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The hadronic cross section measurement at KLOE

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KLOE uses the radiative return to measure cross section $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ at the electron-positron collider DAΦNE. Divinding by a theoretical radiator function, we obtain the cross section $\sigma(e^+e^- \to \pi^+\pi^-)$ for the mass range $0.35 < s_\pi < 0.95$ GeV^2. We calculate the hadronic contribution to the muon anomaly for the given mass range: $a_\mu = 388.7 \pm 0.8_{stat} \pm 3.5 syst \pm 3.5_{th}$.

1. Introduction

1.1. Motivation

The hadronic contribution to the vacuum polarization to the anomalous magnetic moment is not calculable at low energy by perturbative QCD. It can be obtained connecting the immaginary part of the hadronic piece of the spectral function by unitarity to the cross section $e^+e^- \to hadrons$ [1,2]. A dispersion integral can be derived:

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

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. The process $e^+e^- \to \pi^+\pi^-$ below 1 GeV contributes to 62% of the total hadronic contribution [3].

A previous measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ for values of $\sqrt{s_\pi}$ around the ρ peak comes from the CMD-2 experiment at VEPP-2M. Their data have been used together with τ and e^+e^- data up to 3 GeV to produce a firm prediction for comparison with the direct measurement performed by E821, at BNL [4]. Comparing theoretical evaluations with the experimental values, one finds a deviation of 2.7σ for the e^+e^--based theoretical prediction, while the τ-based value shows only a 0.9σ effect. In order to solve the situation more and better information on hadronic cross section is needed.

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1.2. The radiative return

In the past the standard way to measure the hadronic cross section was to perform an energy scan, in which the collision energy of the accelerator is changed to the desired value. The Frascati collider DAΦNE has been designed to work at a fixed center of mass energy equal to the ϕ resonance mass of 1020 MeV. As a consequence, a complementary method has been worked out, where the cross section $\sigma(e^+e^- \rightarrow hadrons)$ is obtaind by using the radiative reaction $\sigma(e^+e^- \rightarrow hadrons + \gamma)$. In this process the photon is radiated in the initial state in one of the electrons (positrons), lowering in this way the collision energy. The radiative cross section and the $\pi^+\pi^-$ cross section can be related through the radiator function H:

$$s_\pi \frac{d\sigma_{\pi^+\pi^-\gamma}}{ds_\pi} = \sigma_{\pi^+\pi^-}(s_\pi) \cdot H(s_\pi) \tag{2}$$

where $s_\pi = M^2_{\pi\pi}$, which coincides with the invariant mass of the intermediate photon in case of Initial State Radiation (ISR) only. 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 state $\pi^+\pi^-\gamma$[5–7]. Our analysis makes use of the theoretical Motecarlo codes PHOKHARA [7–10] and EVA[11] .

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

2.1. Signal selection

The KLOE detector consists of a high resolution drift chamber ($\sigma_{p_T}/p_T \leq 0.4\%$,[12]) and an electromagnetic calorimeter ($\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$,[13]). Since for small polar angles of the radiated photon the ISR process vastly dominates over the Final State Radiation (FSR) process [11], we have selected events in which the photon is emitted at angles $< 15^o$ or $> 165^o$. The direction of the photon is calculated from the pion tracks by closing the kinematics, under the assumption of only one single photon emitted ($\vec{p}_{miss} = -\vec{p}_\gamma = \vec{p}_{\pi^+} + \vec{p}_{\pi^-}$). For the two tracks it is requested $50^o < \theta_\pi < 130^o$. The fiducial volume together to a section of the KLOE detector

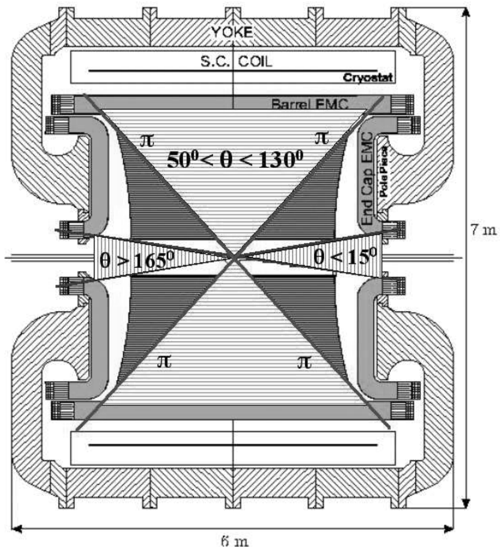

Figure 1. Schematic view of the KLOE detector with the angular acceptance regions for pions (*horizontally hatched area*) and photons (*vertically hatched area*). The photon angle is evaluated from the two pion tracks.

is shown in Fig.1

The selection of $e^+e^- \rightarrow \pi^+\pi^-\gamma$ events is performed according to the following steps:

- *Detection of two tracks connected to a vertex*: two charged tracks with polar angle between 50^o and 130^o connected to a vertex in IR the fiducial volume and with $R_{xy} < 8$ cm, $|z| < 7$ cm are requested. Additional cuts on transverse momentum, $p_T >$160 MeV and on longitudinal momentum, $|p_z| >$90 MeV are applied to reject spiralizing tracks and ensure good reconstruction conditions.

- *Identification of pion tracks*: the separation of pions from electrons is performed using a likelihood function, which parametrizes the time of flight and the signal shape of the charged tracks in the calorimeter. An event is accepted if at least one of the two tracks is recognised as a pion. In this way the amount of $e^+e^-\gamma$ is drastically reduced, while the efficiency for $\pi^+\pi^-\gamma$ is still very high (>98%).

- *Cut on track mass*: the track mass is a kinematic variable calculated from the reconstructed pion momenta $\vec{p}_{\pi^+}$, $\vec{p}_{\pi^-}$ applying four-momentum conservation, under the hypothesis that the final state consists of two particles with the same mass and one photon. Removing events with $M_{trk} < 120$ MeV rejects $\mu^+\mu^-\gamma$ events, while in order to reject $\pi^+\pi^-\pi^0$ events a $M^2_{\pi\pi}$ - dependent cut is used (see Fig.2)

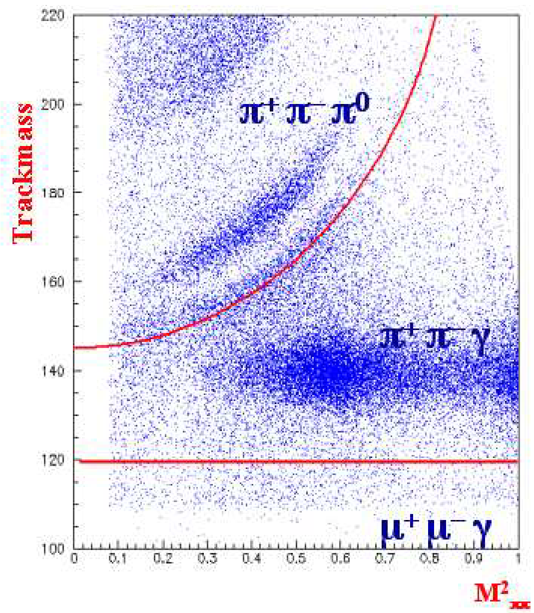

Figure 2. 2-dimensional cut in the plane M_{trk}/MeV and $M^2_{\pi\pi}$/GeV^2.

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

The sample used (corresponding to 140 pb^{-1}) has been collected from July to December 2001. To obtain the effective cross section $\pi^+\pi^-\gamma$ one has to subtract the residual background from this spectrum and divide by the selection efficency and by the integrated luminosity:

$$\frac{d\sigma_{\pi^+\pi^-\gamma}}{ds_\pi} = \frac{\Delta N_{\rm Obs} - \Delta N_{\rm Bkg}}{\Delta s_\pi} \frac{1}{\epsilon_{\rm Sel}\epsilon_{\rm Acc}} \frac{1}{\int \mathcal{L} dt} \quad (3)$$

2.2. Background subtraction

After the selection described above, a residual background of $e^+e^-\gamma$, $\mu^+\mu^-\gamma$ and $\pi^+\pi^-\pi^0$ events remains. Background from $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ is concentrated at low M_{trk} values. The amount of these two kind of backgrounds is obtained by fitting the M_{trk} spectra of the selected events in slices of s_π (from MonteCarlo for $\mu^+\mu^-\gamma$, directly from data for $e^+e^-\gamma$). Background from $\pi^+\pi^-\pi^0$ appears at higher M_{trk} values and the missing mass $m^2_{miss} = (p_\phi - p_+ - p_-)^2$ is peaked at $m^2_{\pi^0}$. The number of $\pi^+\pi^-\pi^0$ in the signal region is obtained by fitting the m_{miss} distribution with the shape taken from MonteCarlo. The contribution of all background to the observed signal is below 2% above 0.5 GeV^2, while it increases up to 10% at $s_\pi = 0.35$ GeV^2.

2.3. Selection efficiency

The selection efficiency is the product of the efficiencies associated with the trigger, reconstruction, filtering, π/e separation and track mass cut.

The trigger includes also a veto for cosmic rays. The overall trigger efficiency, including the effect of cosmic-ray veto, has been evaluated from the probability for single pion to fire trigger sector in $\pi^+\pi^-\gamma$ events.

During the reconstruction an offline filter recognises and rejects background events. The efficiency of this filter has been studied with a dedicated sample of $\pi^+\pi^-\gamma$ that were rejected by the filter itself and its value has been found 96% flat in s_π, with a systematic error of 0.6%.

The tracking efficiency was evaluated using $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-$ events.

The efficiency on the vertex finding algorithm has been evaluated with a sample of $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\gamma$ events: the systematic error associated to this procedure is 0.3%

The efficiency for π/e separation has been studied by selecting $\pi^+\pi^-\gamma$ events on the basis of one track and examining the distribution of the likeli-

hood estimator for the other one. In the analysis only one track is requested to be a pion, so the efficiency on pion identification is >99.9%.
The efficiency of the M_{trk} cut is obtained as a by-product of the residual background evaluation: the result of the fit provides the efficiency in each s_π bin. It has been obtained by our reference MonteCarlo (PHOKHARA).

2.4. Luminosity measurement

The integrated luminosity is measured using large angle Bhabha events, in the interval $55^o < \theta_{+,-} < 125^o$. The effective cross section for these events is big enough ($\sim$430 nb) so that the statistical error on the measurement is negligible. The number of Bhabha are counted and normalized to the effective cross section, after having subtracted the residual background:

$$\int \mathcal{L}dt = \frac{N_{\rm VLAB}(\theta_i)}{\sigma^{\rm MC}_{\rm VLAB}(\theta_i)}(1-\delta_{\rm Bkg}). \quad (4)$$

The precision on the measurement depends on the correct inclusion of higher-order term in computing the Bhabha cross section. We have used the Bhabha event generator BABAYAGA [14], where the QED radiative corrections are taken into account in the framework of the parton-shower method. The claimed precision is 0.5%.
All the selection effeciencies (trigger, EmC cluster, DC tracking) are >99% and well reproduced by MonteCarlo. Background from $\mu^+\mu^-(\gamma)$, $\pi^+\pi^-(\gamma)$ and $\pi^+\pi^-\pi^0$ is well below 1% and is subtracted. Corrections are applied on a run-by-run basis for fluctuations in the center-of-mass energy of the machine and in calorimeter calibration. The experimental uncertainty due to all these effects is 0.3%. The total systematic error on the measurement is $\delta\mathcal{L} = 0.5\%_{\rm th} \oplus 0.3\%_{\rm exp}$. The luminosity measurement is independently checked using $e^+e^- \to \gamma\gamma$ events. We have found agreement to within 0.2%.
Our result for the differential cross section $d\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ with $0^o < \theta_\pi < 180^o$ and $\theta_{\pi\pi} < 15^0, > 165^o$ is plotted if Fig.3.

3. Extraction of $\sigma(e^+e^- \to \pi^+\pi^-)$

In order to extract the $e^+e^- \to \pi^+\pi^-$ cross section, we have to divide by the radiator function

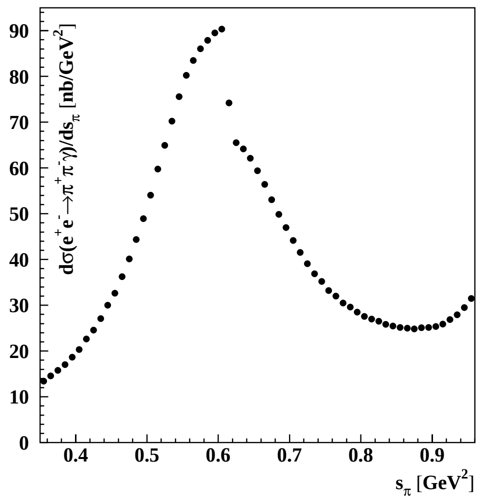

Figure 3. Differential cross section for $e^+e^- \to \pi^+\pi^-\gamma$, inclusive in θ_π and with $\theta_{\pi\pi} < 15^0$ ($\theta_{\pi\pi} > 165^0$).

H, which is obtained from PHOKHARA, setting $F_\pi(s) = 1$ and *switching off* the vacuum polarization of the intermediate photon in the generator. Appliyng Eq.2 and taking in accout FSR corrections as described in the following, the cross section has been obtained as a function on the invariant mass of the virtual photon, $s = m^2_{\gamma^*}$ (Fig.4)

3.1. FSR corrections

Events with one or more photons emitted by pions (FSR) without any emission from the electron or the positron, have to be considered as a background. Our selection strongly suppresses this contribution, whose amount is below 1% in the whole range of s_π. However, events with a simultaneous emission of one photon from the electron (positron) and from one of the two pions, are part of our signal and have to be included in the sample [15]. The kinematic cuts described above allow to reject almost the totality of pure FSR. The relative contribution after the event analysis of this process is well below 1% in all the $M_{\pi\pi}$ region. To obtain $e^+e^- \to \pi^+\pi^-$ cross section, two

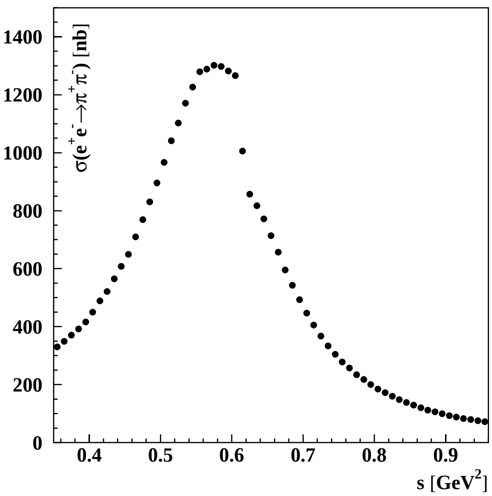

Figure 4. Cross section for $e^+e^- \to \pi^+\pi^-$.

complementary methods have been performed. In the first one we have kept the events with simultaneuos emission of initial and final-state photon, and to take into account that the invariant mass of final state is not equal to the invariant mass of the virtual photon, due to the emission of the FSR photon, we have applied a correction. The event analysis is performed and the acceptance corrections and the track mass efficiency are evaluated by a MonteCarlo simulation having sinultaneos ISR and FSR in.
In the second method we have corrected the observed spectrum $e^+e^- \to \pi^+\pi^-\gamma$ for the amount of FSR expected from PHOKHARA, obtaining a sample containing only ISR event. The event analysis has been performed, with the acceptance corrections and trackmass efficiency evaluated by a simulation where only ISR events were in, and finally after the division by the radiator H, FSR corrections to the cross section $e^+e^- \to \pi^+\pi^-$ have been applied [17,18]. The cross section $e^+e^- \to \pi^+\pi^-$ has been obtained under the assumption of scalar QED (sQED) for FSR (point-like pions) and of the factorization, *i.e.* the absence of interference effects between the initial and final states [16].

The results obtained with the two methods agree to within 0.2% and we assign an error of 0.3% due to FSR corrections.

This error comes from two different contributions added in quadrature: 0.2% is the difference we have observed between the two methods we have worked out and another 0.2% comes from the model used to simulate FSR. If we assign an error of 20% on the sQED assumption (see 3.2), having an amount of 1% of FSR, we obtain an error of 0.2% for the model.

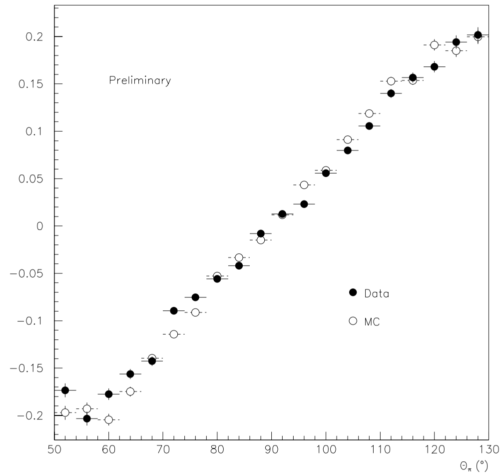

Figure 5. Charge asymmetry as a function of polar pion angle.

3.2. Charge asymmetry

The model dependence of FSR can be checked by observing the charge asymmetry as a function of the polar angle of the pions and comparing it with a MonteCarlo prediction within the model of the sQED. The charge asymmetry is defined as

$$A(\theta_\pi) = \frac{N(\theta_{\pi^+}) - N(\theta_{\pi^-})}{N(\theta_{\pi^+}) + N(\theta_{\pi^-})} \qquad (5)$$

and it arises from the interference between initial and final state radiation. To study this quan-

Table 1
List of systematic errors on a_μ

Acceptance	0.3%
Trigger	0.3%
Reconstruction Filter	0.6%
Tracking	0.3%
Vertex	0.3%
Particle ID	0.1%
Trackmass	0.2%
Background subtraction	0.3%
Unfolding	0.2%
Total exp systematics	0.9%
Luminosity	0.6%
Vacuum Polarization	0.2%
FSR resummation	0.3%
Radiator function (H_{s_π})	0.5%
Total theory error	0.9%

tity it is necessary to collect $\pi^+\pi^-\gamma$ events with the photon emitted at large polar angles. In this case the amount of FSR is large and a sizeable charge asymmetry can be measured. At large photon polar angles it is possible to performe a photon tagging, which allows to reject considerably background. After having applied some further dedicated kinematic cuts to reject $\pi^+\pi^-\pi^0$ events we obtain a preliminary result shown in Fig.5. The charge asymmetry is plotted both for data and MonteCarlo (signal plus residual background). An agreement between data and MonteCarlo of 10% is reached. This justifies the error of 20% we have considered arising from the model of FSR.

3.3. Vacuum polarization

In order to obtain the *bare* cross section, hadronic and leptonic vacuum polarization have to be subtracted. This can be done by correcting the cross section for the running of α as follows:

$$\sigma_{\rm bare} = \sigma_{\rm dressed} \left(\frac{\alpha(0)}{\alpha(s)}\right)^2 . \tag{6}$$

While the leptonic contribution $\Delta\alpha_{\rm lep}(s)$ can be analytically calculated, for the hadronic contribution, $\Delta\alpha_{\rm had}(s)$, we have used $\sigma_{\rm had}(s)$ values measured previously [19].

4. Evaluation of $a_\mu^{\pi\pi}$

The $\sigma(e^+e^- \to \pi^+\pi^-)$ cross section, divided by the vacuum polarization, has been used to evaluate the contribution to a_μ^{hadr} due to the $\pi^+\pi^-$ channel in the energy range $0.35 < s_\pi < 0.95$ GeV^2. The resulting value (in 10^{-10} units) is

$$a_\mu^{\pi\pi}(0.35, 0.95) = 388.7 \pm 0.8_{stat} \pm 3.5 syst \pm 3.5_{th} \tag{7}$$

The various contributions to the systematic error on a_μ are listed in Table 1.
By integrating our spectrum in the energy range $0.37 < s_\pi < 0.93$ GeV^2 we have obtained (in 10^{-10} units)
$a_\mu^{\pi\pi}(0.37, 093) = 375.6 \pm 0.8_{stat} \pm 4.8_{syst+th}$
Our value agrees with the result of CMD-2 [20,21], being this latter (in 10^{-10} units) $a_\mu^{\pi\pi} = 378.6 \pm 2.7_{stat} \pm 2.3_{syst+th}$ in the same energy interval ($0.37 < s_\pi < 0.93$ GeV^2), and confirms the present discrepancy of the hadronic contribution on a_μ using data of electron-positron annihilation and τ decay data.

5. Conclusion

We have measured the cross section for the process $e^+e^- \to \pi^+\pi^-\gamma$ with the pion system emitted at small polar angle in the energy region $0.35 < s_\pi < 0.95$ GeV^2. We have derived the cross section for the process $e^+e^- \to \pi^+\pi^-$. After correction for vacuum polarization, we have derived the corresponding part of the hadronic contribution to the muon anomalous magnetic moment with a negligible statistical error and with a systematic error of 0.9%(exp) $\oplus$ 0.9% (th).

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