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Status report on the KLOE measurement of the hadronic cross section with ISR

The KLOE collaboration*
presented by G. Venanzoni[a]

[a]Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy
E-mail: graziano.venanzoni@lnf.infn.it

The e^+e^- hadronic cross section is measured at the Frascati ϕ-factory DAΦNE with the KLOE detector using initial state radiation (ISR). Two different analyses have been developed for the channel $e^+e^- \to \pi^+\pi^-\gamma$, which differ by the photon polar angle direction. The so-called small angle analysis, in which the photon is not detected, has been published with a total error on the pion form factor of 1.3%. In a second approach, where the photon is emitted at large polar angles, the mass region below 0.35 GeV^2 becomes accessible. The status and the prospects of these analyses are reported.

1. The radiative return and its connection to the muon anomaly

The precision measurement of the muon anomaly a_μ at the Brookhaven National Laboratory [1], $a_\mu = (11659208.0 \pm 6) \cdot 10^{-10}$, has led to renewed interest in accurate measurements of the cross section for e^+e^- annihilation into hadrons. Contributions to the photon spectral functions due to quark loops, are not calculable for low hadronic-mass states because of the failure of perturbative QCD in such conditions. However, they can be obtained by connecting the imaginary part of the hadronic piece of the polarization function by unitarity to the cross section for $e^+e^- \to hadrons$. A dispersion relation can thus be derived, giving the contribution to a_μ as an integral over the hadronic cross section multiplied by an appropriate kernel, which decreases monotonically for increasing energy. A stronger weight is given to low-energy data: in particular, the process $e^+e^- \to \pi^+\pi^-$ below 1 GeV is of special importance since it contributes to $\sim 60\%$ to the total integral.

1.1. Radiative Return

Initial state radiation, ISR, is a convenient mechanism by which the entire range from $2m_\pi$ to W, the center of mass energy of the colliding beams, becomes available [2]. In the case of interest it is potentially vitiated by the possibility of final state radiation. For a photon radiated prior to the annihilation of the e^+e^- pair, the invariant mass of the $\pi^+\pi^-$ system is[2] $m(\pi^+\pi^-) = \sqrt{W^2 - 2WE_\gamma}$. Instead, for a photon radiated by the final state pions, the virtual photon coupling to the $\pi^+\pi^-$ pair has a mass

*The KLOE Collaboration: F. Ambrosino, A. Antonelli, M. Antonelli, C. Bacci, P. Beltrame, G. Bencivenni, S. Bertolucci, C. Bini, C. Bloise, S. Bocchetta, V. Bocci, F. Bossi, D. Bowring, P. Branchini, R. Caloi, P. Campana, G. Capon, T. Capussela, F. Ceradini, S. Chi, G. Chiefari, P. Ciambrone, S. Conetti, E. De Lucia, A. De Santis, P. De Simone, G. De Zorzi, S. Dell'Agnello, A. Denig, A. Di Domenico, C. Di Donato, S. Di Falco, B. Di Micco, A. Doria, M. Dreucci, G. Felici, A. Ferrari, M. L. Ferrer, G. Finocchiaro, S. Fiore, C. Forti, P. Franzini, C. Gatti, P. Gauzzi, S. Giovannella, E. Gorini, E. Graziani, M. Incagli, W. Kluge, V. Kulikov, F. Lacava, G. Lanfranchi, J. Lee-Franzini, D. Leone, M. Martini, P. Massarotti, W. Mei, L. Meola, S. Miscetti, M. Moulson, S. Müller, F. Murtas, M. Napolitano, F. Nguyen, M. Palutan, E. Pasqualucci, A. Passeri, V. Patera, F. Perfetto, L. Pontecorvo, M. Primavera, P. Santangelo, E. Santovetti, G. Saracino, B. Sciascia, A. Sciubba, F. Scuri, I. Sfiligoi, T. Spadaro, M. Testa, L. Tortora, P. Valente, B. Valeriani, G. Venanzoni, S. Veneziano, A. Ventura, R. Versaci, G. Xu.

[2]Neglecting the small ϕ momentum.

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W. By just counting vertices, the relative probability of ISR and FSR are of the same order. This requires very careful estimates of the two processes in order to be able to use the reaction $e^+e^- \to \pi^+\pi^-\gamma$ to extract $\sigma(e^+e^- \to \pi^+\pi^-)$.

The Karlsruhe/Katowice group have computed the radiative corrections up to NLO for different exclusive channels, and implemented in the event generator PHOKHARA [3–7]. The current precision for $2\pi\gamma$ final state is 0.5% [8].

The PHOKHARA Monte Carlo has been used to evaluate the contribution for the ISR process (via the radiation function H) in order to derive the hadronic cross section:

$$s_\pi \frac{d\sigma_{\pi^+\pi^-\gamma}}{ds_\pi} = \sigma_{\pi^+\pi^-}(s_\pi)H(s_\pi), \qquad (1)$$

where $s_\pi = m^2_{\pi^+\pi^-}$, which coincides with the invariant mass s of the intermediate photon for the case of ISR radiation only. [3].

2. The KLOE detector

KLOE [9] is a typical e^+e^- multiple purpose detector with cylindrical geometry, consisting of a large helium based drift chamber (DC, [10]), surrounded by an electromagnetic calorimeter (EmC, [11]) and a superconducting magnet ($B = 0.52$ T). The detector has been designed for the measurement of CP violation in the neutral kaon system, i.e. for precise detection of the decay products of K_S and K_L. These are low momenta charged tracks ($\pi^\pm, \mu^\pm, e^\pm$ with a momentum range from 150 MeV/c to 270 MeV/c) and low energy photons (down to 20 MeV).
The DC dimensions (3.3 m length, 2 m radius), the drift cell shapes (2x2 cm^2 cells for the inner 12 layers, 3x3 cm^2 cells for the outer 46 layers) and the choice of the gas mixture (90% Helium, 10% Isobutane; $X_0 = 900$ m) had to be optimized for the requirements prevailing at a ϕ factory. The KLOE design results in a very good momentum resolution: $\sigma_{p_\perp}/p_\perp \leq 0.4\%$ at high tracking efficiencies ($> 99\%$).
The EmC is made of a matrix of scintillating fibres embedded in lead, which guarantees a good energy resolution $\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$ and excellent timing resolution $\sigma_t = 57\text{ps}/\sqrt{E(\text{GeV})} \oplus 100$ ps. The EmC consists of a barrel and two endcaps which are surrounding the cylindrical DC; this gives a hermetic coverage of the solid angle (98%). However, the acceptance of the EmC below $\approx 20^\circ$ is reduced due to the presence of quadrupole magnets close to the interaction point and does not allow to measure e.g. the photon of $\pi^+\pi^-\gamma$ events with low θ_γ angles.

3. KLOE results on the pion form factor at small angle analysis

KLOE ha recently [12] published a measurement of the pion form factor in which the ISR-photon is emitted at "small" polar angles $\Theta_\gamma < 15^\text{o}$ and $\Theta_\gamma > 165^\text{o}$ with respect to the beam axis. In this way, the contribution from FSR to the $\pi^+\pi^-\gamma$ cross section accounts for less than 1% over the entire s_π spectrum. The radiated photon is not detected, and s_π and θ_γ are reconstructed using the excellent momentum resolution provided by the KLOE drift chamber.

From the radiative cross section $e^+e^- \to \pi^+\pi^-\gamma$ the non-radiative cross section $e^+e^- \to \pi^+\pi^-$ (pion form factor) has been extracted using a radiator function (obtained from the Monte-Carlo generator PHOKHARA), as in eq.(1).

Special attention has been given to events, in which simultaneously an ISR- and FSR-photon are emitted (NLO-FSR). Those events must not be considered as a background and are also not suppressed by the acceptance cuts. The relative contribution of NLO-FSR events is known with a precision of 0.3%. A total experimental error of 0.9% has been achieved for the $e^+e^- \to \pi^+\pi^-\gamma$ cross section measurement (see Figure 1, *up*). The error consists of the individual contributions of the selection efficiencies and of the precision, with which the residual background after all selection cuts is known; further details can be found in ref. [12]. The pion form factor, which can be obtained from the non-radiative cross section $e^+e^- \to \pi^+\pi^-$, is extracted with a total error of 1.3% (see Figure 1, *down*). This includes also

[3]The equation above is correct at leading order if FSR emission can be neglected.

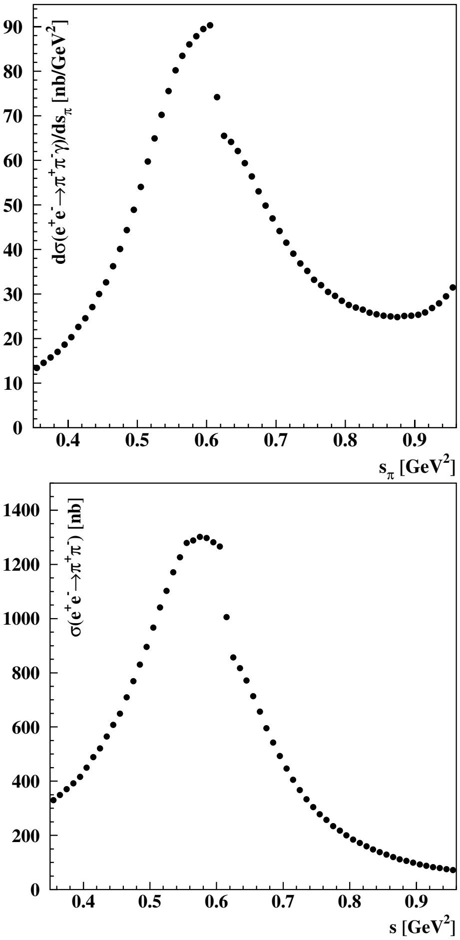

Figure 1. *Up*: Differential cross section for the process $e^+e^- \to \pi^+\pi^-\gamma$, inclusive in pion emission angles and with $\theta_\gamma < 15°$ ($\theta_{\pi\pi} > 165°$). *Down*: Pion form factor.

the theory uncertainties associated with the radiator function and with the large-angle Bhabha cross section. The Bhabha cross section is needed for the luminosity measurement and its uncertainty will diminish with the new version of the BABAYAGA event generator, see ref. [13].

Calculating the dispersion integral, one obtains

$$a_\mu^{had-\pi\pi}(0.35 < s_\pi < 0.95 \text{ GeV}^2) = (388.7 \pm 0.8_{stat} \pm 3.5_{syst} \pm 3.5_{th}) \times 10^{-10}$$

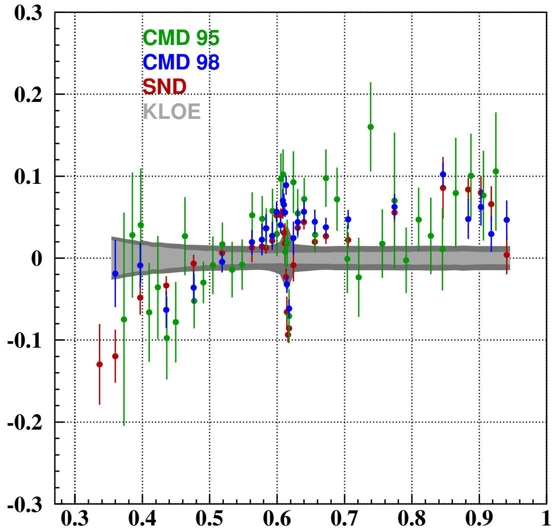

Figure 2. Relative difference of the pion form factor measurements from the experiments CMD-2 (triangles) and SND (circles), relative to the KLOE measurement. The KLOE data points have been interpolated and the statistical (light grey) and systematic (dark grey) error bands are shown in the plot.

The KLOE result agrees within 0.5 standard deviations[4] with values for $a_\mu^{\pi\pi}$ computed from the data sets of the experiments CMD-2 [14] and SND [15], which were operated in the last years at the VEPP-2M-collider in Novosibirsk. The relative difference of the mass spectra is shown in Figure 2. For this comparison the KLOE data points have been interpolated and the measured data points of CMD-2 and SND are used in the plot. We observe relatively large deviations of up to some percent between KLOE and SND at high and low masses, while the overall agreement is better with CMD-2. The good agreement in the dispersion integral is partly due to a compensation effect at lower and higher energies.

All three experiments CMD-2, KLOE and SND show large deviations of up to 15% in the mass range above the ρ peak with respect to spec-

[4] in the somewhat smaller mass mass region $0.37 < M^2_{\pi\pi} < 0.93$ GeV^2.

tral functions obtained from hadronic τ decays, which can be related to the $\pi^+\pi^-$ cross section by means of the conserved vector current (CVC) theorem and after correcting for isospin breaking effects [16]. The origin of the deviation between e^+e^-- and τ-data is not understood [16].

4. Prospects for the small angle analysis with 2002 data

The KLOE measurement presented above refers to data taken in 2001 with a total integrated luminosity of ~ 140 pb^{-1}. KLOE is now performing an analysis using 2002 data (~ 240 pb^{-1}), for which a total systematic error (experimental and theoretical) <1% is expected. The acceptance cuts of this analysis will be unchanged; the improvement will be due to better and more stable running conditions as well as to modifications in the online and offline environment, which will result in lower systematic errors associated to the trigger and background-filter efficiencies. Concerning theory, a new version of BABAYAGA is available [13], which allows to reduce the luminosity error by about a factor 2. The final goal of the analysis is a measurement of R, which requires that $e^+e^- \to \mu^+\mu^-\gamma$ events are selected with equally high precision as $\pi^+\pi^-\gamma$ events.

4.1. Large angle analysis

The analysis described above, in which the ISR-photon is emitted at small polar angles, does not allow to cover the threshold region $M^2_{\pi\pi} < 0.35\text{GeV}^2$, since in this kinematic region the two pions are emitted essentially back-to-back to the ISR-photon and hence cannot be detected simultaneously in the fiducial volume defined for the pion tracks $50^o < \Theta_\pi < 130^o$. In order to measure the pion form factor at threshold, KLOE is now performing a complementary analysis, in which the ISR-photon is tagged at large polar angles $50^o < \Theta_\gamma < 130^o$. Due to the $1/s^2$ dependence in the dispersion integral for a_μ^{hadr}, the low mass region of the two-pion cross section is actually giving a $\sim 20\%$ contribution to the total integral and hence an improved determination of the cross section at threshold is needed.

At large photon angles,

- background from $\phi \to \pi^+\pi^-\pi^0$ is huge and dedicated selection cuts, like a cut on the angle between the missing momentum and the tagged photon direction, as well as a kinematic fit in the background hypothesis with a cut on $\chi^2_{\pi\pi\pi}$ are needed to suppress this contribution;
- irreducible background from events with the same $\pi^+\pi^-\gamma$ final state is not negligible anymore.

This background category, which has to be subtracted relying on Monte-Carlo prediction, is given by FSR-events and by the ϕ radiative decay into the scalar $f_0(980)$ with $f_0(980) \to \pi^+\pi^-$. A possible model dependence of FSR (the model of scalar QED is used in PHOKHARA) and of the description of the scalar $f_0(980)\gamma$ amplitude, can be tested by means of the forward-backward asymmetry [17]. In a recent KLOE publication [18], good agreement between data and simulation has been found for the forward-backward asymmetry, setting upper limits for the systematic errors associated with these model uncertainties.

The main limitation for the measurement of the pion form factor at threshold will arise from the background channels $\phi \to \pi^+\pi^-\pi^0$ and $\phi \to f_0(980)\gamma \to \pi^+\pi^-\gamma$ [19]. In order to further reduce the systematic errors associated to these channels, the DAΦNE collider has taken data off-resonance at a center-of-mass energy of $\sqrt{s} = 1.00$ GeV in its last KLOE run (December 2005 to March 2006, $250\,\text{pb}^{-1}$ integrated luminosity). The off-peak analysis will allow a considerably improved determination of the threshold region. Moreover, together with the data taken on-peak, it will be possible to study the interference of the $f_0(980)$ amplitude with FSR.

5. Conclusion and future prospects

At DAΦNE the KLOE experiment has measured the pion form factor with a precision of 1.3%. An update of the analysis using 2002 data will lead to a further reduction of the systematic error and a normalization to radiative muon pairs is foreseen. Moreover, KLOE has collected data with the collider running off-resonance, which will allow an improved determination of the threshold mass region.

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