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Evaluation of $a^{\pi\pi}_\mu$ between 0.35 and 0.95 GeV$^2$ with data from the KLOE Detector

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Abstract. The KLOE Experiment at the $\phi$ factory DAΦNE has measured the cross section $\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma))$ using two different selection criteria: requiring the photon emission at small polar angle and detecting the photon at large polar angle in the calorimeter. Using a theoretical radiator function we extract the cross section $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ and obtain the $\pi\pi$ contribution to the muon anomalous magnetic moment. Results presented come from the analysis of 240 pb$^{-1}$ collected in 2002, with improved systematic uncertainty with respect to the published KLOE analysis.

1. Introduction
One of the best known quantities in Particle Physics is the anomalous magnetic moment of the muon, $a_\mu$. Recent theoretical evaluations [1, 2] find a discrepancy of 3.2 - 3.4 standard deviations with the value obtained from the g-2 experiment at Brookhaven [3]. A large part of the uncertainty on the theoretical estimates comes from the leading order hadronic contribution $a^{\text{had,lo}}_\mu$, which at low energies is not calculable by perturbative QCD, but has to be evaluated by a dispersion integral using experimentally measured $e^+e^-$ hadronic cross sections. The process with $\pi^+\pi^-$ in the final state contributes with $\sim 70\%$ to $a^{\text{had,lo}}_\mu$, and $\sim 60\%$ to its uncertainty.

2. Measurement of the $\sigma_{\pi\pi}$ cross section
The measurement has been performed with the KLOE detector at the DAΦNE $e^+e^-$ collider in Frascati. DAΦNE is a $\phi$-factory running at $\sqrt{s} \simeq M_\phi$, which has delivered ca. 2.5 fb$^{-1}$ of data to the KLOE experiment up to the year 2006. In addition, about 250 pb$^{-1}$ of data have been collected at $\sqrt{s} \simeq 1$ GeV, ca. 20 MeV below the $\phi$ resonance. The presented results are obtained from 240 pb$^{-1}$ of data taken in 2002.

The KLOE detector (Fig. 1, left) consists of a high resolution drift chamber ($\sigma_p/p < 0.4\%$) [4] and an electromagnetic calorimeter with excellent time ($\sigma_t \sim 57$ ps/$\sqrt{E\, [\text{GeV}]} \oplus 100$ ps) and good energy ($\sigma_E/E \sim 5.7\%$/\$\sqrt{E\, [\text{GeV}]}$) resolution [5].

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As DAΦNE was designed to operate at the fixed energy of $M_\phi$, the differential cross section $d\sigma(e^+e^-\rightarrow \pi^+\pi^- + \gamma_{\text{ISR}})/dM^2_{\pi\pi}$ is measured, and the total cross section $\sigma_{\pi\pi} = \sigma_{e^+e^-\rightarrow \pi^+\pi^-}$ is evaluated using the formula [6]:

$$M^2_{\pi\pi} \frac{d\sigma_{\pi\pi\gamma_{\text{ISR}}}}{dM^2_{\pi\pi}} = \sigma_{\pi\pi} (M^2_{\pi\pi}) \ H(M^2_{\pi\pi}),$$  \hspace{1cm} (1)$$

$H$ is the theoretical radiator function. Note that Final State Radiation (FSR) terms are neglected in Eq. 1, but are taken into account in the analyses [7].

2.1. Event selection

Two different selection regions are considered: In the small angle analysis, photons are emitted within a cone of $\theta_\gamma < 15^\circ$ around the beamline (narrow cones in Fig. 1, left), while in the large angle analysis there should be at least one photon at a polar angle of $50^\circ < \theta_\gamma < 130^\circ$ (large central cones in Fig. 1, left). In both cases the two charged pion tracks should have $50^\circ < \theta_\pi < 130^\circ$. The photon is not explicitly detected in the small angle analysis, its direction is reconstructed from the tracks’ momenta by closing kinematics: $\mathbf{p}_\gamma \approx \mathbf{p}_{\text{miss}} = -(\mathbf{p}_{\pi^+} + \mathbf{p}_{\pi^-})$. The separation of pion- and photon selection regions in this analysis greatly reduces the contamination from the resonant process $e^+e^-\rightarrow \phi \rightarrow \pi^+\pi^-\pi^0$ in which the $\pi^0$ mimicks the missing momentum of the photon(s) and from the final state radiation process $e^+e^-\rightarrow \pi^+\pi^-\gamma_{\text{ISR}}$. 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 $M^2_{\pi\pi} < 0.35$ GeV$^2$. This is not the case for the large angle analysis, which allows us to measure the spectrum down to the 2-pion threshold of $4m^2_\pi$. The price to pay in this case is an increased contribution from irreducible, model-dependent background processes such as events with final state radiation and the decays $\phi \rightarrow f_0\gamma \rightarrow \pi^+\pi^-\gamma$ and $\phi \rightarrow \pi^\pm\rho^\mp \rightarrow \pi^\pm\pi^\mp\gamma$.

Contaminations from the processes $\phi \rightarrow \pi^+\pi^-\pi^0$ and $e^+e^-\rightarrow \mu^+\mu^-\gamma$ are rejected by cuts in the kinematical variables $\text{trackmass}^2$ and $\text{missing mass}^3$, (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.

The large angle analysis allows the closure of the kinematics by requiring the detection of at least one photon with energy larger than 50 MeV and $50^\circ < \theta_\gamma < 130^\circ$ in the calorimeter. A cut on the angle between the photon direction and the missing momentum $\mathbf{p}_{\text{miss}}$ and a kinematic fit in the $\pi^0$ hypothesis are applied to reject the $\pi^+\pi^-\pi^0$ contamination, which is much larger than in the small angle analysis.

2.2. Luminosity

The absolute normalization of the data sample is performed by measuring Bhabha events at large angles ($55^\circ < \theta < 125^\circ$), with an effective cross section of $\approx 430 \text{ nb}$. To obtain the integrated luminosity, $L$, the observed number of Bhabha events is divided by the effective cross section evaluated by the Monte Carlo generator Babayaga [8], which includes QED radiative corrections with the parton shower algorithm, and which has been interfaced with the KLOE detector simulation. Recently, an updated version of the generator, Babayaga@NLO [9], has been released, in which the new predicted cross section decreases by 0.7% and the theoretical

2 Defined under the hypothesis that the final state consists of two charged particles with equal mass $M_{\tau\tau}$, and one photon.

3 Defined as $M_{\text{Miss}} = \sqrt{E_X^2 - |\mathbf{p}_X|^2}$ assuming that the underlying process is $e^+e^-\rightarrow \pi^+\pi^-X$. It is peaked at the $\pi^0$ mass for $\pi^+\pi^-\pi^0$ events.
uncertainty improves from 0.5% to 0.1% with respect to the older version. Table 1 summarizes contributions to the uncertainty of the luminosity measurement. A detailed description of the KLOE luminosity measurement can be found in [10].

| Systematic errors on $L$ (%) |
|-----------------------------|
| Theory, $\sigma_{th}$       | 0.10 |
| Acceptance                  | 0.25 |
| Background                  | 0.08 |
| $e^\pm$ reconstruction      | 0.13 |
| Energy calibration          | 0.10 |
| Knowledge of $\sqrt{s}$     | 0.10 |
| Total: $\sigma_{th} \oplus \sigma_{exp}$ | 0.34 |

Table 1. Relative systematic error on the luminosity measurement

2.3. Improvements with respect to the published analysis [11]

The analyses of data taken since 2002 benefit from the cleaner and more stable running conditions of DAΦNE, which result in less machine background. Moreover, the following changes are applied with respect to the data taken in 2001:

- an additional third trigger level was implemented during 2002 to reduce the inefficiency on the signal $\pi\pi\gamma$ events due to the KLOE detector’s cosmic muon trigger-veto, bringing this inefficiency down to few per mill. This has to be confronted with the trigger condition during 2001 data taking, in which the signal efficiency was reduced by as much as 30% due to the misidentification of pions as cosmic events,
- an improved offline background filter was used with the new data sample. This filter contributed the largest experimental systematic uncertainty to the published analysis. The
implementation of a downscaling algorithm providing an unbiased control sample greatly facilitates the evaluation of the filter efficiency, with negligible systematic uncertainty.

In addition, the knowledge of the detector response and of the KLOE simulation program has been improved [12].

3. Evaluation of $a_{\mu}^{\pi\pi}$

From the spectrum of observed events, $N_{\text{obs}}$, the differential cross section is obtained after subtracting the residual background events, $N_{\text{bkg}}$, and dividing for the selection efficiency, $\varepsilon_{\text{sel}}(M_{\pi\pi}^2)$, and the integrated luminosity via

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

where the observed events are selected in bins of $\Delta M_{\pi\pi}^2 = 0.01 \text{ GeV}^2$. The residual background content is found by fitting the $M_{\text{Trk}}$ spectrum of the selected data sample with a superposition of Monte Carlo distributions describing the signal and background sources. The fit parameters are the relative weights of signal and background in data, obtained in intervals of $M_{\pi\pi}$. The radiator function $H$ used to get $\sigma_{\pi\pi}$ in Eq. 1 is taken from the PHOKHARA Monte Carlo generator, which calculates the complete next-to-leading order ISR effects [13]. In addition, the cross section is corrected for the vacuum polarisation [14] (running of $\alpha_{\text{em}}$), and the shift between the measured value of $M_{\pi\pi}$ and the virtual photon mass $M_{\gamma\gamma}$ for events with photons from final state radiation. Again the PHOKHARA generator, which includes FSR effects in the pointlike-pions approximation, is used to estimate the latter [15]. The cross section corrected for the above effects and inclusive of FSR, $\sigma_{\pi\pi\gamma}(\gamma)$, is used to determine $a_{\mu}^{\pi\pi}$:

$$a_{\mu}^{\pi\pi} = \frac{1}{4\pi^3} \int_{s_{\text{low}}}^{s_{\text{up}}} ds \sigma_{\pi\pi\gamma}(s) K(s)$$

where the lower and upper bounds of the spectrum measured with the small angle analysis are $s_{\text{low}} = 0.35 \text{ GeV}^2$ and $s_{\text{up}} = 0.95 \text{ GeV}^2$, and the kernel function $K(s)$ is described in [16].

4. Results

Table 2 shows the list of relative systematic uncertainties in the evaluation of $a_{\mu}^{\pi\pi}$, in the mass range $[0.35,0.95] \text{ GeV}^2$, for the published analysis of 2001 data and for the preliminary analysis of 2002 data using the small angle selection cuts.

Revisiting the published analysis, a small bias was found in the evaluation of the trigger efficiency correction, affecting mostly the low $M_{\pi\pi}$ region. Correcting for this effect, and normalizing to the new Bhabha reference cross section the updated 2001 spectrum is compared to the new one from the 2002 analysis in Fig. 2. Inserting the updated 2001 result into the dispersion integral in Eq. 3 yields

$$a_{\mu}^{\pi\pi}(0.35, 0.95) = (384.4 \pm 0.8_{\text{stat}} \pm 4.9_{\text{syst}}) \times 10^{-10}$$

This agrees well with the new preliminary result based on 2002 data

$$a_{\mu}^{\pi\pi}(0.35, 0.95) = (386.3 \pm 0.6_{\text{stat}} \pm 3.9_{\text{syst}}) \times 10^{-10}$$

As the measurement of $\sigma_{\pi\pi}$ with large angle cuts uses an independent selection, it provides an excellent cross check of the $a_{\mu}^{\pi\pi}$ evaluation, and allows to test the knowledge of contributions from FSR. Fig. 3 shows the comparison between the two spectra. The main source of uncertainty in the large angle case is the unknown interference between the FSR process and the decays $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$, which limit the accuracy at low and high $M_{\pi\pi}$ values. The comparison for $a_{\mu}^{\pi\pi}$ is thus limited to the range $[0.5,0.85] \text{ GeV}^2$.
Table 2. Comparison of relative systematic errors on the evaluation of $a_{\mu}^{\pi\pi}$ in the mass range [0.35,0.95] GeV$^2$ between the analysis of 2001 data and the preliminary analysis of 2002 data, using the small angle selection.

| Source of Error         | 2001   | 2002   |
|-------------------------|--------|--------|
| Offline filter          | 0.6    | negligible |
| Background              | 0.3    | 0.3    |
| Kinematic cuts          | 0.2    | 0.2    |
| $\pi/e$ ID              | 0.1    | 0.3    |
| Vertex                  | 0.3    | 0.5    |
| Tracking                | 0.3    | 0.4    |
| Trigger                 | 0.3    | 0.2    |
| Acceptance              | 0.3    | 0.1    |
| FSR corrections         | 0.3    | 0.3    |
| Luminosity              | 0.6    | 0.3    |
| $H$ function eq.(1)     | 0.5    | 0.5    |
| Vacuum polarization     | 0.2    | negligible |
| Total                   | 1.3    | 1.1    |

Figure 3. Comparison between the small and large angle results for $\sigma_{\pi\pi}$ and their relative difference. The grey band in the upper plot represents the systematic uncertainty for the large angle analysis.

2002 small angle: $a_{\mu}^{\pi\pi}(0.5,0.85) = (255.4 \pm 0.4_{\text{stat}} \pm 2.5_{\text{sys}}) \times 10^{-10}$

2002 large angle: $a_{\mu}^{\pi\pi}(0.5,0.85) = (252.5 \pm 0.6_{\text{stat}} \pm 5.1_{\text{sys}}) \times 10^{-10}$

One finds a good agreement in $a_{\mu}^{\pi\pi}$ between the two independent measurements. Note that even restricting the comparison to the range around the mass of the $\varphi$-meson, 60% ($3 \times 10^{-10}$) of the systematic uncertainty in the large angle evaluation of $a_{\mu}^{\pi\pi}$ come from the uncertainty on the parameters used in the $f_0(980)$ background subtraction.

A comparison of the small angle result with the most recent $a_{\mu}^{\pi\pi}$ evaluations released by the CMD-2 [17] and SND [18] experiments, in the mass range $M_{\pi\pi} \in [630,958]$ MeV, yields

CMD-2 [17]: $a_{\mu}^{\pi\pi}(630,958) = (361.5 \pm 1.7_{\text{stat}} \pm 2.9_{\text{sys}}) \times 10^{-10}$

SND [18]: $a_{\mu}^{\pi\pi}(630,958) = (361.0 \pm 2.0_{\text{stat}} \pm 4.7_{\text{sys}}) \times 10^{-10}$

KLOE preliminary: $a_{\mu}^{\pi\pi}(630,958) = (355.5 \pm 0.5_{\text{stat}} \pm 3.6_{\text{sys}}) \times 10^{-10}$

While the new KLOE value is slightly lower, it agrees with the published CMD-2 and SND values within one standard deviation.

5. Conclusions and outlook

The KLOE collaboration has obtained $\sigma_{\pi\pi}$ from the differential cross section for ISR events $e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma)$, and has evaluated $a_{\mu}^{\pi\pi}$ in the range $M_{\pi\pi}^2 \in [0.35, 0.95]$ GeV$^2$. The
preliminary result from 2002 data agrees with the updated result from the published KLOE result based on the small angle analysis of 2001 data. Also both preliminary 2002 results from large and small angle analyses agree in a region $M_{\pi\pi}^2 \in [0.5, 0.85]$ GeV$^2$, in which FSR effects play a minor role. Finally, the small angle 2002 result is also in agreement within one standard deviation with the recent SND and CMD-2 values in the mass range $M_{\pi\pi} \in [630, 958]$ MeV.

Further work is going on to refine the analyses:

- by including the bin-by-bin correlations due to the detector resolution in the small angle analysis;
- by improving the knowledge of the FSR interference effects for the large angle analysis, using KLOE $f_0(980)$ measurements [19,20].

In addition, complementary analyses are in progress to measure the pion formfactor $|F_\pi|^2$

- from the bin-by-bin normalization of $\pi^+\pi^-\gamma$ to $\mu^+\mu^-\gamma$ spectra [21];
- using data taken at $\sqrt{s} \simeq 1$ GeV, in which background from $\phi$-meson decays is suppressed.

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