Measurement of the e^+e^- hadronic cross section at DAΦNE via radiative return

KLOE collaboration*
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The measurement of hadronic cross sections, especially at low centre-of-mass energies, is currently attracting a lot of attention due to the rôle these measurements play in the theoretical evaluation of the anomalous magnetic moment of the muon. The KLOE experiment at the DAΦNE ϕ-factory in Frascati aims at a measurement of the cross section of the dominant process $e^+e^- \to \pi^+\pi^-$ at energies below 1 GeV exploiting the radiative return from the ϕ to the ρ and ω mesons. This method has systematical errors completely different from previous measurements. The method of the measurement as well as the current status of the analysis are presented.

1. Introduction

1.1. Motivation

The hadronic contribution to the muon anomaly $a_\mu = (g_\mu - 2)/2$ can be related to the hadronic cross sections via a dispersion relation

$$a_\mu(\text{hadr}) = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to\text{hadr}}(s)K(s)\text{d}s, \quad (1)$$

where the integral is carried out over the invariant mass squared s of the hadronic system. The kernel $K(s)$ is a monotonously varying function that behaves approximately like $1/s$. The annihilation cross section also has an intrinsic $1/s$ behaviour and is largely enhanced around the mass of the ρ meson. Data at low energies contribute therefore strongly to a_μ(hadr). Since perturbative QCD fails at energies below ~ 2.5 GeV, one has to use experimentally measured cross sections in the dispersion integral for low energy regions.
The most recent experimental value for a_μ is [1]
$a_\mu^{exp} = (11659203 \pm 8)\text{x}10^{-10}$ [E821],
while a recent theoretical evaluation gives [2]
$a_\mu^{theo} = (11659193.4 \pm 6.9)\text{x}10^{-10}$ [τ data]
$a_\mu^{theo} = (11659169.1 \pm 7.8)\text{x}10^{-10}$ [e^+e^- data]
The first theoretical evaluation of a_μ is obtained with τ decay data as experimental input to the dispersion integral, using conservation of vector current and isospin symmetry to relate τ decays to e^+e^-annihilation cross sections. The second theoretical evaluation uses e^+e^-data exclusively, including the new results from Novosibirsk (CMD2, [3]) and Beijing (BES, [4]). Comparing the theoretical evaluations with the experimental value, one finds a deviation of 3.0 σ for the e^+e^--based theory value, while the τ-based value shows only a 0.9 σ effect. In order to resolve this ambiguous situation and to be able to claim an

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eventual violation of the standard model, more and better information on hadronic cross sections is needed. For a more detailed discussion, see also [5].

1.2. Radiative return

The standard way to measure hadronic cross sections in the past was to perform an energy scan, in which the energy of the colliding beams was changed to the desired value. The Frascati e^+e^-collider DAΦNE, however, was designed as a particle factory operating at the fixed energy of the ϕ resonance (1020 MeV) with high luminosity and the current physics program does not allow to vary the beam energy away from the ϕ resonance. As a consequence of this, the idea has been worked out to obtain $\sigma(e^+e^- \to \text{hadrons})$ using the radiative process $e^+e^-\to$hadrons + γ, where the photon has been radiated in the initial state by one of the electron or the positron, lowering the collision energy [6] [7]. By measuring this *radiative return* process the hadronic cross sections become accessible from the ϕ mass down to the two-pion threshold. The differential cross section $\mathrm{d}\sigma(e^+e^- \to \text{hadrons})/\mathrm{d}s$ can be obtained by measuring $\mathrm{d}\sigma(e^+e^- \to \text{hadrons} + \gamma)/\mathrm{d}s'$, where $s' = M^2_{\text{hadr}}$. The two quantities can be related by the radiation function H:

$$\frac{\mathrm{d}\sigma(\text{hadrons} + \gamma)}{\mathrm{d}s'} \cdot s = \sigma(\text{hadrons}) \times H(s, \theta_\gamma) \quad (2)$$

H depends on s and on the polar angle of the radiated photon θ_γ. An accuracy better than 1% is needed for H in order to perform a precision measurement. Radiative corrections have been computed by different groups up to next-to-leading order for the exclusive final hadronic states $\pi^+\pi^-\gamma$ [8] [9] [10] and $4\pi + \gamma$ [13]. Our analysis makes use of the theoretical Monte carlo event generators EVA [7] and PHOKHARA [8] [11] [12] [14].
Below 1 GeV, the cross section is dominated by the process $e^+e^- \to \rho\gamma \to \pi^+\pi^-\gamma$, which contributes with 62% to the total hadronic contribution to a_μ. In the following preliminary results obtained for this process with the KLOE detector in Frascati will be reported.

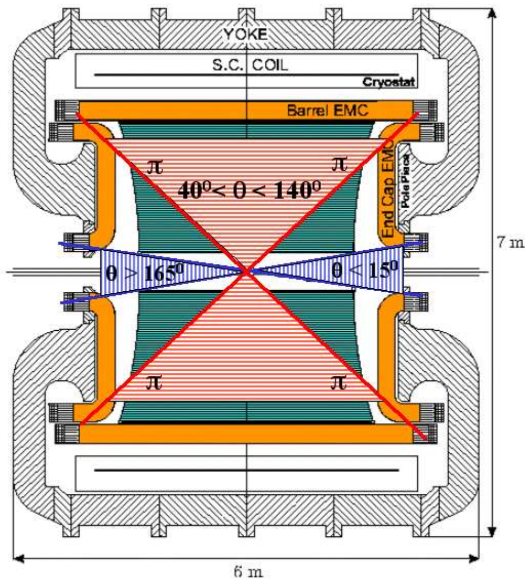

Figure 1. Schematic view of the KLOE detector with the angular acceptance regions for pions (*horizontally hatched area*) and photons (*vertically hatched area*). The photon angle is evaluated from the two pion tracks.

2. Measurement of $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$

2.1. Signal selection

The KLOE detector consists of a high resolution drift chamber ($\sigma_{p_T}/p_T \leq 0.4\%$, [15]) and an electromagnetic calorimeter ($\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$, [16]). In the current analysis we have concentrated on events in which the pions are emitted at polar angles θ_π between 40° and 140°. No explicit photon detection is required and an *untagged* measurement is performed. As a consequence, a cut on the di-pion production angle $\theta_{\pi\pi}$ smaller than 15° (or greater than 165°) is performed instead of a cut on the photon angle θ_γ. $\theta_{\pi\pi}$ is calculated from the momenta of the two pions and is exactly equal to $180° - \theta_\gamma$ if only one photon is emitted. The acceptance regions are shown in Fig. 1. The reason to choose these specific acceptance cuts are a reduced background contamination and a very low relative contribution of final state radiation from the pions. It will

be shown in the following that an efficient and almost background free signal selection can be performed without explicit photon tagging [17] [18] [19] [20].
The selection of $e^+e^- \rightarrow \pi^+\pi^-\gamma$ is performed with the following steps:

- *Detection of two charged tracks connected to a vertex*: Two charged tracks with polar angles between 40° and 140° connected to a vertex in the fiducial volume $R < 8$ cm, $|z| < 15$ cm are required. Additional cuts on transverse momentum $p_T > 200$ MeV or on longitudinal momentum $|p_z| > 90$ MeV reject spiralizing tracks and ensure good reconstruction conditions.

- *Identification of pion tracks*: A π-e separation is done by cutting on a likelihood function which parametrizes the interaction of charged particles with the electromagnetic calorimeter. The function has been built using control samples from data of $\pi^+\pi^-\pi^0$ and $e^+e^-\gamma$ in order to find the calorimeter response for pions and electrons. The event is selected if at least one of the two tracks is identified to be a pion. In this way, $e^+e^-\gamma$ events are drastically removed from the signal sample while the efficiency for $\pi^+\pi^-\gamma$ is still very high ($> 98\%$).

- *Cut on the track mass*: The track mass is a kinematic variable corresponding to the mass of the charged tracks under the hypothesis that the final state consists of two particles with the same mass and one photon. It is calculated from the reconstructed momenta $\vec{p}_+$, $\vec{p}_-$. Cutting at a value of 120 MeV rejects $\mu^+\mu^-\gamma$ events, while in order to reject $\pi^+\pi^-\pi^0$ events a cut in the plane of track mass and $M^2_{\pi\pi}$ is performed (see Fig. 2)

- *Cut on the di-pion angle $\theta_{\pi\pi}$*: The aforementioned cut on the di-pion angle $\theta_{\pi\pi} < 15° or > 165°$ is performed.

2.2. Final state radiation

Events with final state radiation from the pions are a part of the hadronic cross section and should be included in the dispersion integral for a_μ. However for measurements of the hadronic cross sections using the radiative return, Eq. 2 is valid only in the absence of final state radiation. Therefore our approach is to suppress final state radiation in the measurement with kinematical cuts in order to be able to give a *bare* cross section [21]. Since initial state photons are emitted at small polar angles and final state photons follow the $\sin^2\theta_\pi$ distribution of the pions, for the geometrical cuts described above (see Fig. 1) the relative contribution of final state radiation is well below 1% in all the $M_{\pi\pi}$ region, as has been evaluated with the EVA event generator, which contains final state radiation at leading order for pointlike pions.

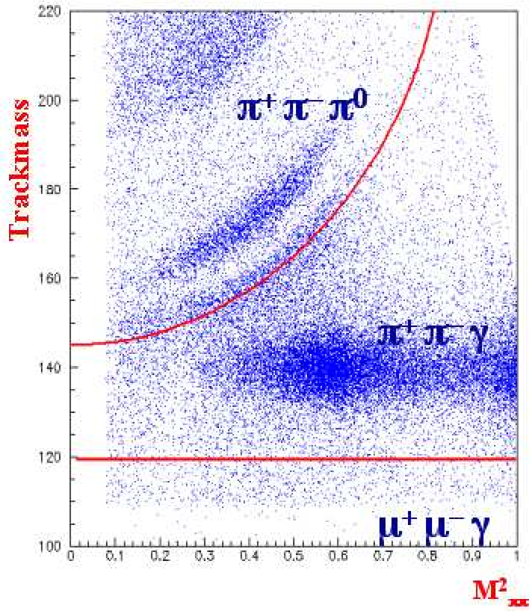

Figure 2. 2-dimensional cut in the plane of track mass/MeV and $M^2_{\pi\pi}/GeV^2$

2.3. Residual background:

Concerning an eventual contribution of the process $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ via two-photon fusion to our signal sample, where the e^+e^- in the final state disappear along the beamline and can not be detected, we found from Monte Carlo [22] that

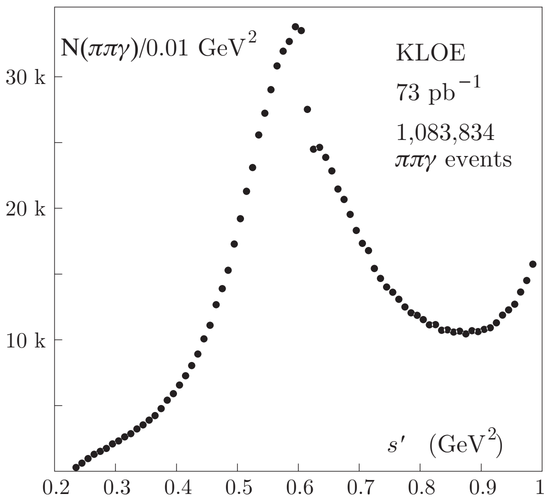

Figure 3. Number of $\pi^+\pi^-\gamma$ events selected by the analysis in the region $\theta_{\pi\pi} < 15°$ or $\theta_{\pi\pi} > 165°$, $40° < \theta_\pi < 140°$.

this process populates a region at low $M^2_{\pi\pi}$ and is eliminated completely by the $M^2_{\pi\pi}$-dependent track mass cut as shown in Fig. 2.

2.4. Effective cross section

Applying the aforementioned selection steps from section 2.1 on a sample of $\sim$ $73pb^{-1}$ of data taken in 2001 (roughly 1/7 of the total KLOE data sample of $\sim$ $500\,pb^{-1}$), ca. 10^6 events are selected, corresponding to $15,000$ events/pb^{-1}. Fig. 3 shows the number of $\pi^+\pi^-\gamma$ events selected in 100 bins between 0.02 GeV^2 and 1.02 GeV^2. The $\rho - \omega$ interference is clearly visible even without unfolding the spectrum from the detector resolution, demonstrating the excellent momentum resolution of the KLOE drift chamber.
To obtain the $\pi^+\pi^-\gamma$ cross section one has to subtract the residual background from this spectrum and divide by the selection efficiency and the integrated luminosity:

$$\frac{d\sigma_{\text{hadrons}+\gamma}}{dM^2_{\pi\pi}} = \frac{dN_{\text{Obs}} - dN_{\text{Bkg}}}{dM^2_{\pi\pi}} \frac{1}{\epsilon_{\text{Sel}}} \frac{1}{\int \mathcal{L}dt} \qquad (3)$$

- *Residual background* N_{Bkg}: Given the angular acceptance regions for pions and photon as described in Fig. 1, the amount of residual background is considered to be negligible (see section 2.3). For this preliminary analysis no further background subtraction other than the one mentioned in section 2.1 has been performed.

- *The selection efficiency* ϵ_{Sel}: The selection efficiency is the product of trigger, reconstruction, filtering, π-e separation and track mass cut efficiencies. Apart from the last one, which has been evaluated from Monte Carlo, all efficiencies have been evaluated from data, using unbiased control samples matching the kinematics of the actual signal. The total selection efficiency is about 60%.

- *Luminosity*: At KLOE, the luminosity measurement is performed using Bhabha events at large angles ($55° < \theta_{+,-} < 125°$, $\sigma = 425$nb). The number of Bhabha candidates is counted and the luminosity is obtained from the effective cross section obtained from Monte Carlo. KLOE uses two independent Bhabha event generators (the Berends/Kleiss generator [23] modified for DAΦNE [24] and the BABAYAGA generator [25]). Both generators agree within 0.1%. Systematical errors of the luminosity measurement are currently evaluated, but the very good agreement of the experimental distributions ($\theta_{+,-}$, $E_{+,-}$) with the event generators and a cross check with an independent counter based on $e^+e^- \to \gamma\gamma(\gamma)$ indicates that our precision is better than 1%.

3. Extracting the pion form factor

Neglecting the final state radiation interference, the pion form factor $|F_\pi|^2$ can be extracted as a function of $M^2_{\pi\pi}$ from the observed $\pi^+\pi^-\gamma$ cross section as:

$$|F_\pi(M^2_{\pi\pi})|^2 = \frac{\sigma_{\pi\pi\gamma}}{\sigma_{\pi\pi\gamma}(F_\pi = 1)} \qquad (4)$$

where $\sigma_{\pi\pi\gamma}(F_\pi = 1)$ is the NLO cross section for $e^+e^- \to \pi^+\pi^-\gamma$ (initial state radiation only) un-

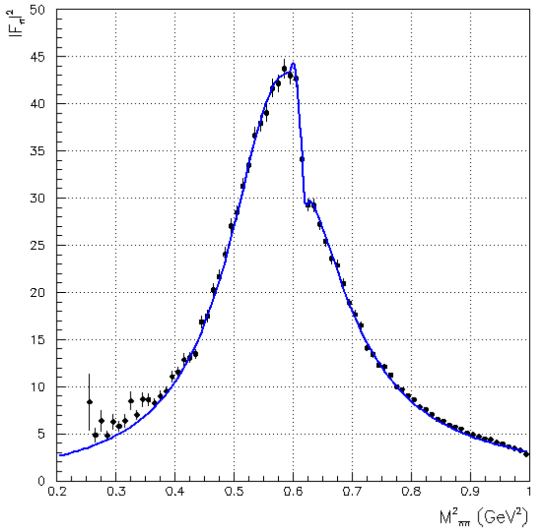

Figure 4. Preliminary pion form factor extraction by dividing for the photon radiation function H, obtained from MC. The blue line is a fit to the data using the Gounaris-Sakurai parametrization [26]

der the assumption of pointlike pions and corresponds to the quantity H from eq. 2. We obtain H bin-by-bin from the theoretical Monte Carlo generator PHOKHARA by setting $F_\pi = 1$. The pion form factor extracted from eq. 4 is shown in Fig. 4. The errors are dominated by the limited Monte Carlo statistics used in the evaluation of the efficiencies and will be reduced in the future.

4. Summary and outlook

A method of measuring hadronic cross sections at particle factories has been presented using the radiative return. This method is complementary to the energy scan used to perform this measurement up to now and has completely different systematical errors, making it the ideal tool to check and improve existing measurements. Such a crosscheck has become very important given the disagreement between the evaluations of a_μ obtained in [2].
The radiative return has been used at the DAΦNE ϕ-factory in Frascati and a preliminary result on the pion form factor based on a subsample of data taken in 2001 with the KLOE detector has been shown.
The next step is to refine this analysis using the full statistics of 2001 data ($\sim 140pb^{-1}$). Current work is focused on a more precise evaluation of all the efficiencies and their systematical errors, systematic studies of the luminosity measurement, unfolding the spectrum from the detector resolution and subtraction of remaining background. All this topics are well advanced, and a publication of the result of this refined analysis is expected to happen in the next months.

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