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

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ABSTRACT

We have measured the ratio $\sigma(e^+e^- \to \pi^+\pi^-\gamma)/\sigma(e^+e^- \to \mu^+\mu^-\gamma)$, with the KLOE detector at DAΦNE for a total integrated luminosity of $\sim$240 pb^{-1}. From this ratio we obtain the cross section $\sigma(e^+e^- \to \pi^+\pi^-)$. From the cross section we determine the pion form factor $|F_\pi|^2$ and the two-pion contribution to the muon anomaly a_μ for $0.592 < M_{\pi\pi} < 0.975$ GeV, $\Delta^{\pi\pi}a_\mu = (385.1 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys+theo}}) \times 10^{-10}$. This result confirms the current discrepancy between the Standard Model calculation and the experimental measurement of the muon anomaly.

1. Introduction

Measurements of the muon magnetic anomaly $a_\mu = (g_\mu - 2)/2$ performed at the Brookhaven Laboratory have reached an accuracy of 0.54 ppm: $a_\mu = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$ [1,2]. The quoted value differs from Standard Model estimates by 3.2–3.6 standard deviations [3–6].[5] The difference between measurement and calculations is of great interest since it could be a signal of New Physics. The authors of Ref. [8] have proposed an interpretation in terms of Supersymmetry, which can be probed at the Large Hadron Collider. Another proposal suggests the existence of a light vector boson in the Dark Matter sector, coupled with ordinary fermions through photon exchange, which is not excluded by present low energy tests of the Standard Model [9,10]. A new round of measurements of a_μ is expected at Fermilab [11] and J-PARC [12], with the aim of considerably reducing the experimental error. To fully exploit the significance of improved measurements of a_μ it is important to confirm the present estimate of the hadronic corrections (see below) and possibly to decrease the corresponding error.

The main source of uncertainty in the Standard Model estimates of a_μ [3,4] is due to hadronic loop contributions which are not calculable in perturbative QCD. To lowest order, the hadronic contribution, $\Delta^{\text{h,lo}}a_\mu$, can be obtained from a dispersion integral [13,14] over the "bare" cross section $\sigma^0(e^+e^- \to \text{hadrons}(\gamma))$. σ^0 is obtained from the physical cross section, inclusive of final state radiation, removing vacuum polarization, VP, effects and contributions due to additional photon emission in the initial state. The leading-order hadronic contribution is $\sim 690 \times 10^{-10}$, the precise value depending on the authors' different averaging procedures, as discussed in Refs. [3–6]. The $e^+e^- \to \pi^+\pi^-(\gamma)$ process contributes approximately 75% of the $\Delta^{\text{h,lo}}a_\mu$ value and accounts for about 40% of its uncertainty.

In the following, we discuss the measurement of the cross sections as a function of the $\mu^+\mu^-$ and $\pi^+\pi^-$ invariant masses $M_{\mu\mu}$ and $M_{\pi\pi}$:

$$\frac{d\sigma(e^+e^- \to \mu^+\mu^-\gamma)}{ds_\mu} \quad \text{and} \quad \frac{d\sigma(e^+e^- \to \pi^+\pi^-\gamma)}{ds_\pi}$$

with $s_\mu = M^2_{\mu\mu}$, $s_\pi = M^2_{\pi\pi}$, to be used for the determination of $\sigma^0(e^+e^- \to \pi^+\pi^-)$. From the latter we obtain the two-pion contribution to the anomaly, $\Delta^{\text{h,lo}}a_\mu$ and the pion form factor $|F_\pi|^2$ for comparison to other results.

[5] A recent evaluation [7] finds a difference between 4.7 and 4.9 standard deviations.

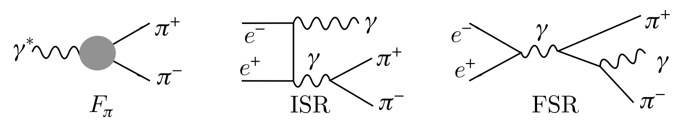

Fig. 1. Simplified amplitudes for $\gamma^* \to \pi^+\pi^-$, $e^+e^- \to \pi^+\pi^-\gamma$ (ISR) and $e^+e^- \to \pi^+\pi^-\gamma$ (FSR).

2. Measurement of $\sigma(\pi^+\pi^-)$ at DAΦNE

The KLOE detector operates at DAΦNE, the Frascati ϕ-factory, an e^+e^- collider running at fixed energy, $W = \sqrt{s} \sim 1020$ MeV, the ϕ meson mass. Initial state radiation (ISR) provides a means to produce $\pi^+\pi^-$ pairs of variable s_π. Counting $\pi^+\pi^-\gamma$ events leads to a measurement of $d\sigma(e^+e^- \to \pi^+\pi^-\gamma)/ds_\pi$ if the integrated luminosity is known, from which $\sigma(e^+e^- \to \pi^+\pi^-)$ can be extracted. We have published three measurements [15–17] of $\sigma(e^+e^- \to \pi^+\pi^-)$ for $0.1 < M^2_{\pi\pi} < 0.95$ GeV^2, with results consistent within errors and a combined fractional uncertainty of about 1%. The luminosity was obtained by counting Bhabha scattering events and using the QED value of the corresponding cross section. To lowest order, the pion form factor is defined by:

$$\langle \pi^+\pi^- | J^{\text{em}}_\mu(\pi) | 0 \rangle = (p_{\pi^+} - p_{\pi^-})_\mu \times F_\pi\big(s_\pi = (p_{\pi^+} + p_{\pi^-})^2\big), \quad (1)$$

where p_{π^+}, p_{π^-} are the momenta of π^+ and π^-. The differential cross section for $e^+e^- \to \pi^+\pi^-\gamma$ due to the ISR amplitude of Fig. 1 is related to the dipion cross section $\sigma_{\pi\pi} \equiv \sigma(e^+e^- \to \pi^+\pi^-\gamma)$ [18]:

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

where the radiator function H is computed from QED with complete NLO corrections [19–23] 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 Fig. 1). In the following we only use events where the photon is emitted at small angles, as discussed in detail in Refs. [16,17]. The cross section for $e^+e^- \to \pi^+\pi^-\gamma$ is proportional to the two-photon e^+e^- annihilation cross section, which diverges, at lowest order, for the photon angle going to zero. This is not the case for the FSR contribution. Our choice results in a large enhancement of the ISR with respect to the FSR contribution.

Eq. (2) is also valid for $e^+e^- \to \mu^+\mu^-\gamma$ and $e^+e^- \to \mu^+\mu^-$ with the same radiator function H. We can therefore determine $\sigma_{\pi\pi}$ from the ratio of the $\pi^+\pi^-\gamma$ and $\mu^+\mu^-\gamma$ differential cross