KLOE results on hadronic cross section

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Abstract. The KLOE experiment at the φ − factory DAΦNE is the first to have exploited Initial State Radiation (ISR) to precisely determine the $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ cross section below 1 GeV, representing the 70% of the leading order contribution to the muon anomaly. The leading order contribution $a^{\text{hlo}}_\mu$ is presently 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.

A persistent discrepancy of about 3σ between standard model (SM) prediction and experimental measurements of the muon anomalous magnetic moment has been up to now observed. The KLOE collaboration published two measurements of the $\pi^+\pi^-$ cross section with the photon in the initial state emitted at small polar angle in Phys. Lett. B vol. 606 pg. 12 and vol. 670 pg. 285, and an independent measurement with the photon emitted at large polar angle in Phys. Lett. B vol. 700 pg. 102. 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 $\mu^+\mu^\gamma$ final states ratio has been performed. In this paper, the preliminary results of this new measurement and the comparison to the previous published ones, the impact on the evaluation of the hadronic contribution to the muon anomaly, the preliminary $\mu^+\mu^\gamma$ cross section measurement and the comparison with the PHOKHARA-MC prediction are presented.

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1. Introduction

The anomalous magnetic moment of the muon, $a_\mu$, is one of the best known quantities in particle physics. Recent theoretical evaluations [1–3] find a discrepancy of about 3 standard deviations from the value obtained from the g-2 experiment at Brookhaven [4]. The main contribution to the uncertainty on the theoretical estimates come from the leading order hadronic contribution $a_\mu^{\text{had,lo}}$ and the hadronic light-by-light contribution $a_\mu^{\text{LbyL}}$ [5]. The $a_\mu^{\text{had,lo}}$ contribution is not calculable by perturbative QCD at low energies but it can be evaluated using measured hadronic cross sections by the dispersion integral

$$a_\mu^{\text{had}} = \frac{1}{4\pi^3} \sum_f \int_{s_{\text{th}}(f)}^\infty K(s)\sigma(e^+e^- \to f)ds,$$

where $K(s)$ is the QCD kernel function that approximately varies as $1/s$, with $s$ the squared center-of-mass collision energy, and $s_{\text{th}}(f)$ is the production threshold.

The use of Initial State Radiation (ISR) has opened a new way to measure these cross sections at particle factories operating at fixed energies [6]. The region below 1 GeV, which is accessible with the KLOE experiment, is dominated by the $\pi^+\pi^-$ final state and contributes with $\sim 70\%$ to $a_\mu^{\text{had,lo}}$, 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 $a_\mu$, and in turn to the SM prediction for $a_\mu$.

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

The KLOE detector operates at the DAΦNE $e^+e^-$ collider of the INFN Laboratori Nazionali di Frascati. It consists (Fig. 1) of a huge drift chamber providing high momentum resolution ($\sigma_p/p \leq 0.4\%$) [7] on reconstructed tracks and Pb-scintillating fibers calorimeter with excellent time ($\sigma_t \sim 54\,\text{ps}/\sqrt{E\,\text{[GeV]}} \oplus 100\,\text{ps}$) and good energy ($\sigma_E/E \sim 5.7\% / \sqrt{E\,\text{[GeV]}}$) resolution [8].

DAΦNE is a $\phi$-factory (see Fig. 2) running at $\sqrt{s} \simeq M_\phi$, and has delivered ca. 2.5 fb$^{-1}$ of integrated luminosity to the KLOE experiment. So far KLOE has reported two measurements of the $\pi^+\pi^-$ cross section between 0.35 and 0.95 GeV$^2$ called KLOE05 [9] and KLOE08 [10] in the following. In addition, about 250 pb$^{-1}$ of data have been collected at $\sqrt{s} \simeq 1$ GeV, 20 MeV below the $\phi$-meson resonance, from which a new measurement of $\pi^+\pi^-$ cross section was obtained (KLOE10 [11]). Running at energies below the $\phi$-meson resonance reduces considerably the background from the copious $\phi$-meson decay products, including scalar mesons. As DAΦNE was designed to operate at a fixed energy around $M_\phi$, the differential cross section $d\sigma(e^+e^- \to \pi^+\pi^-\gamma)/dM_{\pi\pi}^2$ is measured, and the total cross section $\sigma_{\pi\pi} \equiv \sigma_{e^+e^- \to \pi^+\pi^-}$ is evaluated using the formula [6]:

$$s \cdot \frac{d\sigma_{\pi\pi\gamma}}{dM_{\pi\pi}^2} = \sigma_{\pi\pi}(M_{\pi\pi}^2) \cdot H(M_{\pi\pi}^2, s),$$

(2)
with $s$ 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 method to extract the $\pi^+\pi^-$ cross section uses the $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio [12]:

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

(3)

with $s'$ the four-momentum square of the virtual photon, i.e. the $e^+e^-$ center-of-mass energy squared after ISR emission, $m_\mu$ the muon mass, $\beta_\mu$, $\beta_\pi$ the muon and 

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**Figure 1.** Left: Schematic view of the KLOE detector with selection regions; Right: Pion form factor $|F_\pi|^2$ obtained in KLOE10 and the previous (KLOE08) analysis.

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**Figure 2.** The DAΦNE complex.
pion velocities in the center-of-mass frame, $d\sigma_{\pi\pi\gamma}/ds'$, $d\sigma_{\mu\mu\gamma}/ds'$ the $e^+e^- \to \pi^+\pi^-\gamma$, $e^+e^- \to \mu^+\mu^-\gamma$ differential cross sections, respectively. In both Eqs.(2) and 3) the Final State Radiation (FSR) terms are neglected, but are taken into account properly in the analyses. The differential cross sections ratio in Eq. (3) allows us to completely cancel important contributions to the total uncertainty which are instead present in the measurement performed with Eq. (2), 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 beam line (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: $\vec{p}_\gamma \simeq \vec{p}_{\text{miss}} = -(\vec{p}_{\pi^+} + \vec{p}_{\pi^-})$. 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 $\pi^0$ mimics the missing momentum of the photon(s), and from the final state radiation process $e^+e^- \to \pi^+\pi^-\gamma_{\text{FSR}}$. As a consequence of the event selection, the highly energetic photon emitted at small angle forces the pions also to be also at small angles (and thus outside the selection cuts), resulting in a kinematical suppression of events with $M_{\pi\pi}^2 < 0.35$ GeV$^2$.

![Figure 3](image_url). Left: MC simulation of $M_{TRK}$ vs. $M_{\pi\pi}^2$. $\pi\pi\gamma$ and $\mu\mu\gamma$ events are located around $m_\pi$ and $m_\mu$ respectively, while $\pi^+\pi^-\pi^0$ events occupy a region in the upper left of the plot. Right: MC simulation of $\Omega$ vs. $M_{\pi\pi}^2$. The black lines represent the cuts used in the analysis.

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
in the same angular region as the pions. 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 $\phi$ radiative decays compared to the small polar angle photon acceptance criterion. The model dependence of the $\phi$ radiative decays to the $f_0(980)$ and $f_0(600)$ scalars together with $\phi \rightarrow \rho \pi \rightarrow (\pi \gamma)\pi$, has a strong impact on the measurement [13]. To significantly reduce the contamination from $f_0 \gamma$ and $\rho \pi$ decays of the $\phi$-meson, data were taken at $\sqrt{s} = 1$ GeV below $M_\phi$ of about 5 times the $\phi$-meson decay width ($\Gamma_\phi = 4.26 \pm 0.04$ MeV [14]) outside the narrow peak of the $\phi$ resonance.

This reduces the contamination effect due to contributions from $f_0 \gamma$ and $\rho \pi$ decay $\phi$-meson to within 1%. Contamination from the processes $\phi \rightarrow \pi^+ \pi^- \pi^0$ and $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$ are rejected cutting the kinematical variables trackmass $M_{TRK}$ (see Fig. 3 Left) and $\Omega^2$ (see Fig. 3 Right). 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: $(\sqrt{s} - |\vec{p}_+|^2 + M_{trk}^2)^2 - (|\vec{p}_-|^2 + M_{trk}^2)^2 = 0$. The $\Omega$ variable is the angle between the directions of the detected photon and the reconstructed missing momentum $\vec{p}_{miss}$.

To efficiently suppress the high rate of radiative Bhabha scattering events, a identification particle estimator based on calorimeter information and time-of-flight is used. The residual background content is found by fitting the $M_{TRK}$ spectrum (see 5) of the selected data sample with a superposition of Monte Carlo (MC) distributions.

Figure 4. Pion form factor obtained with KLOE08 and KLOE10 analysis data points include statistical errors, the grey band shows the statistical and systematic uncertainties added in quadrature. KLOE08 points include the combined statistical and systematic uncertainties.
The fit parameters are the fractional normalization factors for the MC distributions, obtained in intervals of $M^2_{\pi\pi}$(see Fig. 5).

Using Eq. (2) the pion form factor $|F_\pi|^2$ is extracted and compared with the previous published one (KLOE08), showing excellent agreement (see Fig. 4). 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 $\alpha_{em}$ and inclusive of FSR.

The bare cross section $\sigma_{bare}^{\pi\pi(\gamma)}$ is used to determine $a_{\mu}^{\pi\pi}$ via a dispersion integral:

$$a_{\mu}^{\pi\pi} = \frac{1}{4\pi^3} \int_{s_{\text{min}}}^{s_{\text{max}}} d s' \sigma_{bare}^{\pi\pi(\gamma)}(s') K(s') ,$$

with $s_{\text{min}} = 0.10$ GeV$^2$ and $s_{\text{max}} = 0.85$ GeV$^2$ the lower and upper bounds in the present analysis, and $K(s)$ the kernel function described in [15].

The final results [11]:

$$\Delta a_{\mu}^{\pi\pi}(0.1 - 0.85 \text{ GeV}^2) = (478.5 \pm 2\text{.0}_{\text{stat}} \pm 4.8_{\text{exp}} \pm 2.9_{\text{theo}}) \times 10^{-10} .$$

(5)

The evaluation of $\Delta a_{\mu}^{\pi\pi}$ in the range between 0.35 and 0.85 GeV$^2$ and its comparison with KLOE08 [10] result is reported in Table 1.

Combining the results from the KLOE measurements one obtains:

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

(6)

The KLOE experiment covers 70% of the leading order contribution to the muon anomaly with 1% total error.
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Analysis $\Delta \sigma_{\mu}(0.35 - 0.85 \text{ GeV}^2) \times 10^{-10}$

|        | KLOE10       | KLOE08       |
|--------|--------------|--------------|
|        | $376.6 \pm 0.9_{\text{stat}} \pm 2.4_{\text{exp}} \pm 2.1_{\text{theo}}$ | $379.6 \pm 0.4_{\text{stat}} \pm 2.4_{\text{exp}} \pm 2.2_{\text{theo}}$ |

Table 1. Comparison between KLOE10 and KLOE08 measurements.

The KLOE measurement has been compared with the results from $e^+e^-$ experiments available in literature [11]. A reasonable agreement has been found with CMD-2 and SND experiments at Novosibirsk [16–18] (especially below the $\rho$), while some deviation is found with respect to new BaBar measurement [19], especially above 0.65 GeV where the BaBar result is higher by 2-3% (see Fig. 6).

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

Equation (3) 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 for 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. (3) 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. 7 (a)). In fact, due to the $\rho$-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$^2$ (see Fig. 7 (b)).

239.2 pb$^{-1}$ KLOE data, the same sample used for 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

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**Figure 7.** (a) Discrimination of the $\mu\mu\gamma$ (filled left histogram) from the $\pi\pi\gamma$ (filled right histogram) events on the $M_{TRK}$ variable. (b) $\pi^+\pi^-$ and $\mu^+\mu^-$ cross-section as a function of $s$.

**Figure 8.** Top: comparison of data (black points) and MC (blue points) for the $\mu\mu\gamma$ absolute cross section as a function of $M^2_{\mu\mu}$ (GeV). Bottom: data to MC ratio. The green band shows the total experimental and theoretical systematic error.
main features: 1) separation between $\mu\mu\gamma$ and $\pi\pi\gamma$ events performed 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 $9 \times 10^5$ (3.1 $\times 10^6$) candidate $\mu\mu\gamma$ ($\pi\pi\gamma$) events. This selection, KLOE11 in the following, has been checked using other techniques, such as a kinematic fit or tighter cuts on the quality of the charged tracks, all giving to consistent results; 2) trigger, particle identification and tracking efficiencies measured with data control samples.

![Figure 9. Pion form factor obtained with $\pi\pi\gamma/\mu\mu\gamma$ ratio (KLOE11) compared to the previous (KLOE10) analysis.](image)

The $\mu\mu\gamma$ cross section measurement has been performed by subtracting the residual background to the observed spectra and dividing it for the selection efficiency and integrated luminosity. The luminosity was evaluated by using large Bhabha events to be $239.2 \text{ pb}^{-1}$, with a systematic error of 0.3 %[20]. This preliminary result was compared with the value estimated by using PHOKHARA MC [12], and a good agreement within the total (theoretical and experimental) systematic error has been found (Fig. 8). Then a preliminary result on the pion form factor has been extracted and compared with the one from KLOE10, showing good agreement (see Fig. 9). As a consequence of the comparison reported in Figure 4 we can deduce it is also in good agreement with KLOE08 measurement. The new measurement represents an important check of previous measurements, because this last one does not rely on the value of the integrated luminosity and on the radiator knowledge.

The preliminary value for $a^{\pi\pi}_\mu$ has been computed and compared with previous KLOE results (see Table 2). These results are consistent with the previous estimation
5. Conclusions

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, analyzing the 239.2 pb$^{-1}$ KLOE data. The comparison of this preliminary measurement with the previous KLOE08\cite{10} and KLOE10\cite{11} showed a good agreement and represents a powerful check, the $\pi\pi\gamma/\mu\mu\gamma$ result not depending on the integrated luminosity and on the radiator function knowledge. We also presented the evaluation of $\sigma(e^+e^- \rightarrow \mu^+\mu(\gamma))$ normalized to integrated luminosity showing a good agreement with the PHOKHARA MC \cite{12} prediction. The present preliminary evaluation of hadronic leading order contribution $a_{\mu}^{\text{hlo}}$ confirms the $3\sigma$ discrepancy between SM prediction and experimental measurement \cite{4}. This result remarks the relevance not only of the expected future improvements on the experimental measurements of the muon anomaly, in program at JLAB and JPARC laboratories, but also of its theoretical prediction through the $\pi^+\pi^-$ cross section measurement, with the contribution of the KLOE-2 experiment\cite{5,21,22} for the $a_{\mu}^{\text{hlo}}$ contribution. KLOE-2 will also contribute to the reduction of the $a_{\mu}$ uncertainty from the hadronic light-by-light contribution\cite{5}.

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