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A new measurement of $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$ from the $\pi\pi\gamma/\mu\mu\gamma$ ratio and determination of the $\pi\pi$ contribution to the muon anomaly with KLOE

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The KLOE experiment at the $\phi - factory$ DAΦNE in Frascati (near Rome) is the first to have employed Initial State Radiation (ISR) to precisely determine the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section below 1 GeV. Such a measurement is particularly important to test the Standard Model (SM) calculation for the $(g-2)$ of the muon, where a long standing 3σ discrepancy is observed.
In 2005 and 2008 KLOE published two measurements of the $\pi^+\pi^-$ cross section with the photon emitted at small angle, and an independent measurement of the $\pi^+\pi^-$ cross section with the photon emitted at large angle using data at a collision energy of 1 GeV (*i.e.* 20 MeV below the ϕ-peak) was published this year. While the previous measurements were normalized to the DAΦNE luminosity using large angle Bhabha scattering, a new analysis has been performed which derives the pion form factor directly from measuring the bin-by-bin $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio. We present the final result of this new measurement, as well as the previous published ones, and the impact on the evaluation of the hadronic contribution to the muon anomaly.

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1. Introduction

The anomalous magnetic moment of the muon, a_μ, 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 $a_\mu^{\rm had,lo}$, which at low energies is not calculable by perturbative QCD, but has to be evaluated with a dispersion integral using measured hadronic cross sections. The use of initial state radiation (ISR) has opened a new way to obtain 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, improved precision in 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

The KLOE detector operates at the DAΦNE e^+e^- collider in Frascati. It consists (Fig. 1, left) of a high resolution drift chamber ($\sigma_p/p \leq 0.4\%$) [4] and an electromagnetic 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 data to the KLOE experiment up to the year 2006, from which 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 was obtained (KLOE10 [8]). Running below the ϕ resonance reduces the backgrounds from the copious ϕ 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 is the squared e^+e^- center of mass energy, and H is a 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 [10]:

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

where s' is the four-momentum square of the virtual photon, *i.e. the* e^+e^-*center-of-mass energy squared after ISR emission*, m_μ is the muon mass, β_μ, β_π are the muon and pion velocities in the center-of-mass frame, $\mathrm{d}\sigma_{\pi\pi\gamma}/\mathrm{d}s'$, $\mathrm{d}\sigma_{\mu\mu\gamma}/\mathrm{d}s'$ are the $e^+e^- \to \pi^+\pi^-\gamma$, $e^+e^- \to \mu^+\mu^-\gamma$ differential cross sections. In both Eqs.(2.1), (2.2) Final State Radiation (FSR) terms are neglected, but are taken into account properly in the analyses. In Eq. (2.2) the integrated luminosity as well as the radiation function H cancel completely in the ratio, as does the vacuum polarisation.

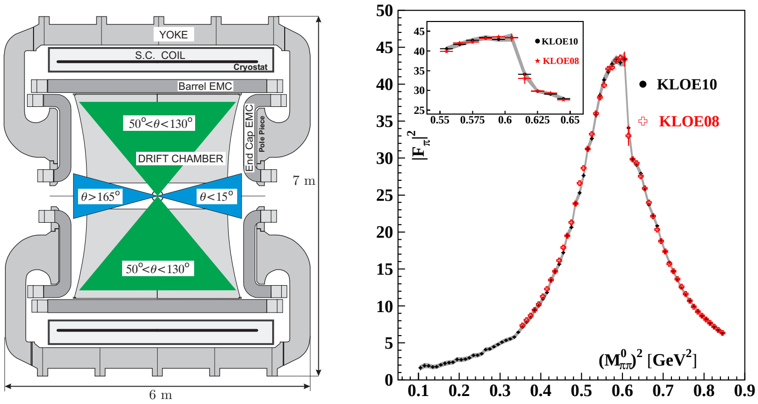


Figure 1: Left: Schematic view of the KLOE detector with selection regions; Right: Pion form factor $|F_\pi|^2$ obtained in KLOE10 and the previous (KLOE08) analysis.

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, left) and the two charged pion tracks have $50^\circ < \theta_\pi < 130^\circ$ (wide cones in Fig. 1, left). In this configuration, the photon is not explicitly detected, its direction is reconstructed from the tracks' momenta by closing kinematics: $\vec{p}_\gamma \simeq \vec{p}_{\rm miss} = -(\vec{p}_{\pi^+} + \vec{p}_{\pi^-})$. While 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 $e^+e^- \to \pi^+\pi^-\gamma_{\rm FSR}$, a 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 that are selected to have a photon at large polar angles between $50^\circ < \theta_\gamma < 130^\circ$ (wide cones in Fig. 1, left), 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 Γ_ϕ outside the narrow peak of the ϕ resonance. 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. 1, right). From the *bare* cross section, *i.e.* corrected for the running of α_{em} and inclusive of FSR, the dipion contribution to the muon anomaly $a_\mu^{\pi\pi}$ is extracted. Combining the results from the two measurements one obtains:

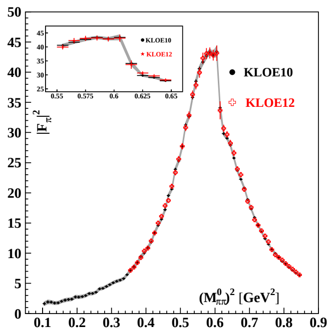
$$a_\mu^{\pi\pi}(0.1 - 0.95\ {\rm GeV}^2) = (488.6 \pm 5.0) \cdot 10^{-10}. \tag{3.1}$$

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

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 [9]. The same sample of 239.2 pb^{1}

of KLOE08, 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 brandly new and is based on following main features: 1) separation between $\mu\mu\gamma$ and $\pi\pi\gamma$ events obtained 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 is checked against other techniques, such as a kinematic fit or tighter cuts on the quality of the charged tracks, all providing consistent results; 2) trigger, particle identification and tracking efficiencies checked from data control samples. The $\mu\mu\gamma$ cross section measurement is compared with the one obtained by PHOKHARA MC [10], and a good agreement has been found [9]. Then the pion form factor (KLOE12 in the following) has been extracted and compared with the one from KLOE10, showing good agreement (see Fig. 2). The value for $a_\mu^{\pi\pi}$ is computed and compared with previous KLOE results (see Table below). These results are in good agreement confirming the 3σ discrepancy between the experimental value and the Standard Model prediction of a_μ.



Analysis	$a_\mu^{\pi\pi}(0.35-0.85\ \text{GeV}^2) \times 10^{10}$
KLOE12	$377.4 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys+theo}}$
KLOE10	$376.6 \pm 0.9_{\text{stat}} \pm 3.3_{\text{sys+theo}}$
	$a_\mu^{\pi\pi}(0.35-0.95\ \text{GeV}^2) \times 10^{10}$
KLOE12	$385.1 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys+theo}}$
KLOE08	$387.2 \pm 0.5_{\text{stat}} \pm 3.3_{\text{sys+theo}}$

Figure 2: Left: Pion form factor $|F_\pi|^2$ obtained by $\pi\pi\gamma/\mu\mu\gamma$ ratio (KLOE12) and the previous (KLOE10) indipendent analysis. Right: Comparison of $a_\mu^{\pi\pi}$ between KLOE12 and the previous KLOE analyses.

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