminosity and $dF(W_{\gamma\gamma}, \sqrt{s})/dW_{\gamma\gamma}$ is the effective $\gamma\gamma$ luminosity per unit energy. The product $dF/dW \times L_{\text{int}}$ is reported in Fig. 3 (left panel) for two DAFNE-2 center of mass (c.m.) energies.

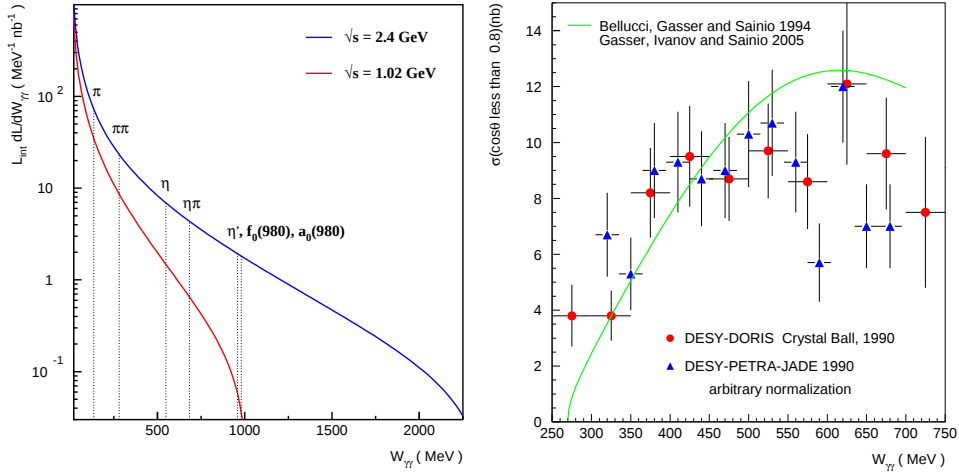


Fig. 3. Left: Effective $\gamma\gamma$ luminosity as a function of $W_{\gamma\gamma}$ corresponding to an integrated luminosity of 1 fb^{-1} at $\sqrt{s} = m_\phi$ (red curve) and at $\sqrt{s}=2.4 \text{ GeV}$ (blue curve). Vertical lines represent from left to right: π -threshold, $\pi\pi$ -threshold, η , $\eta\pi$ -threshold, η' , f_0 , a_0 . Right: Collection of low energy $\gamma\gamma \rightarrow \pi^0\pi^0$ cross-section data compared with a theoretical evaluation based on χ PT [13]. The JADE data are normalized to the same average cross-section of the Crystal Ball data.

2.3.1. The process $\gamma\gamma \rightarrow \pi^0\pi^0$: the σ case

$\gamma\gamma$ -physics provides a complementary view at the light scalar mesons and, in particular, is a powerful tool to search for the σ . $e^+e^- \rightarrow e^+e^- X$ events with $X = \pi\pi$, $\eta\pi$ and possibly $K\bar{K}$, allow to study directly the

$I = 0$ and $I = 1$ scalar amplitudes down to their thresholds. In $\gamma\gamma \rightarrow \pi^0\pi^0$ events with two-photon invariant masses $W_{\gamma\gamma}$ below 1 GeV, the $\pi^0\pi^0$ pair is mostly in s -wave, resulting in $J^{PC} = 0^{++}$ quantum numbers, with negligible contamination from other hadronic processes. The presence of a pole in this amplitude around 500 MeV [11] would be a clean and new signal of the σ .

Unfortunately, the only available experimental information on this channel in the region of interest is relatively poor and do not allow to draw any conclusion about the agreement with either the χ PT calculations nor on the existence of the broad (250–500 MeV) σ resonance (see Fig. 3 (right panel)). A new measurement of $\gamma\gamma \rightarrow \pi^0\pi^0$ in this region would be, therefore, very important [12].

2.3.2. Measurement of the $\gamma\gamma$ widths of $f_0(980)$ and $a_0(980)$

Extending the measurement of $\gamma\gamma \rightarrow \pi\pi$ and $\gamma\gamma \rightarrow \eta\pi$ up to $W_{\gamma\gamma} \sim 1$ GeV, the two-photon width of $f_0(980)$ and $a_0(980)$ can also be measured. This measurement is possible by running at the maximum attainable centre of mass energy, in order to maximize the effective $\gamma\gamma$ luminosity in the GeV region (see Fig. 3, (left panel)). In both cases a peak in the $W_{\gamma\gamma}$ dependence of the $\gamma\gamma \rightarrow \pi\pi(\eta\pi)$ cross-section around the meson mass allows to extract the $\gamma\gamma$ -width.

2.3.3. The two-photon widths of the pseudoscalar mesons

The situation on the decay constants of η and η' is far from being satisfactory and calls for more precise measurements of the two-photon width of these mesons [3]. Even the π^0 two-photon width is poorly known (relative uncertainty of $\sim 8\%$) and its determination can be improved at DAFNE-2. Given the small value of these widths, the only way to measure them is the meson formation in $\gamma\gamma$ reactions. In Table I we report the estimates for the total production rate of a pseudoscalar meson (PS) in the process $e^+e^- \rightarrow e^+e^-$ PS for two DAFNE-2 c.m. energies [3].

TABLE I

$e^+e^- \rightarrow e^+e^-$ PS total rate for an integrated luminosity of 1 fb^{-1} at two different center of mass energies. No tag efficiency is included in the rate calculation.

$\sqrt{s}$ (GeV)	π^0	η	η'
1.02	4.1×10^5	1.2×10^5	1.9×10^4
2.4	7.3×10^5	3.7×10^5	3.6×10^5

2.3.4. Meson transition form factors

The process $e^+e^- \rightarrow e^+e^- + \text{PS}$ with one of the final leptons scattered at large angle gives access to the process $\gamma\gamma^* \rightarrow \text{PS}$, *i.e.* with one off-shell photon, and it allows to extract information on the pseudoscalar meson transition form factor $F_{P\gamma\gamma^*}(Q^2)$. A precise determination of this quantity would be important to test phenomenological models.

By detecting both the leptons at large angle, the doubly off-shell form factor $F_{P\gamma^*\gamma^*}(Q_1^2, Q_2^2)$ can be accessed. A direct and accurate determination of this quantity would be extremely important in order to get less model-dependent estimations of the hadronic light-by-light scattering in $(g-2)_\mu$ [9].

3. Detector consideration

The KLOE detector is well suited for most of the measurement that can be carried out with DAFNE-2. However, some upgrades are expected [2]:

- An inner tracker in the region between the beam pipe and the inner wall of the drift chamber, which is presently not instrumented;
- The equipment of the electromagnetic calorimeter with photomultipliers with higher quantum efficiency;
- New quadrupole calorimeters (QCAL);
- Electron taggers, needed for $\gamma\gamma$ -physics.

The measurement of the nucleon form factors with KLOE can be more problematic, since a proton polarimeter is required. Such a device normally consists of a layer of carbon placed between two precise tracking devices, typically silicon detectors. This object cannot be easily incorporated in the KLOE structure and would spoil the tracking resolution of the detector. It should then be inserted only for a dedicated run, maybe replacing part of the beam pipe or of the vertex detector. Finally the wide program of measurements of the KN interactions in the $p_K \sim 100 \text{ MeV}/c$ momentum region, requires different gaseous targets around the interaction region [2].

4. Conclusion

The physics program of DAFNE-2 has been discussed. It is a wide physics program, based on the possibility to increase the luminosity at the $\phi(1020)$ peak and to extend the center of mass energy up to 2.5 GeV. Such a machine will allow to perform fundamental tests of CPT symmetry and QM, precision tests of the Standard Model, and a large number of relevant measurements in the hadronic sector.

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