Hadronic cross section measurements and contribution to \((g-2)\mu\) with KLOE

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The KLOE experiment at the DAΦNE \(\phi\)-factory has performed a new precise measurement of the pion form factor using Initial State Radiation events. Results based on an integrated luminosity of 240 pb\(^{-1}\) and extraction of the \(\pi\pi\) contribution to \(a_{\mu}\) in the mass range \(0.35 < M_{\pi\pi}^2 < 0.95\) GeV\(^2\) are presented. The new value of \(a_{\mu}^{\pi\pi}\) has smaller statistical and systematic error and is consistent with the KLOE published value (confirming the current disagreement between the Standard Model prediction for \(a_{\mu}\) and the measured value).

1 Introduction

The anomalous magnetic moment of the muon has been measured with an accuracy of 0.54 ppm.\(^{1}\) The main source of uncertainty in the value predicted by the Standard Model is given by the hadronic contribution, \(a_{\mu}^{\text{hlo}}\), to the lowest order. This quantity can be evaluated via a dispersion integral of the hadronic cross section measurements. The pion form factor \(F_{\pi}\) (proportional to the \(\sigma_{\pi\pi}\) cross section) accounts for \(\sim 70\%\) of the central value and for \(\sim 60\%\) of the uncertainty in \(a_{\mu}^{\text{hlo}}\). The KLOE experiment has already published a measurement of \(|F_{\pi}|^2\) using Initial State Radiation (ISR) events, based on 140 pb\(^{-1}\) data taken in 2001,\(^2,3\) with a fractional systematic error of \(1.3\%\).

2 Measurement of \(\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma)\) at DAΦNE

DAΦNE is an \(e^+e^-\) collider running at \(\sqrt{s} \simeq m_\phi\), the \(\phi\) meson mass, which has provided an integrated luminosity of about 2.5 fb\(^{-1}\) to the KLOE experiment. In addition, during the year 2006, about 230 pb\(^{-1}\) of data have been collected at \(\sqrt{s} \simeq 1\) GeV. The results shown in this contribution are based on 240 pb\(^{-1}\) of data taken in 2002 (3.1 Million events).\(^4\) A preliminary spectrum based on the off peak data sample will be also given.\(^5\)

The KLOE detector consists of a drift chamber with excellent momentum resolution (\(\sigma_p/p \sim 0.4\%\) for tracks with polar angle larger than \(45^\circ\)) and an electromagnetic calorimeter with good energy (\(\sigma_E/E \sim 5.7\%\sqrt{E}\) (GeV)) and precise time (\(\sigma_t \sim 54\) ps/\(\sqrt{E}\) (GeV) \(\oplus 100\) ps) resolution. At DAΦNE, we measured the differential spectrum of the \(\pi^+\pi^-\) invariant mass, \(M_{\pi\pi}\), from ISR events, \(e^+e^- \rightarrow \pi^+\pi^-\gamma\), and the total cross section \(\sigma_{\pi\pi} \equiv \sigma_{e^+e^- \rightarrow \pi^+\pi^-\gamma}\) is obtained using the following formula:\(^5\)

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

(1)
where \(H\) is the radiator function, describing the photon emission at the initial state. This formula neglects Final State Radiation (FSR) terms (which are however properly taken into account in the analysis).

In the small angle analysis, photons are emitted within a cone of \(\theta_\gamma < 15^\circ\) around the beam line (narrow blue cones in Fig. 1 left). The two charged pion tracks have \(50^\circ < \theta_\pi < 130^\circ\). The photon is not explicitly detected and its direction is reconstructed by closing the kinematics: \(\vec{p}_\gamma \simeq \vec{p}_\text{miss} = -(\vec{p}_\pi^+ + \vec{p}_\pi^-)\). The separation of pion and photon selection regions greatly reduces the contamination from the resonant process \(e^+e^- \rightarrow \phi \rightarrow \pi^+\pi^-\pi^0\), in which the \(\pi^0\) mimics the missing momentum of the photon(s) and from the final state radiation process \(e^+e^- \rightarrow \pi^+\pi^-\gamma\text{FSR}\). Since ISR-photons are mostly collinear with the beam line, a high statistics for the ISR signal events remains. On the other hand, 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 \(M_{\pi\pi}^2 < 0.35\) GeV\(^2\). Residual contamination from the processes \(\phi \rightarrow \pi^+\pi^-\pi^0\) and \(e^+e^- \rightarrow \mu^+\mu^-\gamma\) are rejected by cuts in the kinematical variable \(\text{trackmass}\), see Fig. 1 right. A particle ID estimator, based on calorimeter information and time-of-flight, is used to suppress the high rate of radiative Bhabhas.

3 Evaluation of \(|F_\pi|^2\) and \(a_{\mu\pi}\)

The \(\pi\pi\gamma\) differential cross section is obtained from the observed spectrum, \(N_{\text{obs}}\), after subtracting the residual background events, \(N_{\text{bkg}}\), and correcting for the selection efficiency, \(\varepsilon_{\text{sel}}(M_{\pi\pi}^2)\), and the luminosity:

\[
\frac{d\sigma_{\pi\pi\gamma}}{dM_{\pi\pi}^2} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\varepsilon_{\text{sel}}(M_{\pi\pi}^2)} \frac{1}{L}. \tag{2}
\]

where the observed events are selected in bins of \(\Delta M_{\pi\pi}^2 = 0.01\) GeV\(^2\). The residual background content is found by fitting the \(M_{\text{Trik}}\) spectrum of the selected data sample with a superposition of Monte Carlo distributions describing the signal and background sources. The radiator function \(H\) used to get \(\sigma_{\pi\pi}\) in Eq. 2 is taken from the PHOKHARA Monte Carlo generator, which calculates the complete next-to-leading order ISR effects. In addition, the cross section is corrected for the vacuum polarisation (running of \(\alpha_{\text{em}}\)), and the shift between the measured value of \(M_{\pi\pi}^2\) and the squared virtual photon mass \(M_{\gamma}^2\) for events with photons from final state radiation. Again the PHOKHARA generator, which includes FSR effects in the pointlike-pions approximation,

\[\text{defined under the hypothesis that the final state consists of two charged particles with equal mass } M_{\text{Trik}} \text{ and one photon.}\]
is used to estimate the latter. The cross section corrected for the above effects and inclusive of FSR, \( \sigma_{\text{bare}}^{\pi\pi} \) (shown in Fig. 4), is used to determine \( a_{\pi\pi}^{\mu\mu} \) via a dispersion integral:

\[
a_{\pi\pi}^{\mu\mu} = \frac{1}{4\pi^3} \int_{s_{\text{min}}}^{s_{\text{max}}} ds \, \sigma_{\text{bare}}^{\pi\pi}(s) K(s),
\]

where the lower and upper bounds of the spectrum measured in this analysis are \( s_{\text{min}} = 0.35 \text{ GeV}^2 \) and \( s_{\text{max}} = 0.95 \text{ GeV}^2 \), and \( K(s) \) is the kernel function. Tab. 1 left shows the list of fractional systematic uncertainties of \( a_{\pi\pi}^{\mu\mu} \) in the mass range \( 0.35 < M_{\pi\pi}^2 < 0.95 \text{ GeV}^2 \).

| Reconstruction Filter                  | negligible |
|----------------------------------------|------------|
| Background subtraction                 | 0.3 %      |
| Track mass/miss. Mass                  | 0.2 %      |
| \( \pi/e \)-ID                         | negligible |
| Tracking                               | 0.3 %      |
| Unfolding                              | negligible |
| Acceptance \( \theta_{\text{miss}} \)  | 0.2 %      |
| Acceptance \( \theta_{\gamma} \)       | negligible |
| Software Trigger (L3)                  | 0.1 %      |
| Luminosity \((0.1_{\text{th}} \oplus 0.3_{\text{exp}})\)% | 0.3 %      |
| \( \sqrt{s} \) dependence of \( H \)   | 0.2 %      |
| Total experimental systematics         | 0.6 %      |
| Vacuum Polarization                    | 0.1 %      |
| FSR resummation                        | 0.3 %      |
| Rad. function \( H \)                  | 0.5 %      |
| Total theory systematics               | 0.6 %      |

Table 1: Left: Systematic errors on the extraction of \( a_{\pi\pi}^{\mu\mu} \) in the mass range \( 0.35 < M_{\pi\pi}^2 < 0.95 \text{ GeV}^2 \). Right: Comparison among \( a_{\pi\pi}^{\mu\mu} \) values.

4 Results

The new KLOE analysis (KLOE08) presented here is compared with the previous published one (KLOE05) based on the 2001 data sample and with the results from the VEPP-2M experiments in the mass range \( 0.630 < M_{\pi\pi} < 0.958 \text{ GeV} \). Tab. 1 right shows the consistency between the KLOE results, and with the CMD-2 and SND values. Fig. 4 shows the absolute difference between the \( a_{\pi\pi}^{\mu\mu} \) values for each energy bin obtained in this analysis and the energy scan experiments. All the experiments are in agreement within errors.

![Figure 2: Left: Differential cross section for \( e^+e^- \rightarrow \pi^+\pi^- \), with \(|\cos \theta_\gamma| > \cos(15^\circ)\). Right: Absolute difference between the dispersion integral value in each energy bin evaluated by CMD-2, SND and KLOE, where for this latter the statistical errors (light band) and summed statistical and systematic errors (dark band) are shown.](image-url)
5 Conclusions and outlook

We have measured the di-pion contribution to the muon anomaly, $a_\mu^{\pi\pi}$, in the interval $0.592 < M_{\pi\pi} < 0.975$ GeV, with negligible statistical error and with an experimental systematic uncertainty of 0.6%. Taking also into account the other 0.6% uncertainty due to the theoretical calculations of the radiative corrections, we find:

$$a_\mu^{\pi\pi}(0.592 < M_{\pi\pi} < 0.975 \text{ GeV}) = (387.2 \pm 3.3) \times 10^{-10}.$$  

This result represents an improvement of 30% on the systematic error with respect to our previous published value. The new result confirms the current disagreement between the Standard Model prediction for $a_\mu$ and the direct measured value of $a_\mu$.

Independent analyses are in progress to: (i) measure $\sigma_{\pi\pi}$ using detected photons emitted at large angle, which would improve the knowledge of the FSR interference effects (in particular the $f_0(980)$ contribution); (ii) measure the pion form factor directly from the ratio, bin-by-bin, of $\pi^+\pi^-\gamma$ to $\mu^+\mu^-\gamma$ spectra; (iii) extract the pion form factor from data taken at $\sqrt{s} = 1$ GeV, off the $\phi$ resonance, where $\pi^+\pi^-\pi^0$ background is negligible. The preliminary $|F_\pi|^2$ result, superimposed on the published result, is shown in Fig. 5 where it is possible to see the agreement between the two spectra.

![Figure 3: Preliminary $|F_\pi|^2$ result obtained with off peak data superimposed to the published result.](image)

References

1. G. W. Bennett et al. [Muon g-2 Coll.], Phys. Rev. D 73, 072003 (2006).
2. A. Aloisio et al. [KLOE Coll.], Phys. Lett. B 606, 12 (2005).
3. F. Ambrosino et al. [KLOE Coll.], arXiv:0707.4078.
4. A. Aloisio et al. [KLOE Coll.], Phys. Lett. B 670, 285 (2009).
5. S. Binner, J. H. Kühn and K. Melnikov, Phys. Lett. B 459, 279 (1999).
6. F. Jegerlehner, Nucl. Phys. Proc. Suppl. 162, 22 (2006).
7. H. Czyż, A. Grzelińska, J. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 563 (2003).
8. H. Czyż, A. Grzelińska, J. Kühn, Phys. Lett. B 611, 116 (2005).
9. S. J. Brodsky, E. De Rafael, Phys. Rev. 168 1620 (1967).
10. R. R. Akhmetshin et al. [CMD-2 Coll.], Phys. Lett. B 648, 28 (2007).
11. M. N. Achasov et al. [SND Coll.], J. Exp. Theor. Phys. 103, 380 (2006).
12. S. E. Müller and F. Nguyen et al. [KLOE Coll.], Nucl. Phys. Proc. Suppl. 162, 90 (2006).
13. P. Beltrame, PhD. Thesis (2009).