CPC(HEP & NP), 2010, **34**(6): 1–6 **Chinese Physics C** Vol. 34, No. 6, Jun., 2010

Status of KLOE-2

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Abstract In a few months the KLOE-2 detector is expected to start data taking at the upgraded DAΦNE ϕ-factory of INFN Laboratori Nazionali di Frascati. It aims to collect 25 fb^{-1} at the ϕ(1020) peak, and about 5 fb^{-1} in the energy region between 1 and 2.5 GeV. We review the status and physics program of the project.

Key words electron-positron annihilation, ϕ-factory, kaon interferometry, discrete symmetries, $\gamma\gamma$ physics, scalar spectroscopy, hadronic cross sections, g-2, α_{em}

PACS 11.30.Er, 12.15.Ji, 13.66.Bc

1 Introduction

From 2000 to 2006 the KLOE experiment has collected 2.5 fb^{-1} of data at the ϕ(1020) peak plus additional 250 pb^{-1} off-peak at the DAΦNE ϕ-factory of INFN Laboratori Nazionali di Frascati. Many important results have been obtained, particularly in the kaon sector, light meson spectroscopy and on the precise measurement of the hadronic cross section below 1 GeV. During 2008 a new interaction scheme of DAϕNE has been successfully tested, allowing to reach a peak luminosity of about 5×10^{32} cm^{-2} s^{-1}, a factor of 3 larger than previously obtained. Following this achievement, new data taking with an upgraded detector will start in 2010. To extend the precise measurement of the hadronic cross sections above 1 GeV a program for running DAΦNE at energies up to 2.5 GeV has also been suggested. The improved KLOE detector is perfectly suited for taking data at energies different from the ϕ peak, while DAΦNE will need some upgrade [1].

We will refer to the entire plan of run discussed above as the KLOE-2 project.

2 The KLOE-2 detector

KLOE is a general purpose detector for e^+e^- physics, consisting mainly of a large cylindrical (helium based) drift chamber, with an internal radius of 25 cm and an external one of 2 m, surrounded by a lead-scintillating fiber electromagnetic calorimeter embedded in a superconducting magnet ($B=0.52$ T). The detector design was optimized for CP studies in the neutral kaon system, for kaons produced in the decay of ϕ almost at rest. The upgrade of the KLOE detector consisting in the installation of an electron tagger for $\gamma\gamma$ physics has been completely funded. Two different tagging detectors will be installed: the Low Energy Tagger, (low energy refers to the $e^\pm$ energy) LET, made of two crystal calorimeters placed close to the DAϕNE Interaction Point (IP) in symmetrical positions, and the High Energy Tagger, HET, made of two position sensitive detectors placed (symmetrically) far from the IP, after the first bending dipoles of DAϕNE.

Figure 1 shows the DAΦNE layout with the positions of LET and HET detectors for $\gamma\gamma$ physics.

Received 26 January 2010

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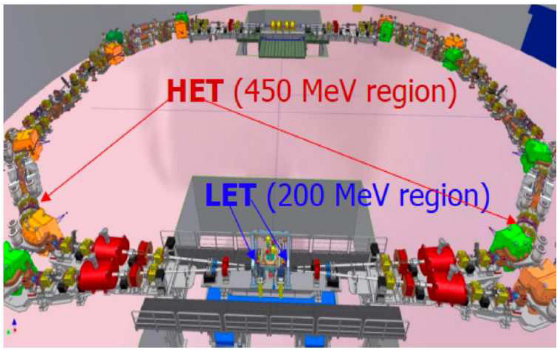

Fig. 1. Layout of DAΦNE with the positions of LET and HET detectors for γγ physics. The average $e^{\pm}$ energy for each detector is shown.

A further detector upgrade has been proposed for a second phase of the data taking, with the insertion of a light internal tracker between the beam pipe and the drift chamber, and crystal calorimeters to cover the polar angle regions down to 8°. This upgrade will be very important for the kaon interferometry and multihadronic cross section measurements (see below). It has been partially funded and the installation is envisaged for late 2011.

3 The KLOE-2 physics program

The KLOE-2 program covers a wide variety of physics topics: tests of CKM Unitarity and Lepton Universality with kaons, tests of discrete symmetries and of Quantum Mechanics with entangled kaon states, rare kaon decays, light meson spectroscopy (scalar and pseudoscalar mesons), measurement of the hadronic cross section from the $2m_{\pi}$ threshold to 2.5 GeV, search for possible Dark Matter signals at low energy. In the following we will summarise some of the above topics. For a detailed discussion see [2].

3.1 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 entagled neutral kaon pairs produced at DAΦNE play a unique role in precision tests of the CPT symmetry [3]. 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 [4]. On phenomenological grounds, they are expected to be $O(m_K^2/M_{Pl}) \sim 2\times10^{-20}$ GeV at most, being $M_{Pl} \sim 10^{19}$ GeV, the Planck mass. Interestingly enough, this model gives rise to observable effects in the behaviour of entagled neutral meson systems, as shown also in [5], that can be experimentally tested. With 2.5 fb^{-1} KLOE has published competitive results on these issues [6]. 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.

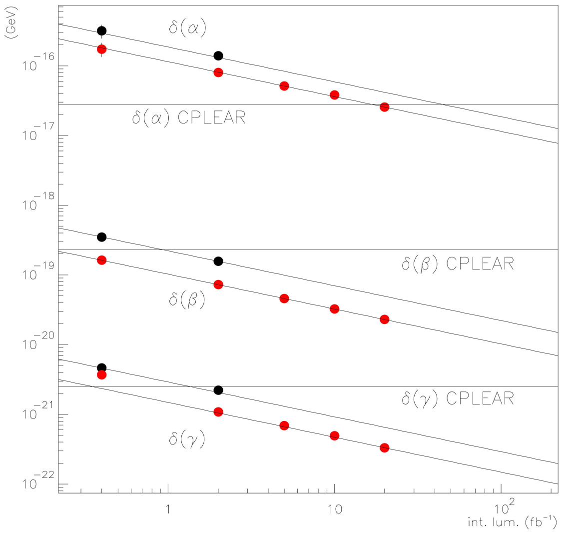

Fig. 2. Limits on the CPT violating parameters α, β, and γ obtainable by KLOE-2 as a function of the integrated luminosity. See the text for details.

Figure 2 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 with vertex resolution of 0.25 τ_S (to be compared with the present KLOE vertex resolution, 0.9 τ_S). In the figure are also given the results from CPLEAR [7]. Without giving too many details, it is clear that with a reasonable integrated luminosity, KLOE-2 can set the best limits on these parameter.

3.2 Other tests of discrete symmetries

CPT symmetry can also be tested using neutral kaon semileptonic decays. Actually, the charge asymmetries of the short- and long-lived K^0 mesons for these reactions must be equal under CPT conservation. The K_L asymmetry is known today with a precision of order 10^{-5} [8], while the K_S one, measured by KLOE using $\sim$ 400 pb^{-1} of data, is known at the per cent level [9]. KLOE-2 aims at reaching a 10^{-3} precision.

K_S decays into three neutral pions are purely CP violating. the branching ratio for this decay is expected to be $\sim 10^{-9}$. KLOE has set the best limit to date on this branching ratio: 1.2×10^{-7} at 90% C.L [10]. KLOE-2 can improve a lot on that, and might hope to observe the signal for the first time. Improvements can arrive not only on the statistics side; in fact, usage of the forward calorimeters can improve the rejection of the $K_S \to 2\pi^0$ events, the most relevant systematic limitation for the measurement.

Unconventional forms of CP violation can also be tested using η meson decays to $\pi^+\pi^-e^+e^-$. Actually, thanks to the ϕ radiative decay to $\eta\gamma$, DAΦNE can also be considered a clean source of well tagged η mesons. KLOE has performed the measurement of the branching ratio $\eta \to \pi^+\pi^-e^+e^-$ with 4% accuracy and has obtained the first measurement of the CP-odd $\pi\pi ee$ decay plane angular asymmetry [11]. About 10^9 η's will be collected by KLOE-2 in a few years of data taking. With this sample an asymmetry as small as 10^{-3} can be measured.

KLOE has already set the best limits on the decay rates of $\eta \to \pi^+\pi^-$ [12] and $\eta \to \gamma\gamma\gamma$ [13], two processes which are forbidden by invariance under P and C transformations. Using the full KLOE-2 statistics one can improve the above results by about two orders of magnitude; these will be the most precise tests ever done of P and C conservation in strong and electromagnetic interactions.

3.3 Light scalar spectroscopy at $\phi(1020)$ peak

It is still controversial whether light scalars are $q\bar{q}$ mesons, $qq\bar{q}\bar{q}$ states, or $K\bar{K}$ molecules. KLOE exploited the radiative decays $\phi \to PP\gamma$ to study $f_0(980)$ and $a_0(980)$, and to look for a signal of the $\sigma(600)$, and extracted the parameters of the scalar resonances from the two pseudoscalar invarant mass distributions [14, 15]. Substantial improvements from KLOE-2 are expected for $\phi \to (f_0/a_0)\gamma \to K^0\bar{K}^0\gamma$: the KLOE upper limit, $Br(\phi \to K^0\bar{K}^0\gamma) < 1.9\times10^{-8}$ [16], can be lowered, with the KLOE-2 statistics, down to 1×10^{-8}. This limit can be further reduced to 0.5×10^{-8} with the insertion of the inner tracker. This value is in the range of the theoretical predictions for the branching ratio, then the first observation of this decay is possible at KLOE-2.

In $\eta' \to \eta\pi\pi$ decays the $\pi\pi$ system has the same quantum numbers of a scalar meson. Moreover, the available kinetic energy of the $\pi\pi$ system is in the range (0, 137) MeV, suppressing high angular momentum contributions, and the exchange of vector mesons is forbidden by G-parity conservation. For these reasons only scalar mesons can participate in the scattering amplitude. The decay can be mediated by the scalar (σ, a_0 and f_0) exchange and by a direct contact term due to the chiral anomaly [17]. The scalar contribution can be determined from a fit to the Dalitz plot. A Monte Carlo simulation of the $\eta' \to \eta\ \pi^+\pi^-$ process shows that KLOE-2 has a good sensitivity to $\sigma(600)$.

3.4 $\gamma\gamma$ physics

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

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- + X$$

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

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

$$N(\mathrm{evts/MeV}) = L_{\mathrm{int}}(\mathrm{nb}^{-1}) \times$$

$$\frac{\mathrm{d}F(W_{\gamma\gamma},\sqrt{s})}{\mathrm{d}W_{\gamma\gamma}}(\mathrm{MeV}^{-1}) \times \sigma(\gamma\gamma \to X)(\mathrm{nb}),$$

where L_{int} is the e^+e^- integrated luminosity and $\mathrm{d}F(W_{\gamma\gamma},\sqrt{s})/\mathrm{d}W_{\gamma\gamma}$ is the effective $\gamma\gamma$ luminosity per unit energy. The product $\mathrm{d}F/\mathrm{d}W \times L_{\mathrm{int}}$ is reported in Fig. 3 (Left) for two DAΦNE center-of-mass (c.m.) energies.

3.4.1 The process $\gamma\gamma \to \pi^o\pi^o$: 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 [15]. $e^+e^- \to e^+e^-X$ 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 $\gamma\gamma \to \pi^0\pi^0$ events with two-photon invariant masses $W_{\gamma\gamma}$ below 1 GeV, the $\pi^0\pi^0$ pair is mostly in the S-wave, resulting in $J^{PC} = 0^{++}$ quantum numbers, with a negligible contamination from other hadronic processes. The presence of a pole in this amplitude around 500 MeV [18] 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 does not allow to draw any conclusion about the agreement with either the χPT calculations or on the existence of the broad (250-500 MeV) σ resonance (see Fig. 3 (Right)). KLOE is finalizing a new measurement of $\gamma\gamma \to \pi^0\pi^0$ in this region using 250 pb^{-1} of data taken at 1 GeV [19].

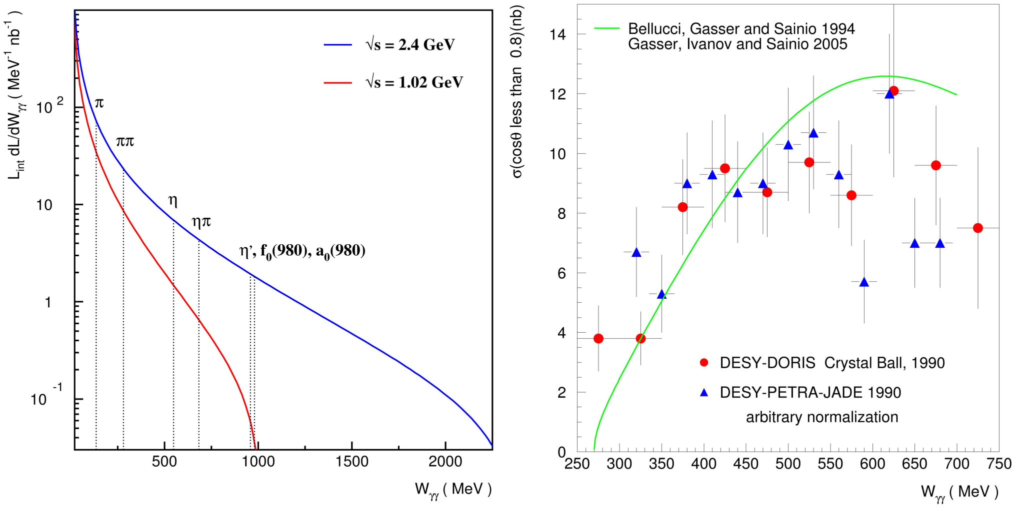

Fig. 3. Left: Effective $\gamma\gamma$ luminosity as a function of $W_{\gamma\gamma}$ corresponding to an integrated luminosity of 1 fb^{-1} at $\sqrt{s} = m_\Phi$ (red curve) and at $\sqrt{s}$=2.4 GeV (blue curve). Vertical lines represent from left to right: π-threshold, $\pi\pi$-threshold, η, ηπ-threshold, η′, f_0, a_0. Right: Collection of low energy $\gamma\gamma \to \pi^0\pi^0$ cross section data compared with a theoretical evaluation based on χPT [20]. The JADE data are normalised to the same average cross section as the Crystal Ball data.

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

Extending the measurement of $\gamma\gamma \to \pi\pi$ and $\gamma\gamma \to \eta\pi$ 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 c.m. energy, in order to maximise the effective $\gamma\gamma$ luminosity in the GeV region (see Fig. 3, Left). In both cases a peak in the $W_{\gamma\gamma}$ dependence of the $\gamma\gamma \to \pi\pi(\eta\pi)$ cross section around the meson mass allows to extract the $\gamma\gamma$-width.

3.4.3 The two-photon widths of the pseudoscalar mesons

The situation wtih 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 [2]. Even the π^0 two-photon width is poorly known (relative uncertainty of ∼8%) and its determination can be improved at DAΦNE. Given the small value of these widths, the only way to measure them is the meson formation in $\gamma\gamma$ reactions. In Table 1 we report the estimates for the total production rate of a pseudoscalar meson (PS) in the process $e^+e^- \to e^+e^-$ PS for two DAΦNE c.m. energies [2].

Table 1. $e^+e^- \to e^+e^-$ PS total rate for an integrated luminosity of 1 fb^{-1} at two different c.m. 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

3.4.4 Meson transition form factors

The process $e^+e^- \to e^+e^- + \mathrm{PS}$ with one of the final leptons scattered at large angle gives access to the process $\gamma\gamma^* \to \mathrm{PS}$, i.e. with one off-shell photon, and it allows to extract information on the pseudoscalar meson transition form factor (TFF) $F_{\mathrm{P}\gamma\gamma^*}(Q^2)$.

By detecting both leptons at large angles the doubly off-shell TFF $F_{\mathrm{P}\gamma^*\gamma^*}(Q_1^2,Q_2^2)$ can be accessed. A direct and accurate determination of these quantities either with one or both leptons scattered at large angle would be extremely important in the region below 1-2 GeV, where few data are available. It would also help to get less model-dependent estimations of the hadronic light-by-light contribution to $(g-2)_\mu$ [21].

3.5 Measurement of the hadronic cross sections in the energy region below 2.5 GeV

In the last years the improved precision reached in the measurement of e^+e^- annihilation cross sections in the energy range below a few GeV has led to a substantial reduction on the uncertainty of the hadronic contribution to the effective fine-structure constant at the scale M_Z, $\Delta\alpha^{(5)}_{\mathrm{had}}(M_Z^2)$, and to the anomalous magnetic moment of the muon a_μ^{HLO} [22, 23]. However, while below 1 GeV the error on the two-pion channel which dominates the cross section in this energy range is below 1%, the region between 1 and 2 GeV is still poorly known, with a fractional accuracy of

$\sim 10\%$. Since this region contributes about 40% [24] to the total error of $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ (and up to $\sim 70\%$ by using the Adler function as proposed in [24]), and about 55% [25] to the error of $a_\mu^{\rm HLO}$, it is evident how desirable an improvement on this region is [2].

KLOE-2 can play a major role by measuring in this energy region the hadronic cross section at 1-2% level. With a specific luminosity of 10^{32} cm^{-2} s^{-1}, DAϕNE upgraded in energy can perform a scan in the region from 1 to 2.5 GeV, collecting an integrated luminosity of 20 pb^{-1} per point (corresponding to a few days of data taking). By assuming an energy step of 25 MeV, the whole region would be scanned in one year of data taking.

As shown in Fig. 4 the statistical yield will be one order of magnitude higher than with 1 ab^{-1} at BaBar, and better than BES-3. Fig. 5 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 DAϕNE upgraded in energy with 20 pb^{-1} per point, compared with BaBar with published (89 fb^{-1}), and tenfold (890 fb^{-1}) statistics.

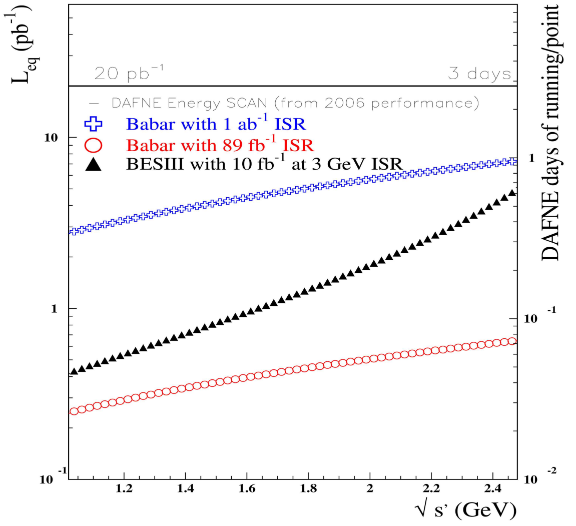

Fig. 4. Equivalent luminosity for: BaBar with 1 ab^{-1} (cross); BaBar with 89 fb^{-1} (circle); BES-3 with 10 fb^{-1}, using ISR at 3 GeV (triangle). A bin width of 25 MeV is assumed. A polar angle of the photon larger than 20° is assumed.

As can be seen, an energy scan allows to reach a statistical accuracy of order of 1% for most of the energy points. (In addition, KLOE-2 can benefit from the high machine luminosity to use ISR as well). The detector hermeticity, the high granularity of the calorimeter, the excellent momentum resolution of the drift chamber and the insertion of the inner tracker would allow to reduce the systematic error to the same level. The beam energy can be determined with an error less than 100 keV, by using the Compton backscattering (CBS) of laser photons against the electron beam.

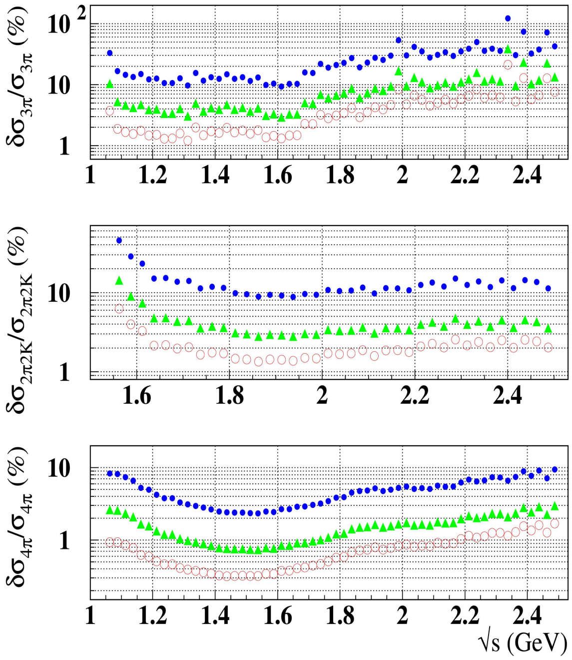

Fig. 5. Comparison of the statistical accuracy in the cross section among DAϕNE upgraded in energy with an energy scan with 20 pb^{-1} per point (○); published BaBar results (●), BaBar with 890 pb^{-1} statistics (▲) for $\pi^+\pi^-\pi^0$ (top), $\pi^+\pi^-K^+K^-$ (middle) and $2\pi^+2\pi^-$ (down) channels. An energy step of 25 MeV is assumed.

To summarize the impact for the g−2 of the muon, KLOE-2 by itself can bring the accuracy on $a_\mu^{\rm HLO}$ to about 2.5×10^{-10}, by measuring the ratio $\pi^+\pi^-(\gamma)$ to $\mu^+\mu^-(\gamma)$ with a 0.4% accuracy at 1 GeV with ISR, and the hadronic cross sections in the region [1–2.5 GeV] with 1%-2% error. This would represent a factor two improvement on the current error of $a_\mu^{\rm HLO}$, which is necessary in order to match the increased precision of the proposed muon g-2 experiments at FNAL [26] and J-PARC [27].

3.6 Summary

The status and the physics program of the KLOE-2 experiment has been discussed. The detector has been upgraded with an electron tagger for $\gamma\gamma$ physics. The insertion of an inner tracker and calorimeters in the forward regions are planned for the end of 2011. KLOE-2 will start data taking in Spring 2010, and will take data for at least 3 years. The physics program is wide, spanning from studies on neutral kaon quantum interferometry to precise measurement of hadronic cross sections in the energy range below 2.5 GeV. It will have a major impact in many tests of the Standard Model (like the g−2 of the muon), tests of discrete symmetries, and searches for new physics.

I would like to thank D. Babusci, C. Bloise, F. Bossi, A. Di Domenico, S. Eidelman, P. Gauzzi and F. Nguyen for a careful reading of the manuscript and useful discussions. Many thanks to the organizers of the workshop, especially Changzheng Yuan, for the warm hospitality and the pleasant and stimulating atmosphere of this conference.

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