Meson form factors and $P \rightarrow \gamma^*\gamma^*$ physics at BESIII

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Abstract. Using data consisting of 2.93 fb$^{-1}$ integrated luminosity at the centre of mass energy $\sqrt{s} = 3773$ MeV, recorded with the BESIII detector at BEPCII, the cross section and form factor $|F_\pi|^2$ was extracted in the energy range 600-900 MeV, using the method of radiative return. The cross section is used as input to calculate the leading-order vacuum polarisation contribution of the $e^+e^- \rightarrow \pi^+\pi^-$ channel to $(g - 2)_\mu$ as $a_{\mu}^{\pi\pi,LO}(600 - 900$ MeV) = $(368.2 \pm 2.5_{stat} \pm 3.3_{sys}) \cdot 10^{-10}$. This result is compatible with corresponding values using KLOE data, but disagrees with BaBar. The ongoing search for $e^+e^- \rightarrow \eta_c$ at BESIII is also discussed.

1. Introduction

Measurements of the process $e^+e^- \rightarrow \pi^+\pi^-$, and processes containing a light pseudoscalar meson interacting with two photons ($P \rightarrow \gamma^*\gamma^*$) are important as experimental input to Standard Model (SM) calculations of the anomalous magnetic moment of the muon $a_{\mu}$. The anomalous magnetic moment of the muon has been measured to great precision by the E821 experiment at Brookhaven [1]. At present time, a deviation of 3.6$\sigma$ [2] is reported between theoretical calculations and experimental measurement of $a_{\mu}$. The theoretical calculation of $a_{\mu}^{theo}$ is broken up into several parts $a_{\mu}^{theo} = a_{\mu}^{QED} + a_{\mu}^{weak} + a_{\mu}^{QCD}$, where the QCD part can be further broken down as $a_{\mu}^{QCD} = a_{\mu}^{VP,LO} + a_{\mu}^{VP,HO} + a_{\mu}^{LbL}$. The largest uncertainties in the calculations arise from experimental input to the leading-order (LO) hadronic vacuum polarisation ($a_{\mu}^{VP,LO}$) and second order light-by-light scattering ($a_{\mu}^{LbL}$) contributions. The contributions to $a_{\mu}^{VP,LO}$ can be further broken down to the individual channels as $a_{\mu}^{VP,LO} = a_{\mu}^{\pi\pi} + a_{\mu}^{\pi\pi\pi} + a_{\mu}^{KK} \ldots$. As can be seen in Fig. 1 the process $e^+e^- \rightarrow \pi^+\pi^-$ dominates the dispersion integral for $a_{\mu}^{VP,LO}$ and high precision measurements are therefore of great importance.

The $P\gamma^*\gamma^*$ vertex which appears in diagrams contributing to $a_{\mu}^{LbL}$, Fig. 2, also appears in the process $\pi^0 \rightarrow e^+e^-$, see Fig. 3. Measurements of this process shows a discrepancy between theory and experiment; for the branching fraction a deviation of $2 - 3.3\sigma$ has been observed compared to theoretical calculations within SM [3, 4]. It has been proposed that pseudoscalar mesons decaying into lepton-antilepton pairs can provide a signal to physics beyond the Standard Model [3, 5, 6]. Within the Standard Model $P \rightarrow l^+l^-$ proceeds via a two-photon intermediate state. Therefore it is a fourth order electromagnetic process, and thus suppressed. Determinations of upper limits has previously been performed for $\pi^0$, $\eta$ and $\eta'$ decaying to lepton-antilepton pairs [7, 8, 9, 10]. However, until now, no attempt has been made to measure $\eta_c \rightarrow e^+e^-$. 
Figure 1. The left panel shows the relative contributions of the most important channels to $a_{\mu,LO}$, the right panel shows the relative uncertainty in each channel [2].

$$P = \pi^0 \eta \eta' \gamma^* \gamma^*$$

Figure 2. Light-by-Light scattering diagram describing the role of the intermediate pseudoscalar mesons.

Figure 3. A pseudoscalar particle decaying into two leptons via two virtual photons.

2. The BESIII Experiment

The Beijing Electromagnetic Spectrometer III (BESIII) is a multipurpose detector located at the Beijing Electron-Positron Collider (BEPC-II), a double-ring electron-positron collider optimized for the charmonium region [11]. BESIII covers 93% of the $4\pi$ solid angle and consists of several sub-systems that provides tracking, calorimetry, particle identification, and muon detection. The main subsystems are (a) the Multilayer Drift Chamber (MDC) which contains helium gas and have 43 layers of wiring providing a 135 $\mu$m spatial resolution, 0.5% momentum resolution for charged tracks at 1 GeV/c and dE/dx resolution of $< 6\%$ in a 1 T magnetic field, provided by a superconducting solenoid. (b) A Time of flight system consisting of 176 plastic scintillators in the barrel and 96 in each endcap. Providing a 80 ps and 110 ps time resolution respectively, which gives a 2$\sigma$ K/$\pi$ discrimination at energies of 1 GeV/c. (c) A CsI(Tl) Electro-Magnetic Calorimeter (EMC) with a 2.5 % energy resolution in the barrel and 5% in the endcaps at energies of 1 GeV/c. (d) The Muon Chamber (MUC) consists of resistive plate chambers in nine layers in the barrel and eight in the endcaps, with a position resolution of 2 cm.

3. The $e^+e^- \rightarrow \pi^+\pi^-$ process

3.1. Measurement of $e^+e^- \rightarrow \pi^+\pi^-$

Data containing 2.93 fb$^{-1}$ integrated luminosity, recorded at the centre of momentum energy of $\sqrt{s} = 3773$ MeV was analysed using the method of radiative return. The method of radiative return exploits Initial State Radiation (ISR) to obtain cross section measurements for a wide range of energies. ISR is when one or more photons are radiated by the initial $e^+e^-$ pair prior to annihilation. The radiated photon(s) effectively lowers the available center-of-mass pair energy of the recoiling $e^+e^-$ pair. High energy $\gamma_{ISR}$ are likely to have a momentum pointing along the
beam axis, subsequently giving the ππ pair a strong boost in the opposite direction, thus both the γ_{ISR} and the ππ are likely to escape detection. Therefore only events where the γ_{ISR} is detected in the EMC are used. The signature for the signal is e^+e^- → π^+π^−γ_{ISR}.

The main background consists of e^+e^- → μ^+μ^-γ. Using an Artificial Neural Network (ANN) from the TMVA package [12] this background was suppressed. The ANN was trained using large Monte Carlo samples containing signal π^+π^-γ and background μ^+μ^-γ events. The Monte Carlo samples were generated with the Phokhara event generator [13, 14] and were then propagated through a detector simulation based on the Geant-4 software [15, 16].

\[ 3.2. \textbf{Determination of } a_{\pi\pi}^{\text{e+e-\rightarrow\pi+\pi-}} \text{ and extraction of } |F^2| \]

To calculate the \( a_{\pi\pi}^{VP,LO} \) contribution to \( a_{\mu}^{VP,LO} \) the bare cross section corrected for Final State Radiation (FSR) is needed. The bare cross section is the observed cross section corrected for vacuum polarization effects. It is determined using two different normalization schemes. In the first scheme the bare cross section is extracted by correcting for vacuum polarization effects directly as

\[ \sigma_{\pi\pi(\gamma_{\text{PSR}})}^{\text{bare}} = \frac{N_{\pi\pi\gamma} \cdot (1 + \delta_{\text{FSR}})}{L \cdot \epsilon_{\text{global}} \cdot H(s) \cdot \delta_{\text{vac}}}, \]

where \( L \) is the luminosity, \( \epsilon_{\text{global}} \) is the global efficiency of measuring a signal event, \( H(s) \) is the ISR radiator function, \( \delta_{\text{vac}} \) is the vacuum polarization correction and \( (1 + \delta_{\text{FSR}}) \) is the FSR correction factor. The vacuum polarization correction is obtained from the Phokhara generator [13, 14]. In the second method the number of signal events \( N_{\pi\pi\gamma} \) is normalized using the measured \( N_{\mu\mu\gamma} \), thus cancelling the vacuum polarization effects. Both methods agree within errors. The detection efficiency is slightly dependent on the invariant mass of the ππ system. To account for the energy dependence of the detector resolution, a singular value decomposition [17] was performed on the mass spectrum. The FSR correction is obtained from Phokhara [13, 14], by first simulating the spectrum including FRS effects to next-to-leading order (NLO). The same spectrum was then simulated again without the FSR effect. The two spectra were the divided to obtain the correction factor. As suggested in [18], the form factor was extracted from the cross section via

\[ |F_{\pi}|^2(s') = \frac{3s'}{\pi \alpha^2 \beta_{\pi}(s')} \sigma_{\pi\pi}^{\text{dressed}}(s'), \]

where, \( \alpha \) is the fine-structure constant, \( \beta_{\pi}(s') \) is the velocity of the charged pions and \( \sigma_{\pi\pi}^{\text{dressed}}(s') \) is the cross section corrected for FSR but not for vacuum polarization.

\[ 3.3. \textbf{Results} \]

The fit of the extracted form factor was performed using a Gounaris-Sakurai parametrisation [18]. The cross section and form factor as a function of \( \sqrt{s} \) can be seen in Fig. 4. The relative difference between the form factor squared from BaBar [19] and KLOE [20, 21, 22] compared to the BESIII [23] fit is shown in Fig. 5. Deviations for \( \sqrt{s} \) above the mass of ρ meson can be seen between BESIII and both BaBar and KLOE data, below the \( \rho - \omega \) interference region the BESIII fit agrees with the KLOE data, where as a shift can be seen between the BESIII fit and the BaBar data.

To calculate the value of the contribution of the ππ channel in the invariant mass range 600-900 MeV/c range to \( a_{\mu}^{\pi\pi,LO} \) the bare cross section is used as input to the integral

\[ a_{\mu}^{\pi\pi,LO}(0.6 - 0.9 \text{ GeV}) = \frac{1}{4\pi^3} \int_{(0.6 \text{ GeV})^2}^{(0.9 \text{ GeV})^2} ds' K(s') \sigma_{\pi\pi}^{\text{bare}}(e^+e^- \rightarrow \pi^+\pi^-(\gamma_{\text{FSR}})) \]
Figure 4. The left figure shows the bare cross section with statistical errors. In the right figure the red line shows the fit of the form factor squared, using a Gounaris-Sakurai parametrization. The black dots are the measured form factor squared, with statistical errors [23].

Figure 5. The left and right panel shows the relative difference between the form factor squared from BaBar [19] and KLOE [20, 21, 22], respectively, to the BESII [23] fit. For the BaBar and KLOE data points both systematic and statistical errors are included, for the BESIII fit the width of the band corresponds to the statistical error [23].

where $K(s')$ is the kernel function [24, Eq. (5)]. The integral in Eq. 3 was calculated to

$$a_{\mu}^{\pi, LO}(600 - 900 \text{ MeV}) = (368.2 \pm 2.5_{\text{stat}} \pm 3.3_{\text{sys}}) \cdot 10^{-10}.$$  

This result is compatible with corresponding values using KLOE data, but disagrees with BaBar as can be seen in Fig. 6. The BESIII results were recently published in [23].

4. Search for $\eta_c \rightarrow e^+e^-$

BESIII have large sets of data collected around the $J/\Psi$ peak. This data could be used to look for $\eta_c \rightarrow \Upsilon^+\Upsilon^-$. A possible signature for the decay would be $e^+e^- \rightarrow \gamma\Upsilon^+\Upsilon^-$, where $e^+e^- \rightarrow J/\Psi$ which further decays $J/\Psi \rightarrow \gamma\eta_c$ where $\eta_c \rightarrow \Upsilon^+\Upsilon^-$. One could in principle obtain $10^7 \eta_c$ candidates. But due to the nature of the final state, large background from electromagnetic continuum processes with the same $e^+e^- \rightarrow \gamma\Upsilon^+\Upsilon^-$ signature is expected. Therefore a dedicated data sample has been collected in order to study the reverse process $e^+e^- \rightarrow \eta_c$, as suggested in [25]. Using the reverse process, one also has the opportunity of choosing the final state(s) to study. Choosing a C-even final state suppresses first order C-odd background processes from the electromagnetic continuum. The dedicated data sample comprise $\approx 60 \text{ pb}^{-1}$ in four points: 2950, 2981, 3000 and 3020 MeV, placing BESIII in a unique position for the search of $e^+e^- \rightarrow \eta_c$. The results will be reported during 2016.
5. Conclusion

Precise measurements of the $a_{\mu}^{\text{bare}}(e^+e^- \to \pi^+\pi^-(\gamma_{\text{FSR}}))$ cross section and the charged pion form factor has been performed at BESIII using the method of radiative return. The charged pion contribution to $(g - 2)_\mu$ was determined: $a_{\mu}^{\pi\pi,\text{LO}}(600 - 900\text{ MeV}) = (368.2 \pm 2.5_{\text{stat}} \pm 3.3_{\text{sys}}) \cdot 10^{-10}$. The new BESIII results are in agreement with previous KLOE measurements but in disagreement with BaBar. The search for $e^+e^- \to \eta_c$ is ongoing, using data recently collected at BESIII.

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