Results on Hadronic cross sections at KLOE

V. De Leo[1)] (on behalf of the KLOE and KLOE-2 Collaborations)

[1] INFN Sezione di Roma Tre

Abstract: The precise determination of the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section is particularly important to evaluate the hadronic loop contribution to the SM calculation of the muon $(g-2)$, where a long standing 3σ discrepancy with the direct experimental determination is observed. The KLOE experiment studied the production of $\pi^+\pi^-$ in the ISR channel and published three measurements (in 2005, 2008 and 2012) of the $\pi^+\pi^-$ cross section with the ISR photon emitted at small angles and an independent measurement (in 2010) with the ISR photon emitted al large angles and using data at a collision energy of 1 GeV. The combination of the last analysis (KLOE12) with two previous published (KLOE08, KLOE10) together with the preliminary fit by using the Gounaris-Sakurai model will be presented in the following.

Key words: Muon anomaly, Initial state radiation, pion form factor.

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1 Introduction

The theoretical evaluations of the muon anomaly, $a_\mu = (g_\mu - 2)/2$, find a discrepancy of about 3 standard deviations from the measurements performed at the Brookhaven Laboratory that have reached an accuracy of 0.54 ppm: $a_\mu = (11659208.9 \pm 6.3) \times 10^{-10}$[1].
A large part of the uncertainty on the theoretical estimates comes from the leading order hadronic contribution $a_\mu^{had,lo}$, which at low energies is not calculable by perturbative QCD, but has to be evaluated with a dispersion integral using the measured hadronic cross sections:

$$a_\mu^{Had}[LO] = \frac{1}{3}\left(\frac{a}{\pi}\right)^2 \int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s). \qquad (1)$$

$K(s)$ is a QED kernel function [2] and $R(s)$ is referred to the ratio of the cross section for e^+e^- annihilation into hadrons to the pointlike muon-pair cross section at center of mass energy $\sqrt{s}$. The region below 1 GeV is dominated by the $\pi^+\pi^-$ final state and contributes with $\approx 70\%$ to $a_\mu^{had,lo}$, and $\approx 60\%$ to its uncertainty. Therefore, improved precision in the dipion cross section would result in a reduction of the uncertainty on the LO hadronic contribution to a_μ, and in turn to the SM prediction for a_μ. This energy region is accessible with the KLOE experiment in Frascati by exploiting the ISR process.

2 KLOE detector

The KLOE detector operates at $DA\Phi NE$, the Frascati ϕ-factory, an e^+e^- collider running at fixed energy, $W = \sqrt{s} \sim 1020\,\mathrm{MeV}$, the ϕ meson mass. It consists of a cylindrical drift chamber (DC) [3] and a calorimeter (EMC) [4]. The DC has a momentum resolution of $\sigma_{p_\perp}/p_\perp \sim 0.4\%$ for tracks with polar angle $\theta > 45°$. Track points are measured in the DC with a resolution in $r-\phi$ of $\sim$ 0.15 mm and $\sim$ 2 mm in z. The EMC has an energy resolution of $\sigma_E/E \sim 5.7\%/\sqrt{E}(\mathrm{GeV})$ and an excellent time resolution of $\sigma_t \sim 54\mathrm{ps}/\sqrt{E}(\mathrm{GeV}) \oplus 100$ ps.

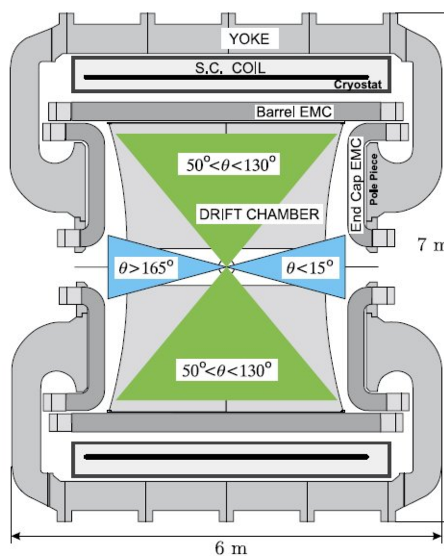

Fig. 1. Vertical cross section of the KLOE detector, showing the small and large angle regions where respectively photons and pions (or muons) are accepted.

Calorimeter clusters are reconstructed grouping together energy deposits close in space and time. A superconducting coil provides an axial magnetic field of 0.52 T along the colliding beam direction, which is taken as

1) E-mail: veronica.deleo@roma3.infn.it

the z axis of our coordinate system. The x axis is horizontal, pointing to the center of the collider rings and the y axis is vertical, directed upwards. A cross section of the detector in the y, z plane is shown in Fig. 1.

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

The differential cross section measured at KLOE is evaluated using the following relation:

$$s\frac{d\sigma(\pi^+\pi^-\gamma)}{d\sigma_\pi}|_{ISR} = \sigma_{\pi\pi}(s_\pi)H(s_\pi, s), \qquad (2)$$

where the radiator function H is computed from QED with complete NLO corrections and depends on the e^+e^- center of mass energy squared s. $\sigma_{\pi\pi}$ obtained from Eq. (2) requires accounting for final state radiation (FSR).

In the 2008 and 2012 KLOE measurements a data sample of integrated luminosity of 240 pb^{-1} collected in 2002 was used. In both analyses the "small photon" selection is chosen. Such selection requires two tracks of opposite sign with $50^\circ < \theta_\pi < 130^\circ$ (wide cones in Fig. 1) and a missing photon emitted within a cone of $\theta_\gamma < 15^\circ$ around the beamline (narrow cones in Fig. 1). Since the photon is not explicitly detected, its momentum has to be reconstructed from kinematics: $\vec{p_\gamma} \simeq \vec{p_{miss}} = -(\vec{p_+} + \vec{p_-})$. However, although these cuts guarantee a high statistics for ISR signal events, and a reduced contamination both from the resonant process $e^+e^- \to \pi^+\pi^-\pi^0$ in which the π^0 mimics the missing momentum of the photon(s) and from the final state radiation process $e^+e^- \to \pi^+\pi^-\gamma_{FSR}$, 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. Using Eq. (2) the pion form factor $|F_\pi|^2$ is extracted. 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 $\Delta^{\pi\pi}a_\mu$ is measured:

$\Delta^{\pi\pi}a_\mu(0.35 < M^2_{\pi\pi} < 0.95\, GeV^2) = (387.2 \pm 0.5_{stat} \pm 2.4_{sys} \pm 2.3_{th}) \times 10^{-10}$.

To access the two pion threshold, in 2010 the KLOE collaboration performed an analysis 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. The 140 pb^{-1} data sample has been collected at CM energy $\sqrt{s}$=1 GeV in order to significantly reduce the contamination from the $f_0\gamma$ and $\rho\pi$ decays of the ϕ-meson. On the other hand, this selection results in a reduction in statistics and an increase of the background from the process $\phi \to \pi^+\pi^-\pi^0$. The following value for the dipion contribution to the muon anomaly $\Delta^{\pi\pi}a_\mu$ was found:

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

In the last KLOE measurement (KLOE12) the $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ ratio is used to extract the dipion cross section. Eq. (2) infact, is also valid for $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \mu^+\mu^-$ with the same radiator function H. The pion form factor is calculated by:

$$|F_\pi(s')|^2 = \frac{3}{\pi}\frac{s'}{\alpha^2\beta^3_\pi}\sigma^0_{\pi\pi(\gamma)}(s')(1+\delta_{VP})(1-\eta_\pi(s')) \qquad (3)$$

where δ_{VP} is the Vacuum Polarization (VP) correction , η_π accounts for FSR radiation assuming point-like pions and $\sigma^0_{\pi\pi}$ is the bare cross section defined as [5]

$\sigma^0(\pi^+\pi^-, s') =$

$$\frac{d\sigma(\pi^+\pi^-\gamma, ISR)/ds'}{d\sigma(\mu^+\mu^-\gamma, ISR)/ds'} \times \sigma^0(e^+e^- \to \mu^+\mu^-\gamma, s') \qquad (4)$$

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

As said before, the data sample used is the same of 2008 analysis.

However, while the analysis for $\pi\pi\gamma$ is essentially the same as for KLOE08, some new elements have been introduced in the $\mu\mu\gamma$ analysis. First of all the separation between the $\pi\pi\gamma$ and $\mu\mu\gamma$ events is obtained by using the track mass variable (M_{TRK}), calculated from the energy and momentum conservation laws, with the following conditions: $M_{TRK} < 115$ MeV for the muons and $M_{TRK} > 130$ MeV for the pions.

This selection has been cross checked using a kinematic fit or applying a quality cut on the helix fit for both $\pi - \mu$ tracks. Consistent results have been obtained with all methods.

The differential $\mu\mu\gamma$ cross section is obtained from the observed number of events N_{obs}, after subtracting the residual background N_{bkg} and dividing for the selection efficiency ($\epsilon(s_\mu)$) and luminosity (L), as:

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

The result on the measured $\mu\mu\gamma$ cross section was compared with the QED calculations to NLO made by the MC code Phokhara [6] and a very good agreement was found within the quoted systematic uncertainties [5].

Then, 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 $\pi\pi\gamma$ and $\mu\mu\gamma$ differential cross sections described above. This cross section is used in the dispersion integral to compute $\Delta^{\pi\pi}a_\mu$. The pion form factor $|F_\pi|^2$ is then calculated using Eq. (3).

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:

$$\Delta^{\pi\pi}a_\mu = \frac{1}{4\pi^3}\int_{s_{min}}^{s_{max}} ds\, \sigma^0_{\pi\pi(\gamma)}(s)K(s) \qquad (6)$$

where the kernel is given in Ref. [7]. Eq. (6) gives $\Delta^{\pi\pi}a_\mu = (385.1 \pm 1.1_{stat} \pm 2.6_{exp} \pm 0.8_{th}) \times 10^{-10}$ in the interval $0.35 < M^2_{\pi\pi} < 0.95$ GeV^2. For each bin contributing to the integral, statistical errors are combined in quadrature and systematic errors are added linearly.

4 Comparison between the KLOE measurements and the results from other experiments

Comparing the results of the KLOE12 and KLOE08 analyses it is possible to see that they are in good agreement, in particular in the ρ mass region (see Fig. 2). Since the KLOE12 result on the pion form factor was determined using the ratio of the dipion and dimuon cross sections, measured with the same data set, the radiator H function is not used, the luminosity of the sample cancels out and the acceptance corrections compensate, resulting in an almost negligible systematic error [5]. Fig. 3 shows the comparison between the $|F_\pi|^2$ distribution obtained in the KLOE12 and KLOE10 measurements, requiring the ISR photon to be reconstructed at large angle, inside the EMC barrel. They are obtained from independent data sets with different running conditions (W = M_ϕ KLOE12, W=1 GeV KLOE10), and also with a different selection, that imply independent systematic uncertainties. The two measurements are in very good agreement.

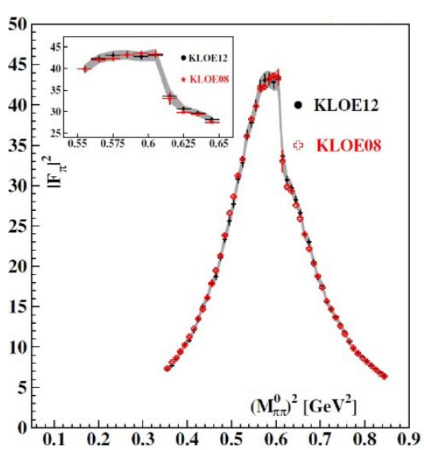

Fig. 2. Comparison of the KLOE12 measurement with the KLOE8 measurement.

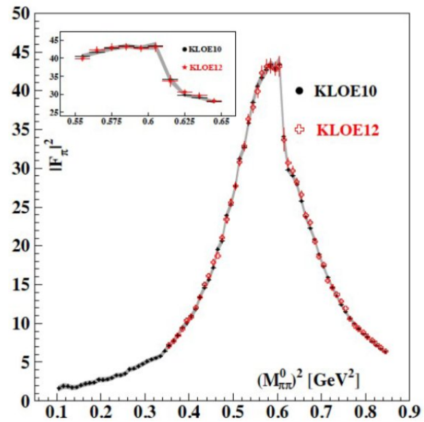

Fig. 3. Comparison of the KLOE12 measurement with the KLOE10 measurement.

In Fig. 4 and 5, the KLOE12 result is compared, respectively, with the result from the BaBar experiment at SLAC [8] which uses the ISR method and the results obtained from the energy scan experiments CMD-2 [9, 10] and SND [11] in Novosibirsk. Whenever several data points fall in one KLOE bin of 0.01 GeV^2, the values are statistically averaged.

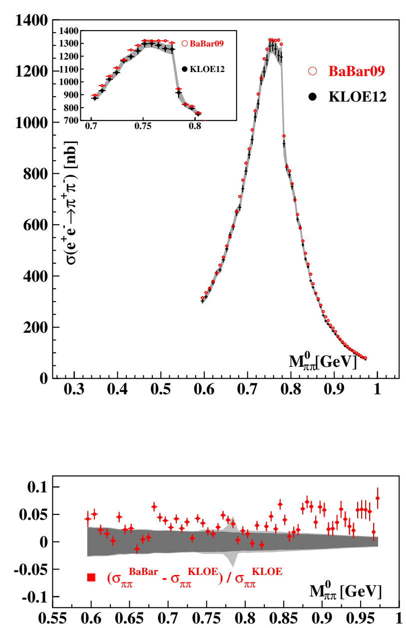

Fig. 4. $|F_\pi|^2$ from the BaBar experiment compared[8] with the KLOE12 result.

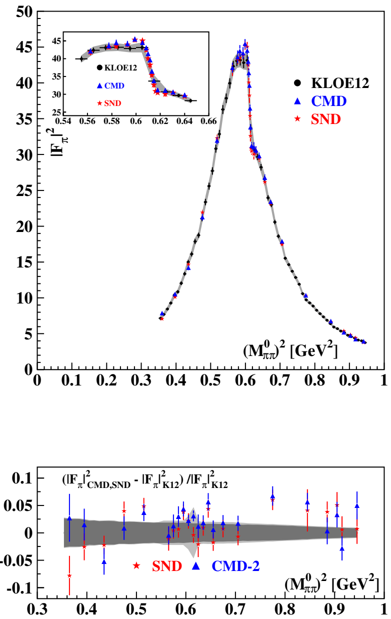

Fig. 5. $|F_\pi|^2$ from CMD-2[9, 10], SND [11] experiments compared with the KLOE12 result.

The preliminary combination of the last three KLOE results (KLOE08, KLOE10, KLOE12) [12] is obtained using the Best Linear Unbiased Estimate (*BLUE*) method [13, 14]. The following $a^{\mu}_{\pi\pi}$ values are found:

$$a^{\mu}_{\pi\pi}(0.1-0.95\text{GeV}^2) = (487.8 \pm 5.7)\cdot 10^{-10}$$
$$a^{\mu}_{\pi\pi}(0.1-0.85\ \text{GeV}^2) = (378.1 \pm 2.8)\cdot 10^{-10}.$$

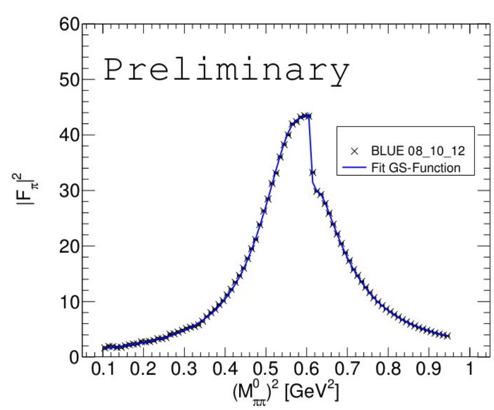

Fig. 6. Preliminary fit to the combination of the last three KLOE results (KLOE08, KLOE10, KLOE12) on the $|F_\pi|^2$.

The combined measurement of the $|F_\pi|^2$ has also been fitted using the Gounaris-Sakurai (GS) model [15] (see Fig. 6). In the table of Fig. 6 preliminary fit results are reported. The determination of the ω-meson mass parameter is very close to the current PDG value (M^{KLOE}_{ω} = 782.7 ± 0.2stat.; PDG M^{PDG}_{ω} = 782.65 ± 0.12) demonstrating the accuracy of the track momentum reconstruction of the KLOE detector.

Parameters (G-S)	KLOE (PDG)
M_ρ(MeV)	$774.3\pm0.1_{stat}$ (775.49±0.34)
Γ_ρ(MeV)	$146.9\pm0.2_{stat}$ (149.1±0.8)
M_ω(MeV)	$782.7\pm0.2_{stat}$ (782.65±0.12)
Γ_ω(MeV)	$7.0\pm0.4_{stat}$ (8.49±0.08)
$\alpha(10^{-3})$	$1.45\pm0.04_{stat}$
$\beta(10^{-3})$	$-83.1\pm0.6_{stat}$
δ(deg.)	$10.2\pm1.7_{stat}$
(χ^2/n.d.f)	221.4/82 (2.7)

Fig. 7. In the table the parameters obtained from the fit are reported.

5 Conclusions

During the last 10 years KLOE has performed a series of precision measurements using the Initial State Radiation process. The preliminary combined measurement of the last analysis (KLOE12) with two previously published results (KLOE08, KLOE10), with the corresponding fit using the GS parametrization, has been presented. The result confirms the current discrepancy ($\approx 3\sigma$) between the Standard Model (SM) calculation and the experimental value of the muon anomaly a_μ.

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