MEASUREMENT OF HADRONIC CROSS SECTION AT KLOE/KLOE-2*

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The measurement of the $\sigma(e^+e^- \to \pi^+\pi^-)$ cross section allows to determine the pion form factor $|F_\pi|^2$ and the two-pion contribution to the muon anomaly a_μ. Such a measurement has been performed with the KLOE detector at DAΦNE, the Frascati ϕ-factory. The preliminary results on the combination of the last analysis (KLOE12) with two previous published (KLOE08, KLOE10) will be presented in the following.

1. Introduction

The anomalous magnetic moment of the muon defined as $a_\mu \equiv \frac{g_\mu - 2}{2}$, can be accurately measured and, within the SM framework, precisely predicted [1]. The experimental value of a_μ ($(11659208.9 \pm 6.3) \times 10^{-10}$) measured at the Brookhaven Laboratory differs from the SM estimates by 3.2–3.6σ [2]. If the deviation is confirmed with higher precision, it would signal of new physics.

The main theoretical uncertainty for a_μ comes from hadronic contributions. The leading order hadronic term can be derived from a combination of experimental cross section data, related to e^+e^- annihilation to hadrons.

At DAΦNE, the differential cross section (as a function of $m_{\pi\pi}$) for the $e^+e^- \to \pi^+\pi^-\gamma$ initial state radiation (ISR) process is measured. Then, the dipion cross section $\sigma_{\pi\pi} \equiv \sigma(e^+e^- \to \pi^+\pi^-)$ has been obtained from

$$s \frac{d\sigma(\pi^+\pi^-\gamma)}{ds_\pi}\bigg|_{\text{ISR}} = \sigma_{\pi\pi}(s_\pi) H(s_\pi, s) , \tag{1}$$

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where the radiator function H is computed from QED with complete NLO corrections and depends on the initial e^+e^- center-of-mass energy squared s. The dipion cross section $\sigma_{\pi\pi}$ obtained from Eq. (1) requires the correction for final state radiation (FSR). Equation (1) is also valid for the $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \mu^+\mu^-$ processes with the same radiator function H. Thus, we can determine $\sigma_{\pi\pi}$ from the ratio of the $\pi^+\pi^-\gamma$ and $\mu^+\mu^-\gamma$ differential cross sections for the same value of the dipion and dimuon invariant mass.

The pion form factor can then be determined using the following equation

$$\left| F_\pi \left(s' \right) \right|^2 = \frac{3}{\pi} \frac{s'}{\alpha^2 \beta_\pi^3} \sigma_{\pi\pi(\gamma)}^0 \left(s' \right) \left(1 + \delta_{\mathrm{VP}} \right) \left(1 - \eta_\pi \left(s' \right) \right) , \qquad (2)$$

where δ_{VP} is the Vacuum Polarization (VP) correction, η_π accounts for the FSR radiation assuming point-like pions. $\sigma_{\pi\pi}^0$ is a bare cross section, *i.e.* corrected for the running of α_{em} and inclusive of FSR, defined as [6]

$$\sigma^0 \left(\pi^+\pi^-, s' \right) = \frac{d\sigma \left(\pi^+\pi^-\gamma, \mathrm{ISR} \right) / ds'}{d\sigma \left(\mu^+\mu^-\gamma, \mathrm{ISR} \right) / ds'} \times \sigma^0 \left(e^+e^- \to \mu^+\mu^-\gamma, s' \right) , \qquad (3)$$

where $s' = s_\pi = s_\mu$.

Many radiative corrections drop out for this ratio method: contributions due to the radiator function (this allows to suppress the related systematic uncertainty of 0.5% for the direct $\sigma_{\pi\pi}$ measurement), to the integrated luminosity (since the data for the $\pi^+\pi^-\gamma$ and $\mu^+\mu^-\gamma$ processes are collected simultaneously) and, finally, to the vacuum polarization.

2. Measurement of the $e^+e^- \to \pi^+\pi^-$ cross section at KLOE

In the 2008 and 2010, two analyses of the $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ have been performed at DAΦNE with the KLOE detector.

A cross section of the detector in the y, z plane is shown in Fig. 1.

The KLOE08 analysis [7] used a data sample corresponding to an integrated luminosity of 240 pb^{-1} collected at $\sqrt{s} = m_\phi$ in 2002 and selection cuts in which the photon is emitted within a cone of $\theta_\gamma < 15°$ around the beamline (narrow cones in Fig. 1) and the two charged pion tracks have $50° < \theta_\pi < 130°$ (wide cones in Fig. 1). In this configuration, the photon is not detected and the photon momentum is reconstructed from missing momentum: $\vec{p_\gamma} \simeq \vec{p_{\mathrm{miss}}} = -(\vec{p_+} + \vec{p_-})$. These selection cuts provide high statistics data sample for the ISR signal events, and significantly reduce contamination from the resonant process $e^+e^- \to \phi \to \pi^+\pi^-\pi^0$.

From the bare cross section, the dipion contribution to the muon anomaly $\Delta^{\pi\pi} a_\mu$ is measured

$$\Delta^{\pi\pi} a_\mu (0.592 < M_{\pi\pi} < 0.975 \text{ GeV}) = (387.2 \pm 3.3) \times 10^{-10} .$$
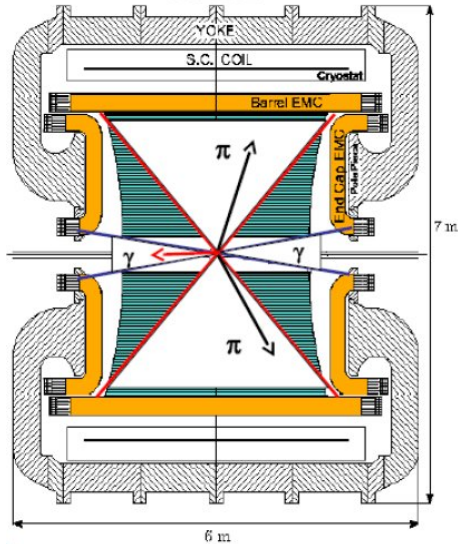
Fig. 1. Schematic view of the KLOE detector with selection regions.

The KLOE10 analysis [8] was performed requiring events that are selected to have a photon at large polar angles between $50° < \theta_\gamma < 130°$ (wide cones in Fig. 1), in the same angular region as the pions.

This selection allows to access the two-pion threshold. However, compared to the measurement with photons at small angles, this condition reduces statistics and increases the background from the process $\phi \to \pi^+\pi^-\pi^0$. The dispersion integral for $\Delta^{\pi\pi}a_\mu$ is computed as the sum of the values for $\sigma^0_{\pi\pi(\gamma)}$ times the kernel $K(s)$, times $\Delta s = 0.01$ GeV^2

$$\Delta^{\pi\pi}a_\mu = \frac{1}{4\pi^3} \int_{s_{\min}}^{s_{\max}} ds\, \sigma^0_{\pi\pi(\gamma)}(s)K(s)\,. \tag{4}$$

The following value for the dipion contribution to the muon anomaly $\Delta^{\pi\pi}a_\mu$ was found

$$\Delta^{\pi\pi}a_\mu(0.1\text{--}0.85)\ \text{GeV}^2 = (478.5 \pm 2.0_{\text{stat}} \pm 5.0_{\text{exp}} \pm 4.5_{\text{theor}}) \times 10^{-10}\,.$$

The last KLOE measurement of the $e^+e^- \to \pi^+\pi^-$ cross section (KLOE12) has been obtained from the ratio between the pion and muon ISR differential cross section. The data sample is the same as for the KLOE08 analysis. The separation between the $\pi\pi\gamma$ and $\mu\mu\gamma$ events is obtained

assuming the final state with two charged particles with equal mass M_{TRK} and one photon. The $M_{\mathrm{TRK}} < 115$ MeV identifies the muons and $M_{\mathrm{TRK}} > 130$ MeV the pions.

The selection procedure has been compared to other techniques, such as a kinematic fit or applying a quality cut on the helix fit for both tracks, all leading to consistent results.

Trigger, particle identification and tracking efficiencies have been checked using control data samples.

The differential $\mu\mu\gamma$ cross section is obtained from the observed event count N_{obs} and background estimate N_{bkg}, as

$$\frac{d\sigma_{\mu\mu\gamma}}{ds_\mu} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\Delta s_\mu} \frac{1}{\epsilon(s_\mu)L} \, , \tag{5}$$

where L is the integrated luminosity from Ref. [9] and $\epsilon(s_\mu)$ the selection efficiency. The bare cross section $\sigma^0_{\pi\pi(\gamma)}$ (inclusive of FSR, with VP effects removed) is obtained from the bin-by-bin ratio of the KLOE08 $\pi\pi\gamma$ and the described above $\mu\mu\gamma$ differential cross sections. The bare cross section is used in the dispersion integral to compute $\Delta^{\pi\pi}a_\mu$. The pion form factor $|F_\pi|^2$ is extracted using Eq. (2).

Equation (4) gives $\Delta^{\pi\pi}a_\mu = (385.1 \pm 1.1_{\mathrm{stat}} \pm 2.6_{\mathrm{exp}} \pm 0.8_{\mathrm{theor}}) \times 10^{-10}$ in the interval $0.35 < M_{\pi\pi}^2 < 0.95$ GeV^2. For each bin contributing to the integral, statistical errors are combined in quadrature and systematic errors are added linearly.

The last three KLOE estimations on the $\Delta^{\pi\pi}a_\mu$ (KLOE08, KLOE10, KLOE12) have been compared and are consistent (as one can see in Table I).

TABLE I

Comparison of $\Delta^{\pi\pi}a_\mu$ between the KLOE12 and the previous KLOE measurements (KLOE08, KLOE10).

Measurement	$\Delta a_\mu^{\pi\pi}\left(0.35\text{--}0.95 \text{ GeV}^2\right) \times 10^{10}$
KLOE12	$385.1 \pm 1.1_{\mathrm{stat}} \pm 2.7_{\mathrm{syst+theor}}$
KLOE08	$387.2 \pm 0.5_{\mathrm{stat}} \pm 3.3_{\mathrm{syts+theor}}$
	$\Delta a_\mu^{\pi\pi}\left(0.35\text{--}0.85 \text{ GeV}^2\right) \times 10^{10}$
KLOE12	$377.4 \pm 1.1_{\mathrm{stat}} \pm 2.7_{\mathrm{syst+theor}}$
KLOE10	$376.6 \pm 0.9_{\mathrm{stat}} \pm 3.3_{\mathrm{syst+theor}}$

The preliminary combination of these KLOE results is reported in figure 2 [10]. It is obtained using the Best Linear Unbiased Estimate (BLUE) method [11, 12]. In Fig. 2 (left), the pion form factor measurements for the

three KLOE analysis and the fractional difference (right) are shown [10]. The cross section ratio method used in the KLOE12 measurement reduces significantly the theoretical and the systematic error.

The following $a_{\pi\pi}^\mu$ values are found:

$$a_{\pi\pi}^\mu\left(0.1\text{–}0.95\ \text{GeV}^2\right) = (487.8 \pm 5.7) \times 10^{-10},$$
$$a_{\pi\pi}^\mu\left(0.1\text{–}0.85\ \text{GeV}^2\right) = (378.1 \pm 2.8) \times 10^{-10}.$$

$$\frac{|F_{\text{KLOEXX}}|^2 - |F_{\text{BLUE}}|^2}{|F_{\text{BLUE}}|^2}.$$
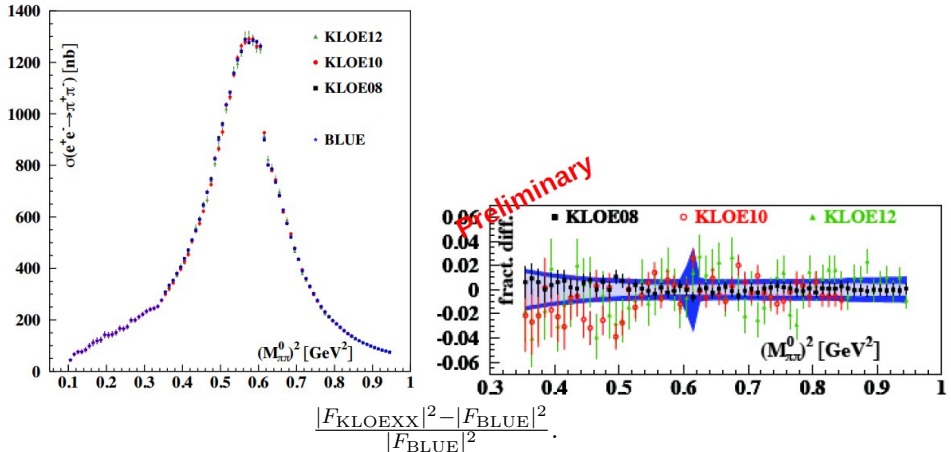
Fig. 2. Preliminary combination of the last three KLOE results (KLOE08, KLOE10, KLOE12) on the pion form factor measurements (left) and the fractional difference (right) using the Best Linear Unbiased Estimate (BLUE) method [11, 12]. The light gray/blue band in the fractional difference is the statistical error and the dark gray/blue band is the combined statistical and systematic uncertainty [10].

3. Conclusion

Precision measurements of the pion vector form factor using the Initial State Radiation (ISR) have been performed by the KLOE/KLOE-2 Collaboration during the last 10 years. The preliminary consolidation of the last analysis (KLOE12) with two previously published (KLOE08, KLOE10) ones has been presented. The result confirms the current discrepancy ($\sim 3\sigma$) between the Standard Model (SM) calculation and the experimental value of the muon anomaly a_μ measured at BNL. In the near future, the $\gamma\gamma$ Physics program of the KLOE-2 experiment [13] will further shed light in this field, with *e.g.* the study of the radiative width of pseudoscalar mesons and of the transition form factors [14], thanks to the luminosity upgrade of DAΦNE and the KLOE upgrade with the addition of new detectors: low energy [15] and high energy [16] e^+e^- taggers, an inner tracker [17], crystal calorimeters (CCALT) [18], and tile calorimeters (QCALT) [19].

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