Measurement of the pion form factor at BESIII in the rho-peak region relevant for $(g-2)_\mu$

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Abstract. Measurements of hadronic cross sections in e^+e^- collisions are an important input for the Standard Model calculations of the hadronic contribution to the anomalous magnetic moment of the muon, $(g-2)_\mu$. We present a new measurement of the cross section $e^+e^- \to \pi^+\pi^-$, the pion form factor, which dominates the hadronic contribution. Using the method of initial state radiation, 2.93 fb^{-1} of data taken with the BESIII detector at the $\psi(3770)$ peak have been evaluated to determine the cross section in the energy range between 600 and 900 MeV with a systematic uncertainty of 0.9%. The new BESIII data are compared to previous measurements by KLOE and BaBar, and their impact on $(g-2)_\mu$ is discussed.

1. Introduction

The anomalous magnetic moment of the muon $a_\mu = \frac{1}{2}(g-2)_\mu$ is one of the most precisely known observables in the Standard Model. It has been determined experimentally since 1961 with ever increasing accuracy. The latest high precision direct measurement has been performed in Brookhaven and resulted in $a_\mu^{exp} = (11659208.9 \pm 6.3) \times 10^{-10}$ [1]. The theoretical prediction of a_μ within the Standard Model achieved a competitive accuracy, however, there remains a discrepancy of three to four standard deviations from the experimental value. In order to clarify the situation new direct measurements are planned at Fermilab, Chicago, USA and J-PARC, Tokai, Japan, which aim at a fourfold improvement of the experimental precision [2, 3].

The Standard Model calculations involve contributions from QED, a_μ^{QED}, the weak interaction, a_μ^{weak}, and the strong interaction, a_μ^{hadr}. The QED contribution accounts for the largest part of the absolute value of a_μ. It has been determined up to the 10^{th} order in perturbation theory [4] and its uncertainty is well under control. The weak contribution is small and also well under control by means of perturbation theory [5]. The hadronic contributions are comparably small, however, their uncertainties completely dominate the total uncertainty of the Standard Model prediction of a_μ [6]. Due to the running of the strong coupling constant, the hadronic contributions cannot be treated perturbatively in the relevant energy regime. However, experimental input can be exploited to improve the prediction.

The hadronic vacuum polarization causes the largest hadronic contribution a_μ^{hVP}. It can be related by the optical theorem to hadronic cross sections measured in e^+e^- annihilations. These are an important input to the Standard Model calculations of the anomalous magnetic moment of the muon a_μ. The accuracy of the hadronic contribution can be systematically improved by the measurement of $\sigma(e^+e^- \to \text{hadrons})$ at e^+e^- colliders with high precision. Due to the energy dependence of the cross sections and of the kernel function in the dispersion integral, which is used to calculate the contribution of individual cross sections to the leading order of a_μ^{hVP}, hadronic cross sections measured below 1 GeV center-of-mass energy are the most relevant input. The energy region is dominated by the ρ-resonance, and it turns out that a_μ^{hVP} can be determined to more than 70% by the measurement of the cross section $\sigma(e^+e^- \to \pi^+\pi^-)$ [6].

High precision measurements of the two pion cross section have already been performed by BaBar [7, 8] and KLOE [9, 10, 11]. Both experiments claim a precision below one percent, however, their results differ by more than 3% in the ρ-peak region. This discrepancy reflects directly in the uncertainty of the leading order contribution $a_\mu^{hVP,LO}$ of the hadronic vacuum polarization. Another high precision measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ with a precision of better than one percent is needed to clarify the situation and reduce the uncertainty of a_μ^{hadr}.

2. The BESIII Detector

The measurement has been done with the BESIII detector [12], which is operated at the symmetric BEPCII e^+e^- collider. The cylindrical detector setup covers 93% of the total solid angle. It consist of several subsystems arranged in layers around the interaction region, which is made from Beryllium. The innermost detector component is a helium-based drift chamber, which is immersed in the 1.0 T magnetic field of a superconducting solenoid. It measures momenta of charged particles with a resolution of 0.5% at 1 GeV, and provides $\frac{dE}{dx}$ information for particle identification. The chamber is surrounded by a time-of-fight system, made from two layers of plastic scintillator, which is used for particle identification. It provides time information for charged particles with a resolution of 90 ps in the barrel part and 110 ps in the end caps. The third detector component located inside the bore of the solenoid is an electromagnetic calorimeter made from 6240 CsI(Tl) crystals. It measures energies of photons with a resolution of 2.5% at 1 GeV. The outermost detector component is the muon counter. It is built into the flux-return yoke of the solenoid and is instrumented with resistive plate counters.

The accelerator allows for data taking at center-of-mass energies between 2.0 GeV and 4.6 GeV, which is routinely performed since 2009. BESIII has collected 1.25×10^9 $e^+e^- \to J/\psi$ events, more than 500×10^6 $e^+e^- \to \psi(2S)$ events, 2.93 fb^{-1} at the $\psi(3770)$ peak, and more than 5 fb^{-1} in the center-of-mass region above 4 GeV, which are devoted to studies of the charmonia and charmonium-like states [13, 14, 15]. These samples are among the world's largest data sets of J/ψ, $\psi(2S)$, and $\psi(3770)$ mesons. Additional data have been acquired for a τ-mass scan and a high statistics R-scan. The BESIII collaboration uses these data to follow a physics program [16], which focuses on charmonium spectroscopy, charm physics, light hadron spectroscopy, τ physics, and R-measurements.

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

The BESIII measurement of the hadronic cross section $\sigma(e^+e^- \to \pi^+\pi^-)$ is based on the 2.93 fb^{-1} sample taken at the center-of-mass energy of $\sqrt{s} = 3.773$ GeV/c^2 [14]. A detailed description of the analysis can be found in Ref. [17].

Events with the final state $\pi^+\pi^-\gamma$ are selected to exploit the method of Initial State Radiation (ISR). The radiated photon reduced the effective center-of-mass energy, so that the energy region of the ρ-peak, 600 MeV/c^2 – 900 MeV/c^2, can be studied. The radiative cross section $\sigma(e^+e^- \to \pi^+\pi^-\gamma_{ISR})$ is related to the non-radiative cross section of interest by the radiator function [18], which describes the probability of emitting a photon depending on the center-of-mass energy, momentum fraction of the radiating particle, and the emission angle of the photon.

The dominating background in the event selection comes from radiative muon pair production $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$. Due to the similarity of pion and muon masses, this background cannot be suppressed based on the event kinematics alone. An artificial neural network has been applied,

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which combines kinematic information with information from different subdetectors, like shower shapes in the calorimeter crystals and the penetration depth in the muon counter, to successfully differentiate pions from muons.

The network has been trained with distributions from Monte Carlo simulations of the signal $\pi^+\pi^-\gamma_{ISR}$ and the background $\mu^+\mu^-\gamma_{ISR}$ processes. Possible discrepancies between the simulation and experimental distributions have been studied carefully, and corresponding corrections are applied in the analysis.

The validity of the systematic corrections and the reliability of the neural network have been tested by using the network to select a clean sample of radiative muons. The result is compared to the QED prediction of muon production, which is taken from the PHOKARA event generator [19, 20]. The accuracy of the prediction implemented in the generator is claimed to be better than 0.5%. Excellent agreement is found between data and Monte Carlo on the full mass range accessible with the ISR method, but also in the mass range relevant for the pion cross section measurement, 600 MeV – 900 MeV, which, due to the peak of the ρ-resonance, makes up for 70% of the total two-pion contribution to a_μ^{hVP}.

In order to calculate the contribution to the anomalous magnetic moment of the muon, the bare cross section of the process $e^+e^- \to \pi^+\pi^-$ has to be determined. There are two ways to extract this cross section. In the first method, the measured number of $\pi^+\pi^-\gamma_{ISR}$ events is normalized to the detection efficiency and the integrated luminosity of the data set to obtain the radiative cross section. After correcting it for vacuum polarization and FSR effects, the radiative cross section is finally divided by the radiator function, in order to obtain the bare, non-radiative cross section $\sigma(e^+e^- \to \pi^+\pi^-)$.

In the second method, the number of efficiency corrected $\pi^+\pi^-\gamma_{ISR}$ events is normalized to the ratio of detected $\mu^+\mu^-\gamma_{ISR}$ events in the same data set and the exact QED prediction for muon production. The advantage compared to the first method is that the integrated luminosity and the vacuum polarization cancel in the ratio. Thus, they do not contribute to the systematic uncertainty. However, this method is limited by the number of detected muons. The results provided by both methods agree well within their errors. Due to the statistical limitation in the number of $\mu^+\mu^-\gamma_{ISR}$ events in data, the first method provides the more precise result and is used to evaluate the contribution to a_μ^{hVP}. A total uncertainty of 0.9% is achieved. The individual contributions to the systematic uncertainty are listed in Table 1.

Table 1. Contributions to the systematic uncertainty. The numbers are taken from Ref.[17]

Source	Contribution
Photon efficiency correction	0.2
Pion tracking efficiency correction	0.3
Pion ANN efficiency correction	0.2
Pion e-PID efficiency correction	0.2
ANN	negl.
Angular acceptance	0.1
Background subtraction	0.1
Unfolding	0.2
FSR correction δ_{FSR}	0.2
Vacuum polarization correction δ_{vac}	0.2
Radiator function	0.5
Luminosity $\mathcal{L}$	0.5
Sum	**0.9**

Taking into account vacuum polarization effects and correcting for FSR, the pion form factor can be calculated from the measured cross section. The Gounaris-Sakurai parametrization of the $\rho - \omega$ interference is fitted to the form factor. Masses and widths of the ρ and ω, as well as the phase and the strength of the interference are free parameters of the fit. The pion form factor and the result of the fit are shown in Figure 1.

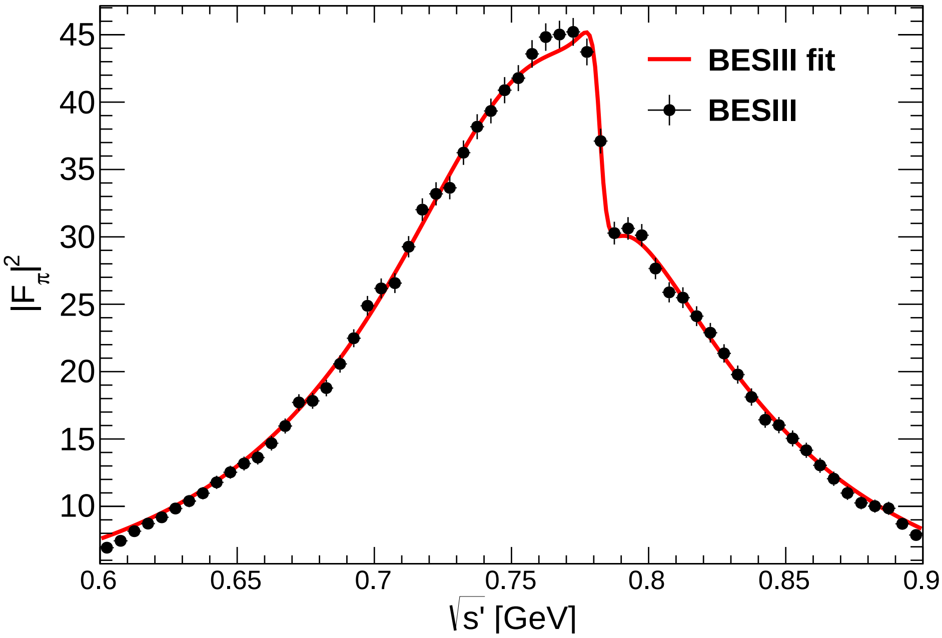

Figure 1. Pion form factor measured by BESIII and fitted with the Gounaris-Sakurai parametrization (red line). Figure is taken from Ref. [17].

The parametrization provides an excellent description of the data. The masses and widths obtained from the fit parameters are in good agreement with the existing values from PDG [21]. The fit is used to compare this measurement with the existing measurements from KLOE [9, 10, 11] and BaBar [7, 8].

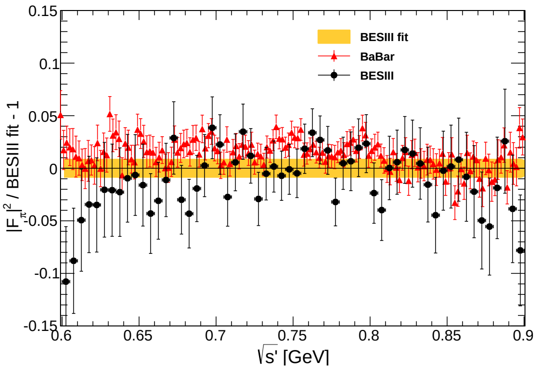

Figure 2. Comparison of the fit to the pion form factor of BESIII and the respective data points (black), as well as the BaBar result [7, 8] (red). Figure is taken from Ref. [17].

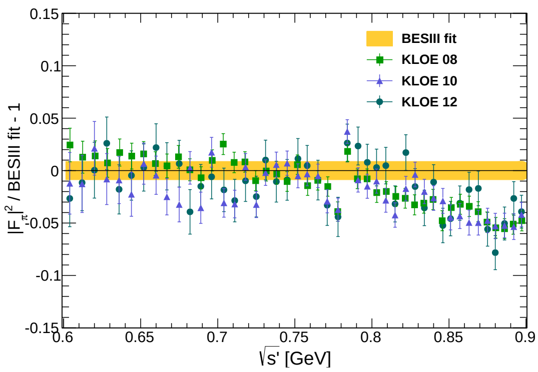

Figure 3. Comparison of the fitted pion form factor of BESIII and the KLOE [9, 10, 11] data points. Figure is taken from Ref. [17].

Figure 2 shows the relative difference between the fit result, the BESIII data points (black) and the BaBar data points (red). Within the error bars both measurements agree. Relative to the fit result a step can be observed in the BaBar data, which is approximately located at the $\rho-\omega$ interference. Above this point, the BaBar data points coincide with the BESIII fit result. However, at lower energies there seems to be an offset relative to the BESIII fit.

The comparison with the KLOE measurements in Figure 3 reveals a close to opposite picture. The data points of the three measurements coincide with the BESIII fit below the $\rho-\omega$ interference. Above the interference region all KLOE measurements show a clear systematic offset. Among the individual KLOE results, the KLOE10 [10] measurement seems to have a slight negative offset on the full mass range.

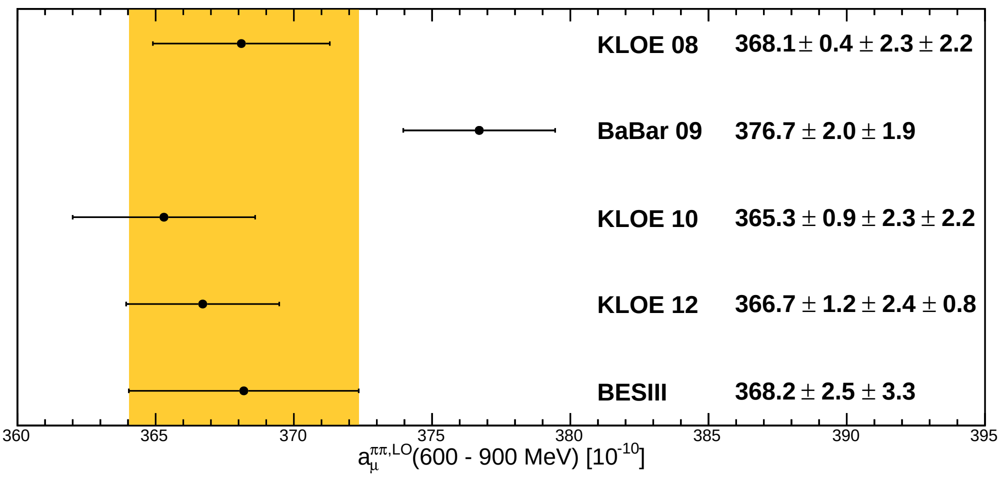

Figure 4. Comparison of $a_\mu^{\pi\pi,LO}(600-900\text{MeV})$ from the measurements of KLOE, BaBar, and BESIII. The error bars include statistical and systematical errors. Figure is taken from Ref. [17].

The leading order contribution of the two-pion cross section $a_\mu^{\pi\pi,LO}$ to the total hadronic vacuum polarization contribution to a_μ is calculated from the cross section $\sigma(e^+e^- \to \pi^+\pi^-)$, which has been corrected for vacuum polarization effects and includes FSR effects. The result of the BESIII measurement is $a_\mu^{\pi\pi,LO}(600-900\text{ MeV}) = 368.2 \pm 2.5_{\text{stat}} \pm 3.3_{\text{syst}} \cdot 10^{-10}$ [17].

Figure 4 shows the comparison of this result with the contributions calculated from the results of BaBar and KLOE. The yellow band indicates the total uncertainty of the BESIII result and demonstrates the competitiveness of the precision with the previous measurements. The three KLOE results agree well with the result of BESIII. Their values of $a_\mu^{\pi\pi,LO}(600-900\text{ MeV})$ reside within the BESIII error band. The result of the BaBar collaboration is shifted towards larger values of $a_\mu^{\pi\pi,LO}(600-900\text{ MeV})$. These deviations coincide with the observed shifts between the different results of the measured cross sections for invariant masses of the pions below the $\rho-\omega$ interference region. Due to the peak of the ρ resonance this mass region dominates the statistics.

The BESIII result confirms the deviation between the experimental value of a_μ and its Standard Model prediction of three to four standard deviations. The BaBar result would hint at a deviation of only 2.4 standard deviations [22].

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