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KLOE measurement of the $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$ and its contribution to the muon anomaly evaluation

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The muon anomalous magnetic moment is one of the most precisely measured quantities in particle physics and a persistent discrepancy of about 3 σ between standard model (SM) prediction and experimental measurements has been up to now observed. The leading order contribution a_μ^{hlo} is actually the main source of uncertainty in the theoretical evaluation of the muon anomaly, and it can be evaluated by dispersion integral using the experimental measurement of hadronic cross section. The KLOE experiment at the $\phi - factory$ DAΦNE in Frascati (near Rome) is the first to have exploited Initial State Radiation (ISR) to precisely determine the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section below 1 GeV representing the 70% of the leading order contribution to the muon anomaly. The KLOE-collaboration published two measurements of the $\pi^+\pi^-$ cross section with the photon in the initial state emitted at small angle in 2005 and 2008, and an independent measurement of the $\pi^+\pi^-$ cross section with the photon emitted at large angle in 2011. These measurements were normalized to the DAΦNE luminosity. Recently, a new analysis deriving the pion form factor directly from measuring the bin-by-bin $\pi^+\pi\gamma$ and $\mu^+\mu\gamma$ ratio has been performed. We present the preliminary results of this new measurement, compared to the previous published ones, and the impact on the evaluation of the hadronic contribution to the muon anomaly.

8th International Conference on Nuclear Physics at Storage Rings-Stori11,
October 9-14, 2011
INFN, Laboratori Nazionali di Frascati, Italy

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PoS(STORI11)056

1. Introduction

The anomalous magnetic moment of the muon, am , is one of the best known quantities in particle physics. Recent theoretical evaluations [1] find a discrepancy of about 3 standard deviations from the value obtained from the g-2 experiment at Brookhaven [2]. A large part of the uncertainty on the theoretical estimates comes from the leading order hadronic contribution $a_\mu^{\rm had,lo}$, not calculable by perturbative QCD at low energies, which is evaluated with a dispersion integral using measured hadronic cross sections. The use of Initial State Radiation (ISR) has opened a new way to measure these cross sections at particle factories operating at fixed energies [3]. The region below 1 GeV, which is accessible with the KLOE experiment in Frascati, is dominated by the $\pi^+\pi^-$ final state and contributes with $\sim 70\%$ to $a_\mu^{\rm had,lo}$, and $\sim 60\%$ to its uncertainty. Therefore, an improved precision on the $\pi\pi$ cross section would result in a reduction of the uncertainty on the leading order hadronic contribution to a_μ, and in turn to the SM prediction for a_μ.

2. Measurement of $\sigma_{\pi\pi}$ with ISR

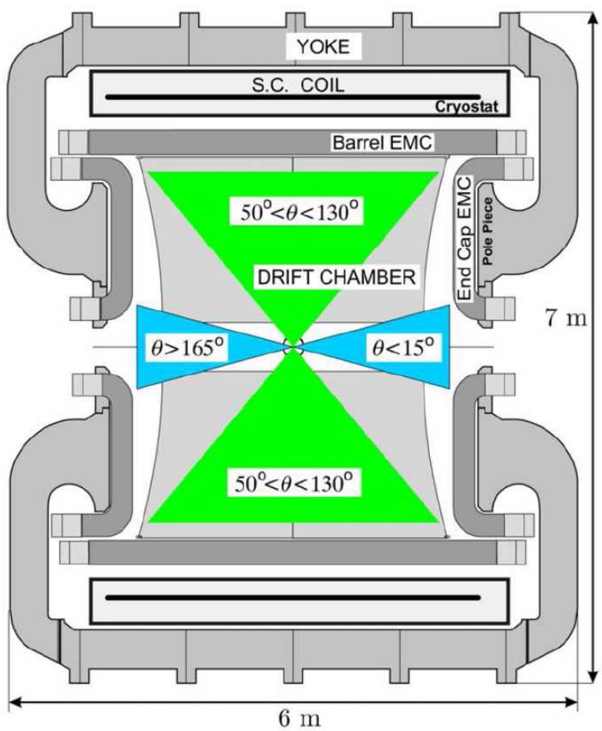

Figure 1: Schematic view of the KLOE detector with selection regions.

The KLOE detector operates at the DAΦNE e^+e^- collider in Frascati. It consists (Fig. 1) of a high resolution drift chamber ($\sigma_p/p \leq 0.4\%$) [4] and an Pb-scintillating fibers calorimeter with excellent time ($\sigma_t \sim 54$ ps$/\sqrt{E\ [\mathrm{GeV}]}\ \oplus 100$ ps) and good energy ($\sigma_E/E \sim 5.7\%/\sqrt{E\ [\mathrm{GeV}]}$) resolution [5]. DAΦNE is a $\phi - factory$ running at $\sqrt{s} \simeq M_\phi$, and has delivered ca. 2.5 fb^{-1} of integrated luminosity to the KLOE experiment up to the year 2006. So far KLOE has reported two measurements of the $\pi\pi$ cross section between 0.35 and 0.95 GeV^2 (called KLOE05 [6] and KLOE08 [7] in the following). In addition, about 250 pb^{-1} of data have been collected at $\sqrt{s} \simeq 1$ GeV, 20 MeV below the ϕ resonance, from which a new measurement of $\pi\pi$ cross section was obtained (KLOE10 [8]). Running at energies below the ϕ-meson resonance reduces considerably the background from the copious ϕ-meson decay products, including scalar mesons. As DAΦNE was designed to operate at a fixed energy around M_ϕ, the differential cross section $\mathrm{d}\sigma(e^+e^- \to \pi^+\pi^-\gamma)/\mathrm{d}M^2_{\pi\pi}$ is measured, and the total cross section $\sigma_{\pi\pi} \equiv \sigma_{e^+e^-\to\pi^+\pi^-}$ is evaluated using the formula [3]:

$$s \cdot \frac{\mathrm{d}\sigma_{\pi\pi\gamma}}{\mathrm{d}M^2_{\pi\pi}} = \sigma_{\pi\pi}(M^2_{\pi\pi})\, H(M^2_{\pi\pi}, s) \,, \tag{2.1}$$

in which s the squared e^+e^- center of mass energy, and H the radiator function obtained from theory describing the photon emission in the initial state. An alternative way to extract the $\pi\pi$ cross section uses the $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio [9]:

$$\sigma_{\pi\pi(\gamma)} = \sigma_{\mu\mu(\gamma)} \frac{\mathrm{d}\sigma_{\pi\pi\gamma}/\mathrm{d}s'}{\mathrm{d}\sigma_{\mu\mu\gamma}/\mathrm{d}s'} = \frac{4\pi\alpha^2}{3s'}(1+2m^2_\mu/s')\beta_\mu \, \frac{\mathrm{d}\sigma_{\pi\pi\gamma}/\mathrm{d}s'}{\mathrm{d}\sigma_{\mu\mu\gamma}/\mathrm{d}s'}, \tag{2.2}$$

where s' the four-momentum square of the virtual photon, *i.e.* the e^+e^-center-of-mass energy squared after ISR emission, m_μ the muon mass, β_μ, β_π the muon and pion velocities in the center-of-mass frame, $\mathrm{d}\sigma_{\pi\pi\gamma}/\mathrm{d}s'$, $\mathrm{d}\sigma_{\mu\mu\gamma}/\mathrm{d}s'$ the $e^+e^- \to \pi^+\pi^-\gamma$, $e^+e^- \to \mu^+\mu^-\gamma$ differential cross sections, respectively. In both Eqs.(2.1), (2.2) Final State Radiation (FSR) terms are neglected, but are taken into account properly in the analyses. The differential cross sections ratio presented in Eq. (2.2) allows us to completely cancel important contributions to the total uncertainty which are instead present in the measurement performed by Eq. (2.1), namely the integrated luminosity, the radiation function H and the vacuum polarization.

3. Measurements of Pion form factor normalized to Luminosity from Bhabha events

The first two KLOE published analyses (KLOE05 and KLOE08) used selection cuts in which the photon is emitted within a cone of $\theta_\gamma < 15^\circ$ around the beamline (narrow cones in Fig. 1) and the two charged pion tracks have $50^\circ < \theta_\pi < 130^\circ$ (wide cones in Fig. 1). In this configuration, the photon is not explicitly detected, and its direction is reconstructed from the two detected charged pion tracks' momenta as: $\vec{p}_\gamma \simeq \vec{p}_{\mathrm{miss}} = -(\vec{p}_{\pi^+} + \vec{p}_{\pi^-})$. These cuts guarantee a high statistics for ISR signal events, and a reduced contamination from the resonant process $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$ in which the π^0 mimics the missing momentum of the photon(s) and from the final state radiation process $e^+e^- \to \pi^+\pi^-\gamma_{\mathrm{FSR}}$. As a consequence of these event selection conditions, the highly energetic photon emitted at small angle forces the pions also to be at small angles (and thus outside the selection cuts), resulting in a kinematical suppression of events with $M^2_{\pi\pi} < 0.35$ GeV^2. To access the two pion threshold, a new analysis has been performed (KLOE10) requiring events with photon at large polar angles with $50^\circ < \theta_\gamma < 130^\circ$ (wide cones in Fig. 1), in the same angular region as the pions. To significantly reduce the contamination from $f_0\gamma$ and $\rho\pi$ decays of the ϕ-meson, data were taken at $\sqrt{s} = 1$ GeV about 5 times the ϕ-meson decay width ($\Gamma_\phi = 4.26 \pm 0.04$ MeV [10]) outside the narrow peak of the ϕ resonance. The drawback in using such acceptance cuts is about a factor 5 reduction in statistics, as well as an increase of background events from final state radiation and from ϕ radiative decays compared to the small angle photon acceptance criterion. The model dependence of the ϕ radiative decays to the $f_0(980)$ and $f_0(600)$ scalars together with $\phi \to \rho\pi \to (\pi\gamma)\pi$, has a strong impact on the measurement [11]. To overcome this, KLOE10 measurement uses the data acquired by the KLOE experiment at a $\sqrt{s}$ = 1 GeV.

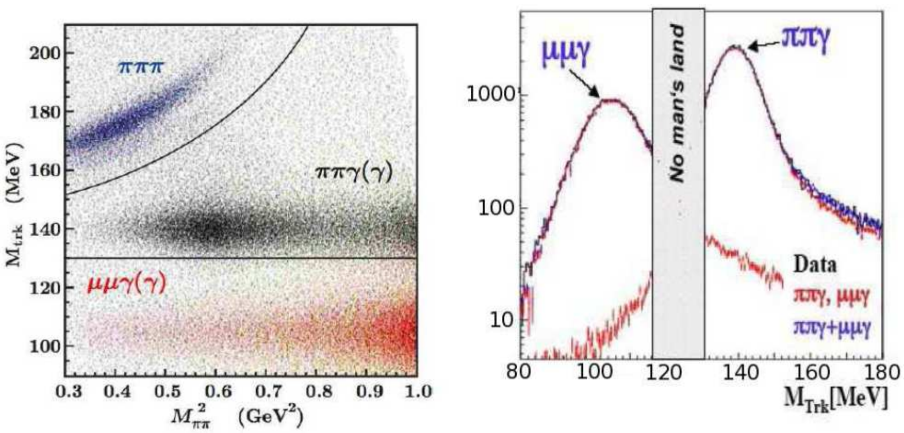

Figure 2: MC simulation of M_{TRK} vs. $M^2_{\pi\pi}$. $\pi\pi\gamma$ and $\mu\mu\gamma$ events are located around m_π and m_μ respectively, while $\pi^+\pi^-\pi^0$ events occupy a region in the upper left of the plot. The black lines represent the cuts used in the analysis.

This reduces the contamination effect due to contributions from $f_0\gamma$ and $\rho\pi$ decay ϕ-meson to within 1%. Contamination from the processes $\phi \to \pi^+\pi^-\pi^0$ and $e^+e^- \to \mu^+\mu^-\gamma$ are rejected cutting the kinematical variables M_{TRK} [1] (see Fig. 2) and Ω [2] (see Fig.2 left in Ref. [8]).

To efficiently suppress the high rate of radiative Bhabhas scattering events, a particle ID estimator based on calorimeter information and time-of-flight is used. The residual background content is found by fitting the M_{TRK} spectrum of the selected data sample with a superposition of Monte Carlo (MC) distributions describing the signal and background sources. The fit parameters are the fractional normalization factors for the MC distributions, obtained in intervals of $M^2_{\pi\pi}$.

Using Eq. (2.1) the pion form factor $|F_\pi|^2$ is extracted and compared with the previous published one (KLOE08), showing excellent agreement (see Fig. 3). The dipion contribution to the muon anomaly $a_\mu^{\pi\pi}$ is then extracted from the bare cross section, *i.e.* corrected for the running of electromagnetic coupling α_{em} and inclusive of FSR.

The cross section corrected for the running of α_{em} and inclusive of FSR, $\sigma^{bare}_{\pi\pi(\gamma)}$, is used to determine $\Delta a_\mu^{\pi\pi}$ via a dispersion integral:

$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3}\int_{s_{min}}^{s_{max}} \mathrm{d}s'\ \sigma^{bare}_{\pi\pi(\gamma)}(s')K(s')\ , \tag{3.1}$$

with $s_{min} = 0.10$ GeV^2 and $s_{max} = 0.85$ GeV^2 the lower and upper bounds in the present

[1]The trackmass is defined using conservation of 4-momentum under the hypothesis that the final state consists of two charged particles with equal mass M_{trk} and one photon: $(\sqrt{s} - \sqrt{|\vec{p}_+|^2 + M^2_{mtr}} - \sqrt{|\vec{p}_-|^2 + M^2_{mtr}})^2 - (\vec{p}_+ + \vec{p}_-)^2 = 0$

[2]Ω is the three-dimensional angle between the direction of the selected photon and the missing momentum.

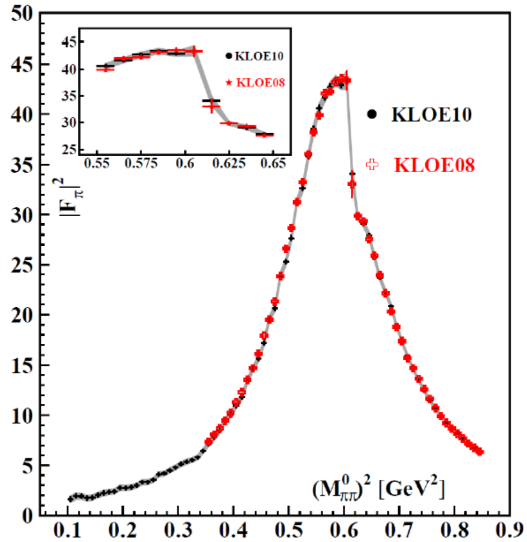

Figure 3: KLOE10 data points have statistical error attached, the grey band gives the statistical and systematic uncertainty (added in quadrature). Errors on KLOE08 points contain the combined statistical and systematic uncertainty.

Analysis	$\Delta a_\mu^{\pi\pi}(0.35 - 0.85 \text{ GeV}^2) \times 10^{-10}$
KLOE10	$376.6 \pm 0.9_{\text{stat}} \pm 2.4_{\text{exp}} \pm 2.1_{\text{theo}}$
KLOE08	$379.6 \pm 0.4_{\text{stat}} \pm 2.4_{\text{exp}} \pm 2.2_{\text{theo}}$

Table 1: Comparison between KLOE10 and KLOE08 measurements.

analysis, and $K(s)$ the kernel function described in [12]. We obtain a value [8] of:

$$\Delta a_\mu^{\pi\pi}(0.1 - 0.85 \text{ GeV}^2) = (478.5 \pm 2.0_{\text{stat}} \pm 4.8_{\text{exp}} \pm 2.9_{\text{theo}}) \cdot 10^{-10}. \tag{3.2}$$

The evaluation of $\Delta a_\mu^{\pi\pi}$ in the range between 0.35 and 0.85 GeV^2 and its comparison with KLOE08 [7] result is reported in Table 1.

The KLOE measurement has been compared with the results from e^+e^- experiments available in literature [8]. Combining the results from the two measurements one obtains:

$$a_\mu^{\pi\pi}(0.1 - 0.95 \text{ GeV}^2) = (488.6 \pm 5.0) \cdot 10^{-10}. \tag{3.3}$$

The KLOE experiment covers 70% of the leading order contribution to the muon anomaly with 1% total error.

A reasonable agreement has been found with CMD-2 and SNDexperiments at Novosibirsk [13] (especially below the ρ),while some deviation is found with respect to new BaBar measurement [14], especially above 0.65 GeV where the BaBar result is higher by 2-3%.

4. Measurement of the pion form factor from the $\pi\pi\gamma/\mu\mu\gamma$ ratio

Equation (2.2) has been used to extract the pion form factor via a bin-by-bin ratio between the observed pion and muon ISR differential cross sections. This new approach has several benefits especially radiative corrections with respect to the previous published results. The integrated luminosity as well as the radiation function H and the vacuum polarisation cancel completely in the $\pi\pi\gamma/\mu\mu\gamma$ ratio. In addition the ratio of the acceptance enters in eq. (2.2) giving corrections of the order of few percents. The additional analysis on muon events has to be performed at subpercent level, not a trivial task especially for the pion/muon separation(see Fig. 2, right). In fact, due to the ρ-resonance enhancement, the $\pi\pi$ cross section is up to one order of magnitude larger than the $\mu\mu$ cross section around 0.6 GeV^2.

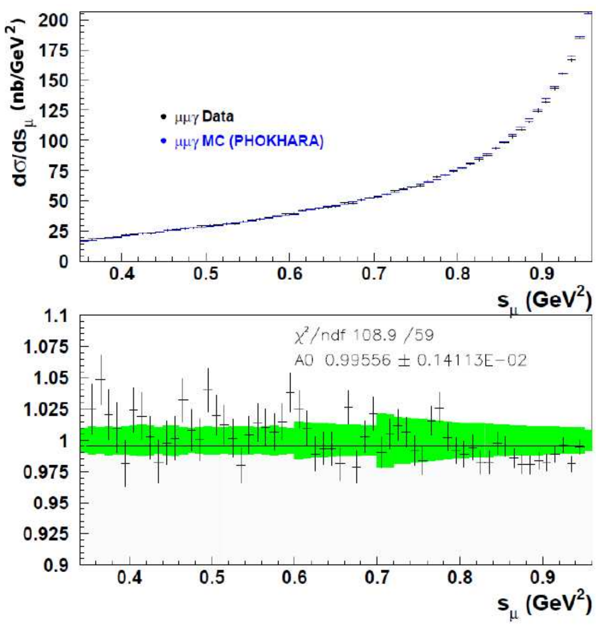

Figure 4: Up: Comparison of data (black points) and MC (blue points) of $\mu\mu\gamma$ absolute cross section; (Down) ratio of the two. The green band shows the total (experimental and theoretical) systematic error.

The same sample of pb^1 of KLOE08 measurement, is analyzed with the small angle photon selection. While the analysis for $\pi\pi\gamma$ is essentially the same as for KLOE08, the analysis for $\mu\mu\gamma$ is completely new and is based on following main features: 1) separation between $\mu\mu\gamma$ and $\pi\pi\gamma$ events realized assuming the final state of two charged particles with equal mass M_{TRK} and one photon: the $M_{TRK} < 115$ MeV ($M_{TRK} > 130$ MeV) selection leads to 9×10^5 (3.1×10^6) candidate $\mu\mu\gamma$ ($\pi\pi\gamma$) events. This selection has been checked using other techniques, such as a kinematic fit or tighter cuts on the quality of the charged tracks, all bringing to consistent results; 2) trigger, particle identification and tracking efficiencies measured with data control samples. The $\mu\mu\gamma$ cross section measurement (KLOE11 in the following) has been compared with the value estimated by using PHOKHARA MC [9], and a good agreement has been found (see Fig.4). Then the preliminary pion form factor has been extracted and compared with the one from KLOE10, showing good agreement (see Fig. 5).

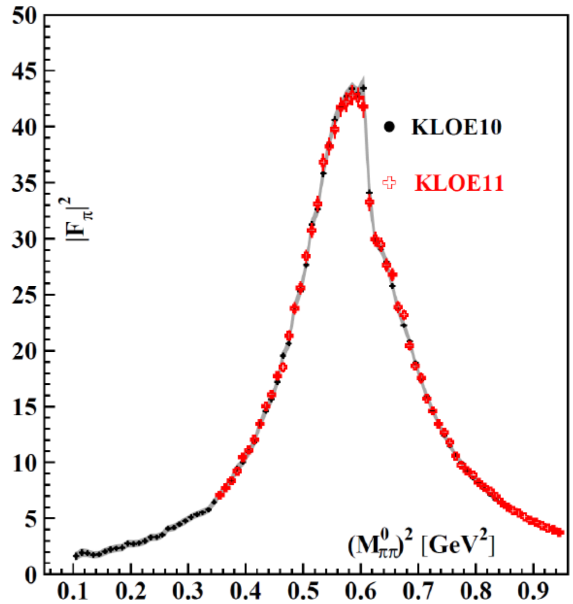

Figure 5: Pion form factor obtained by $\pi\pi\gamma/\mu\mu\gamma$ ratio (KLOE11) and the previous (KLOE10) analysis.

The preliminary value for $a_\mu^{\pi\pi}$ has been computed and compared with previous KLOE results (see Table 2). These results are in good agreement confirming the 3σ discrepancy between the experimental value and the Standard Model prediction of a_μ .

Analysis	$a_\mu^{\pi\pi}(0.35-0.85\ \mathrm{GeV}^2)\times 10^{10}$
KLOE11	$376.4\pm1.2_{\mathrm{stat}}\pm4.1_{\mathrm{sys+theo}}$
KLOE10	$376.6\pm0.9_{\mathrm{stat}}\pm3.3_{\mathrm{sys+theo}}$
	$a_\mu^{\pi\pi}(0.35-0.95\ \mathrm{GeV}^2)\times 10^{10}$
KLOE11	$384.1\pm1.2_{\mathrm{stat}}\pm4.0_{\mathrm{sys}}\pm1.2_{\mathrm{theo}}$
KLOE08	$387.2\pm0.5_{\mathrm{stat}}\pm2.4_{\mathrm{sys}}\pm2.3_{\mathrm{theo}}$

Table 2: Comparison between the new preliminary result KLOE11 and the published KLOE10 and KLOE08.

5. Conclusions

Analyzing the 239.2 pb1 KLOE data sample (the same used for the KLOE08 measurement), a preliminary evaluation of dipion cross section, pion form factor, and leading order contribution to muon anomaly by using the $\pi\pi\gamma/\mu\mu\gamma$ ratio measurement (KLOE11) has been performed and here showed. These preliminary results and the previous KLOE measurements (KLOE08 and KLOE10) are in good agreement. We also presented the evaluation of $\sigma(e^+e^- \to \mu^+\mu(\gamma))$ cross section normalized to integrated luminosity of DAΦNE showing a good agreement with the PHOKHARA MC [9] prediction. The present preliminary evaluation of hadronic leading order contribution a_μ^{hlo} confirms the about 3σ discrepancy between SM prediction and experimental measurement [2], pointing out the role of the expected future improvements in direct experimental measurement (in program at JLAB and JPARC laboratories) and in theoretical prediction of the muon anomaly (with the help of KLOE-2 and other experiments around the world) in order to solve this puzzle.

References

[1] F. Jegerlehner and A. Nyffeler,*"The Muon g-2"*, Phys. Rept. **477** (2009) 1;
M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, *"Reevaluation of the Hadronic Contributions to the Muon g-2 and to alpha(MZ)"*, Eur. Phys. J. C **71** (2011) 1515;
K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner,*"$(g-2)_m u$ and $\alpha(M_Z^2)$ re-evaluated using new precise data"*, J. Phys. G **38** (2011) 085003.

[2] G. W. Bennett *et al.* [Muon g-2 Coll.], Phys. Rev. D **73** (2006) 072003.

[3] S. Binner, J. H. Kühn and K. Melnikov, Phys. Lett. B **459**, (1999) 279;
S. Actis *et al.*, arXiv:0912.0749 [hep-ph].

[4] M. Adinolfi *et al.*, Nucl. Inst. Meth. A **488**,(2002) 51 .

[5] M. Adinolfi *et al.*, Nucl. Inst. Meth. A **482**, (2002) 364.

[6] A. Aloisio *et al.* [KLOE Coll.], Phys. Lett. B **606** (2005) 12.

[7] F. Ambrosino *et al.* [KLOE Coll.], *"Measurement of $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ and the dipion contribution to the muon anomaly with the KLOE detector"*, Phys. Lett. B **670**,(2009) 285 .

[8] F. Ambrosino *et al.* [KLOE Collaboration], *"Measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ from threshold to 0.85 GeV^2 using Initial State Radiation with the KLOE detector"*, Phys. Lett. B **700** (2011) 102.

[9] H. Czyż, A. Grzelińska,, J. Kühn, G. Rodrigo, Eur. Phys. J. C 39 (2005), 411

[10] C. Amsler *et al.*, Particle Data Group, Phys. Lett. B **667** (2008) 1.

[11] F. Ambrosino et al. [KLOE Collaboration], *" Measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ from threshold to 0.85 GeV^2 using Initial State Radiation with the KLOE detector"* Phys. Lett. B **634** (2006) 148.

[12] S. Brodsky, E. de Rafael, Phys. Rev. **174** (1968) 1835.

[13] R.R. Akhmetshin *et al.*, [CMD-2 Collaboration], Phys. Lett. B **648** (2007) 28;
R.R. Akhmetshin *et al.*, [CMD-2 Collaboration], JETP Lett. **84** (2006) 413;
M.N. Achasov *et al.*, [SND Collaboration], J. Exp. Theor. Phys. **103** (2006) 380.

[14] B. Aubert *et al.*, [BaBar Collaboration], Phys. Rev. Lett. **103** (2009) 231801