Form Factor Measurements at BESIII for an Improved Standard Model Prediction of the Muon $g-2$

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The anomalous part of the magnetic moment of the muon, $(g-2)_\mu$, allows for one of the most precise tests of the Standard Model of particle physics. We report on recent results by the BESIII Collaboration of exclusive hadronic cross section channels, such as the 2π , 3π , and 4π final states. These measurements are of utmost importance for an improved calculation of the hadronic vacuum polarization contribution of $(g-2)_\mu$, which currently is limiting the overall Standard Model prediction of this quantity. BESIII has furthermore also initiated a programme of spacelike transition form factor measurements, which can be used for a determination of the hadronic light-by-light contribution of $(g-2)_\mu$ in a data-driven approach. These results are of relevance in view of the new and direct measurements of $(g-2)_\mu$ as foreseen at Fermilab/USA and J-PARC/Japan.

Keywords: $(g-2)_\mu$; BESIII; multi- π cross section.

1. Anomalous Magnetic Moment of the Muon

The muon anomalous part of the magnetic moment (MAMM) is one of the most interesting topics which could be addressed in modern experiments. The Standard Model prediction are extremely accurate, and the high quality of the data collected by the various experiments allows an increasing precision on this measurement. The Standard Model prediction^{1,2} differs from the experimental data.

The magnetic moment of a spin-1/2 particle (a lepton) can be defined as $\bar{\mu} = g \frac{Qe}{2m} \bar{s}$, where Q and m are the charge and the mass of the lepton, g is the gyromagnetic ratio, and $\bar{s}$ is the lepton spin. According to the Dirac theory, the gyromagnetic ratio can be defined as $g = 2(1 + a)$, where a is the MAMM, that, in the case of the muon, is $a_\mu = \frac{g_\mu - 2}{2}$. The muon anomaly arises mainly from quantum fluctuation, but in order to provide a precision measurement, also the weak and the

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hadronic contributions have to be taken into account. From the theoretical point of view, the prediction is limited by the hadronic contributions. By comparing the prediction with the experimental data, a discrepancy of $\alpha_\mu^{theo} - \alpha_\mu^{exp} = 27.6 \cdot 10^{-10}$ arises. It is worth to notice that this difference is even higher than the weak contribution.

The hadronic effects could be divided into two classes, depending on the process they undergo: the hadronic vacuum polarization (HVP) and the hadronic light-by-light (HLBL) processes. The first class could be investigated in elementary processes which, by means of the optical theorem, could be connected to the muon anomaly via dispersion integrals $a_\mu^{HVP,LO} = \frac{1}{4\pi^3} \int_{m_{\pi^0}}^\infty ds K(s) \sigma_{had}(s)$, where $K(s)$ is the kernel function, and $\sigma_{had}(s)$ is the hadronic cross section. The latter could be evaluated by means of two-photon collisions.

The fact that the dispersion integral is proportional to $1/s^2$ suggests that the main contribution to the HVP comes from the low mass region. In particular it depends on pionic events, especially from the 2π final state. KLOE³ and BABAR⁴ measurements managed to reach the sub-percent precision, but they have a 3-5% discrepancy, which limits our knowledge. The BESIII experiment is able to provide a high precision measurement of the pionic contributions, offering a wider mass range and a lower suppression of ISR events, which is connected with the radiator function of the dispersion integral.

2. BEPCII and BESIII Spectrometer

The Beijing Electron-Positron Collider II (BEPCII), with beam currents up to 0.93 A, has reached in 2016 its design Luminosity of $1 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$. The beam energy can be tuned according to the required center of mass energy, ranging from 1.0 up to 2.3 GeV. The BESIII (BEIJING Spectrometer III)⁵, hosted on the BEPCII $e^+ e^-$ collider at the Institute of High Energy Physics (IHEP) in Beijing, with its excellent performances offers the appropriate scenario to provide a high precision measurement of the hadronic contributions. The wide geometrical acceptance provided by the spectrometer, of about 93% of the solid angle, is a consequence of its shell like structure. From the interaction point, a 43 small-cell, helium-based main drift chamber (MDC) chambers, a time-of-flight (TOF) system, and an electromagnetic calorimeter (EMC) composed of 6240 CsI (Tl) crystals arranged in a cylindrical shape (barrel) plus two end-caps inside a 1T solenoidal magnetic field provide charged tracks reconstruction and charged and neutral energy and particle identification information. A muon chamber (MUO) system, composed of resistive plate chambers arranged in 9 layers in the barrel and 8 layers in the end-caps, is hosted in the segmented magnet iron yoke.

The excellent performances provided by the BESIII spectrometer allowed to collect the world largest data sample of J/ψ , $\psi(3686)$, and $\psi(3770)$. The 2.93 fb^{-1} from the latter were used to investigate the multi-pionic final states cross sections by means of the ISR method.

3. Hadronic Vacuum Polarization

In order to address the HVP contribution, the ISR technique was implied. With this technique, the emission of a high energetic photon radiated from one of the beam particles is exploited in order to reduce the center of mass available energy. In this way, it is possible to address the proper energy range suitable for the measurement.

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

A third, independent high precision measurement of the $e^+e^- \rightarrow \pi^+\pi^-$ cross section was suggested by the 3% discrepancy observed between KLOE ³ and BABAR ⁴ data. The BESIII measurement ⁶ was performed by applying the tagged ISR technique, i.e. the radiative photon was explicitly detected. In order to properly identify the two pions in the final state, the leptonic events have to be removed. The electron pairs were rejected with the PID algorithm by exploiting MDC, TOF and EMC information. Muon-pion separation is performed by means of Artificial Neuronal Network (ANN). The Zernicke moments of the EMC clusters, the ratio of the energy deposited by a track in the EMS and its momentum, the ionization energy loss, and the depth of a track in the MUC were investigated, and a very clean $\pi^+\pi^-$ sample was obtained. The $e^+e^- \rightarrow \pi^+\pi^-$ cross section was calculated by taking into account final state radiation and vacuum polarization ⁷ effects.

The squared pion form factor ($|F_\pi|^2$) in the $\rho(770)$ resonance region (600-900 MeV) is shown in Fig. 1 (left). The Gounaris-Sakurai parametrization was used for the fit. In this histogram the ρ - ω interference is clearly visible. BESIII data are found to be in agreement ⁶ with KLOE and BABAR data. A small shift after the ρ - ω interference with respect to the BABAR data was appreciated. The contribution to MAMM was found to be $a_\mu^{\pi\pi, LO}(600 - 900 \text{ MeV}) = (368.2 \pm 2.5 \pm 3.3) \cdot 10^{10}$, thus confirming a deviation of more than 3σ from the theoretical expectation. A comparison of the MAMM results from KLOE, BABAR and BESIII is shown in Fig. 1 (right).

Contributions coming from higher energies are expected to be quite smaller. The corresponding cross sections are reported in the following.

Fig. 1. The measured squared pion form factor $|F_\pi|^2$ (left), and comparison of KLOE, BABAR and BESIII results (right).

3.2. $e^+e^- \rightarrow \pi^+\pi^-\pi^0$

The three pion final state was measured in the ω and φ energy regions by means of the tagged ISR technique, and above the φ resonance by means of both tagged and untagged ISR methods. The topology of the events above the φ energy allows to exploit the untagged ISR technique, in which the ISR photon is not detected, but its 4-momentum can be predicted by imposing 4-momentum conservation. In this way, one gains the access to those reactions in which the photon is emitted in the most forward direction, which dominate the topology, thus increasing the statistics. The cross sections, shown in Fig. 2, range from 0.75 to 3 GeV. The calculated cross sections are corrected for final state interaction and vacuum polarization effects. BESIII data agree well with CMD2^{8,9} and SND^{10,11} results in the ω and φ regions. At higher masses, BESIII confirms the two structures found by BABAR¹² above the φ . If those structures are ω recurrences, one would expect that increasing the mass the width would increase accordingly, while we observe that the first structure is quite larger than the second one. The measured cross sections could be used as input in the calculation of the muon anomalous magnetic moment contribution coming from three pions final states.

3.3. $e^+e^- \rightarrow \pi^+\pi^-2\pi^0$

Also for this analysis, both tagged and untagged ISR methods were exploited. In this work, the background is dominated by $e^+e^- \rightarrow \pi^+\pi^-3\pi^0$ events, characterized by a poorly known cross section. For this reason, this background is modeled via HelpWA, which uses the real data to perform a PWA of the final state and then generates the events according to the PWA result. The $e^+e^- \rightarrow \pi^+\pi^-2\pi^0$ cross section combined from the tagged and untagged modes is shown in Fig. 3 (left). The process $e^+e^- \rightarrow \omega\pi^0$ was investigated as well and its cross section is shown in Fig. 3 (right). Final state radiation and vacuum polarization effects were taken into account. For both processes, BESIII results are in good agreement with the ones in the literature¹³, except the ND experiment. The contribution to MAMM was found to be $a_\mu^{\pi^+\pi^-2\pi^0, LO} = (18.6 \pm 0.3 \pm 0.6) \cdot 10^{10}$.

Fig. 2. The measured $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ cross section in the ω (left), φ (middle), and above φ (right) energy ranges.

3.4. $e^+e^- \rightarrow \pi^+\pi^-3\pi^0$

In order to improve the MC description of the background contribution to the 4π final states, the processes $e^+e^- \rightarrow \pi^+\pi^-3\pi^0$, $e^+e^- \rightarrow \omega 2\pi^0$, and $e^+e^- \rightarrow \eta\pi^+\pi^-$ were investigated. The obtained cross sections are shown in Fig. 4, where the final state radiation and the vacuum polarization effects are taken into account. The J/ψ resonance appears smeared, because the cross section spectrum is not unfolded for detector resolution.

4. Hadronic Light-by-Light

The second hadronic contribution to the definition of the muon anomaly is the light-by-light contribution, which arises from the interaction of virtual mesons with real or virtual photons. Unfortunately, this contribution is not directly related to measurable quantities. From the literature, two approaches are suggested. Hadronic models combine chiral perturbation theory and perturbative QCD, but it is not clear their interplay in the intermediate region ¹⁴. On the other hand, data-driven approaches, based on dispersion relations, exploit the transition form factors as experimental input ¹⁵. An investigation method could be the study of two-photon collisions, which allow to access different final states. This study is characterized

Fig. 3. The measured $e^+e^- \rightarrow \pi^+\pi^-2\pi^0$ (left) and the $e^+e^- \rightarrow \omega\pi^0$ (right) cross sections.

Fig. 4. The measured cross sections for $e^+e^- \rightarrow \pi^+\pi^-3\pi^0$, $e^+e^- \rightarrow \omega 2\pi^0$, and $e^+e^- \rightarrow \eta\pi^+\pi^-$.

by a forward peaked kinematic, which makes it experimentally challenging. An important improvement could come from special tagging detector placed in the most forward regions. The current accuracy of the measurement is about $6 \cdot 10^{-10}$. But in such scenario, η and η' contributions are becoming relevant, since they are expected to be in the order of 10^{-10} , according to the theoretical calculations. The BESIII Collaboration is already working on a two-photon physics program.

5. Conclusions

Using the 2.93fb^{-1} of data collected at the center of mass energy of $s = 3.773$ GeV, the BESIII Collaboration performed new high precision measurements of the multi-pionic final states cross sections. The obtained results are compatible with the ones in the literature. For the leading-order vacuum polarization parts of the anomalous magnetic momentum of the muon, $a_{\mu}^{\pi\pi, LO} = (368.2 \pm 2.5 \pm 3.3) \cdot 10^{10}$ and $a_{\mu}^{\pi^+\pi^-2\pi^0, LO} = (18.6 \pm 0.3 \pm 0.6) \cdot 10^{10}$ were obtained. We expect encouraging results from the two new experimental measurements planned at J-PARC¹⁶, in Japan, and at Fermilab¹⁷, in USA.

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