Frascati Physics Series Vol. 69 (2019)
PHOTON 2019 - International Conference on the Structure and the Interactions of the Photon
June 3-7, 2019

TRANSITION FORM FACTOR MEASUREMENTS AT BESIII

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Abstract

Motivated by the recent developments in data-driven approaches to improve the hadronic light-by-light scattering calculations of the Standard Model prediction of the anomalous magnetic moment of the muon a_μ, the BESIII collaboration has embarked on a dedicated two-photon physics program. The momentum dependence of transition form factors of single pseudoscalar mesons, as well as of multi-meson systems is studied. Based on the high statistics data, collected at the τ-charm factory BESIII operated at the BEPCII accelerator in Beijing, the information can be provided in the relevant momentum region for a_μ. In this presentation we discuss recent results, the current status of ongoing measurements, and the prospects for $\gamma\gamma$ collision studies at BESIII.

1 Introduction

The anomalous magnetic moment of the muon a_μ is defined as the relative deviation of the muon's Landé factor g_μ from the Dirac solution, which predicts a value of $g = 2$. It is one of the most precisely known observables in the Standard Model, and is determined in theory and experiment to a precision of 0.5 ppm [1, 2]. However, there is a long standing discrepancy of more than three standard deviations between the Standard Model prediction and the direct measurement of a_μ. Since it can be a hint for New Physics, the discrepancy triggered a worldwide effort to increase the accuracy in both theory and experiment. In the course of this endeavor, two new direct measurements of a_μ are planned, which aim at improving the accuracy of the current value by a factor four. The E989 experiment at Fermilab [3] reuses the storage ring of the BNL E821 experiment. Due to a higher beam intensity and an improved apparatus, a first result with a statistical accuracy equivalent to the BNL result is expected by the end of 2019. A second experiment is planned at J-PARC, Tokai, which makes use of ultra-cold muon beams eliminating the need for focusing electric fields in the experimental apparatus [4]. Thus, the measurement will be a systematically independent cross check of the Fermilab result.

In the same way the direct measurement is improved, also the Standard Model prediction needs to be improved. While the absolute value of a_μ is almost completely determined from quantum electrodynamics (QED), its uncertainty is completely dominated by the hadronic contributions to the quantum corrections. These cannot be calculated perturbatively due to the running of the strong coupling constant at the relevant energy scale. Non-perturbative efforts like lattice QCD have not yet reached the necessary precision [5]. Other non-perturbative approaches need information from experiments as input to provide a prediction of the hadronic contributions. Generally, the hadronic contributions to a_μ are separated into two parts, the hadronic vacuum polarization (HVP) and the hadronic light-by-light scattering (HLbL) contributions. While the former can at leading order be systematically improved with the help of a dispersion integral [6], which takes cross sections measured at e^+e^- colliders as input, the calculations of the latter process are more involved. The contribution of HLbL can be split up in a dominating contribution of pseudoscalar meson pole exchanges, a contribution of pion and kaon loops, and minor contributions due to scalar and axial resonances as well as quark loops [7]. Recently, dispersive frameworks have been devised, which allow to determine the two leading contributions in a data-driven way [8]. The relevant experimental inputs are transition form factors of pseudoscalar mesons at arbitrary virtualities, and the partial waves of the process $\gamma^*\gamma^* \to \pi\pi$. It can be shown that information on these observables at small spacelike momentum transfer, below approximately $1\,\mathrm{GeV}^2$, is most relevant [9]. However, existing data is scarce and is mostly acquired at B-factories with large momentum transfers [10, 11]. The BESIII experiment can provide data in the relevant momentum range with high accuracy.

2 The BESIII detector at BEPCII

The BESIII detector is a magnetic spectrometer [12] located at the Beijing Electron Positron Collider (BEPCII) [13]. The cylindrical core of the BESIII detector consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identifier modules interleaved with steel. The acceptance of charged particles and photons is 93% over 4π solid angle. The charged-particle momentum resolution at $1\,\mathrm{GeV}/c$ is 0.5%, and the dE/dx resolution is 6% for the electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution of the TOF barrel part is 68 ps, while that of the end cap part is 110 ps. The end cap TOF system is upgraded in 2015 with multi-gap resistive plate chamber technology, providing a time resolution of 60 ps [14].

BEPCII provides e^+e^- collisions at center of mass energies between 2.0 GeV and 4.6 GeV. The design luminosity of the machine of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the center of mass energy $\sqrt{s} = 3.773\,\mathrm{GeV}$ has been achieved. The data taking campaigns focus on the many aspects of the BESIII physics program of charmonium spectroscopy, open charm physics, light hadron spectroscopy and precise τ-mass and R scan measurements. The worlds largest data sets on e^+e^- collisions in the τ-charm region have been acquired. As of 2019, these correspond in total to an integrated luminosity of more than $20\,\mathrm{fb}^{-1}$, which includes among others a sample of 10^{10} J/ψ decays recorded on disk [15].

3 Transition Form Factors of Pseudoscalar Mesons

At BESIII, transition form factors (TFF) of pseudoscalar mesons can be measured in three different reactions. Dalitz decays of pseudoscalar mesons, as well as their radiative production in e^+e^- annihilations allow to determine TFF in the timelike regime. The meson mass puts a lower and upper limit on the momentum transfer range accessible in the respective process. The spacelike regime of the momentum dependence of TFFs can be studied in two-photon fusion reactions. In an e^+e^- collision both leptons can exchange a photon, which in turn fuse and form mesons of the quantum numbers $J^{PC} = 0, 2^{\pm +}$. These states are not directly accessible in the dominating annihilation processes, where only a single photon is exchanged. The cross section of these two-photon reactions is directly proportional to the square of the TFF, which in turn is a function of the virtualities of the two photons. The virtuality can be measured as it corresponds to the momentum transfer $q^2 = -Q^2$ of the scattered leptons. Limitations in the accessible range of Q^2 come from the detector acceptance. Like most detectors at e^+e^- colliders, at BESIII the region of polar angles below $\cos\theta \geq 0.93$ is not covered by detector elements, due to the beam optics necessary to establish the collisions. Unfortunately, the differential cross section of two-photon fusion reactions is peaked towards small scattering angles of the leptons. A practical way to still learn about the momentum dependence of meson TFFs are single-tagged measurements. In this analysis technique, apart from the produced meson, only one of the two scattered leptons is required to be registered in the active detector volume. The four-momentum of the second lepton is reconstructed from energy and momentum conservation. By requiring the polar angle of the missing momentum to be small, also the momentum transfer of the respective lepton will be small. In the selected two-photon events a virtual and a quasi-real photon are exchanged. The measured TFF $F_{p\gamma^*\gamma^*}(Q_1^2, Q_2^2)$ of a meson p depends now only on a single virtuality $F_{p\gamma^*\gamma}(Q_1^2, Q_2^2 = 0) \equiv F_{p\gamma^*\gamma}(Q^2)$.

As a first measurement at BESIII the spacelike TFF of π^0 is measured in a single-tagged analysis of $2.318\,\mathrm{fb}^{-1}$ taken at $\sqrt{s} = 3.773\,\mathrm{GeV}$. The meson is reconstructed from its dominating decay mode in two photons. The selected event topology of an electron or positron and at least two photons has a dominating background contribution from radiative Bhabha scattering. Apart from the single-tag condition explained above, these events can be effectively rejected with conditions on the helicity angle of the photons assigned to the π^0 candidate, as well as their polar angle difference in the lab frame. The latter condition addresses effects of cluster splitting observed for high energetic photons. An additional condition, successfully used by the BaBar collaboration to reduce background contributions of radiative effects in two-photon events [11], turned out to efficiently remove remaining background contributions from annihilation reactions producing $q\bar{q}$ continuum events. Remaining background contributions are subtracted from the differential momentum transfer distribution, by fitting the π^0 peak above the continuous background distribution in the two photon invariant mass distribution for each bin in Q^2. The background subtracted distribution is normalized to the respective bin widths, the detection efficiency, and the integrated luminosity of the data, in order to determine the differential cross section. The TFF is extracted by dividing out the pointlike cross section using Monte Carlo generated distributions based on the Ekhara 3.0 event generator [16].

Figure 1 shows the preliminary result of the spacelike π^0 TFF measurement. Momentum transfers from $0.3\,\mathrm{GeV}^2$ to $3.1\,\mathrm{GeV}^2$ are covered. The left panel compares the BESIII measurement to previous results in the same region of momentum transfer. At largest values of Q^2 the accuracy is compatible with the results of the CLEO collaboration [10], while below $1.5\,\mathrm{GeV}^2$ the accuracy of BESIII exceeds that of all previous measurements. Furthermore, the range of available information is extended, as the CELLO result only provided data down to $0.5\,\mathrm{GeV}^2$ [10]. The center panel of fig.1 confronts the preliminary

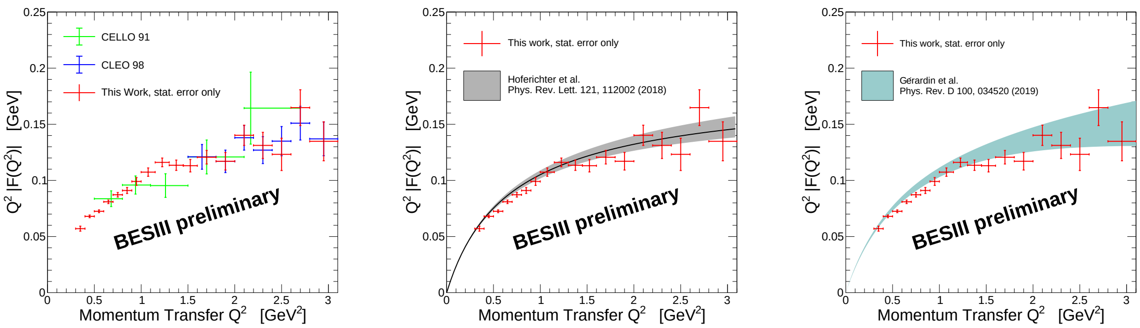

Figure 1: *The preliminary result of the* π^0 *TFF measurement.* **Left:** *A comparison to previous measurements* [10]. **Center:** *A comparison to the prediction of a dispersive construction of the TFF* [17]. **Right:** *A comparison to a lattice calculation of the TFF* [18].

BESIII result with a prediction of the pion TFF, which is constructed in dispersive theory from existing time-like data [17]. The data show good agreement, although especially at smaller values of Q^2 the data rather seem to follow the edge of the error band of the prediction than its central value. In the right panel of fig.1 the preliminary data are compared to the lattice calculation [18] of the singly-virtual pion TFF. A similar relation between experiment and theory as for the dispersive calculation is observed, where the data points rather agree with the edge of the error band corresponding to one standard deviation. The preliminary BESIII result does not yet include a proper treatment of radiative effects. This will be taken into account using full calculations of radiative corrections implemented in the Ekhara 3.0 event generator [16].

4 Transition Form Factors of the Two-Pion System

With the exception of a recent Belle result on neutral pion pairs [19], all information on the two-photon production of pion pairs has been acquired in collisions of quasi-real photons [20]. Additionally, information on the two pion systems with small invariant masses barely exists. At BESIII a single-tagged analysis has been started, using a combined data set of $7.5\,\mathrm{fb}^{-1}$ at $3.773 \leq \sqrt{s}\,[\mathrm{GeV}] \leq 4.6$, with the aim to measure $\gamma\gamma^* \to \pi^+\pi^-$ over a wide range of the parameter space relevant for the data-driven calculations of the HLbL contributions to a_μ. The strategy of the analysis follows the techniques successfully applied for single pseudoscalar mesons. The dominating background contributions come from two distinct sources. On the one hand, the conventionally applied means of particle identification cannot sufficiently separate pions from muons, which leads to a strong contribution of the reaction $e^+e^- \to e^+e^-\mu^+\mu^-$. On the other hand, the radiative Bhabha scattering process, where the photon couples to a ρ meson, which in turn decays into charged pion pairs, leads to an irreducible background of the reaction $e^+e^- \to e^+e^-\rho \to e^+e^-\pi^+\pi^-$.

The former source of background is well understood in terms of existing Monte Carlo event generators [21]. These are used to train and apply machine learning techniques based on boosted decision trees in order to achieve a track based separation of pions and muons. In this way, the background from muon pair production can be efficiently suppressed. The irreducible source of background from pion production is subtracted from data using the precise knowledge of the pion form factor and its available parametrizations. Taking into account the $\gamma\gamma$ luminosity function, the background subtracted data allow to study the reaction $\gamma\gamma^* \to \pi^+\pi^-$ for the first time at momentum transfers between $0.2 \leq Q^2[\mathrm{GeV}^2] \leq 2.0$ at invariant masses starting from the two pion threshold up to 2 GeV, at a full coverage of the pion helicity angle.

5 Outlook

The successful measurement of the pion TFF is being extended to other pseudoscalar mesons. The η meson has already been observed in the decay photon invariant mass spectrum used for the background subtraction in the π^0 TFF measurement. Additional, feasibility studies are performed, where the η production is tagged using the three pion decay modes. All tests indicate a TFF result covering the same Q^2 range as achieved for the π^0 with competitive accuracy. Similar studies have been done for the η' meson, where the decay mode $\eta' \to \pi^+\pi^-\eta$ is exploited. The studies also showed the feasibility of measurements of TFFs of axial and tensor mesons, since the $a_2(1360)$ is seen in the three pion invariant mass spectrum and the $f_1(1285)$ is seen in the $\pi^+\pi^-\eta$ invariant mass spectrum. A good knowledge of the contributions of these mesons to the HLbL contribution to a_μ is necessary to bring the precision of the Standard Model prediction of a_μ to the final accuracy aimed at by the new direct measurements. Similarly, the measurement of the two pion system is extended to neutral systems, including $\pi^0\eta$ and $\eta\eta$ final states.

So far only fractions of the complete data acquired at BESIII have been exploited. Feasibility studies have shown that by combining all data sets measurements of the doubly virtual TFF of pseudoscalar mesons are possible. Currently, only a single measurement of the η' TFF is published [22]. However, a region of momentum transfer is covered, which is of minor impact for the calculations of a_μ. At BESIII, the TFFs of π^0, η and η' will be measured at values of Q^2 around ($Q_1^2 \approx 1\,\mathrm{GeV}^2, Q_2^2 \approx 1\,\mathrm{GeV}^2$). The expected precision will allow for model independent determinations of the TFF, and is expected to have a considerable impact on the precision of the data-driven approaches to HLbL [9]. At the same time, additional tagging detectors at small angles are developed, which will extend the prospects for double-tagged two-photon measurements towards regions of smaller momentum transfer.

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