The $\gamma\gamma$ Physics Program at BESIII

C.F. Redmer for the BESIII Collaboration[1,⋆]

[1] *Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, J.-J.-Becher Weg 45, 55128 Mainz, Germany*

Abstract. A key motivation for the two-photon physics program of the BESIII collaboration is the need of high precision data on electromagnetic transition form factors as input to the calculations of the contribution of hadronic Light-by-light scattering to the anomalous magnetic moment of the muon. The data collected with the BESIII detector allow to study the momentum dependence of the form factors at small momentum transfers, which is of special relevance for a_μ. In this presentation the ongoing measurements of the transition form factors of π^0, η and η' mesons, as well as pion pairs, are discussed, and the potential for first double-tagged measurements at BESIII are pointed out.

1 Introduction

The production and investigation of hadrons at electron-positron colliders mostly relies on the annihilation of the beam particles. All states produced in this reaction are bound to the quantum numbers of the virtual photon, which is exchanged: $J^{PC} = 1^{--}$. In order to study hadrons with other quantum numbers usually the different decay modes of the produced resonances are exploited.

Final states with quantum numbers different from $J^{PC} = 1^{--}$ can be produced directly at e^+e^- colliders in two-photon collisions. Instead of annihilating, the leptons scatter and exchange two photons in the process, which fuse into a new, hadronic state. The investigation of these processes provides a clean laboratory for the spectroscopy of light hadronic $J^{PC} = 0, 2^{\pm+}$ states. In contrast to hadronic systems produced in e^+e^- annihilations, the mass of these hadrons is well below the center-of-mass energy of the collider. As they are produced in a purely electromagnetic environment, studying these light hadrons provides important input to the search for gluonium or gluon-rich states.

The cross section of hadronic final states in $\gamma\gamma$ collisions is proportional to their respective radiative width $\Gamma_{\gamma\gamma}$ and the squared transition form factor (TFF) $|F(Q_1^2, Q_2^2)|^2$, with $Q_i = -q_i$ being the momentum transfer of the scattered leptons and, thus, the virtuality of the colliding photons [1]. Therefore $\gamma\gamma$ physics also provides access to structural information of the produced hadronic states. This presentation focuses on the measurement of the TFF of light mesons at the BESIII experiment, which is motivated by the ongoing efforts in theory and experiment to determine the anomalous magnetic moment of the muon, a_μ.

The anomalous magnetic moment of the muon is one of the most precisely known observables in particle physics. Over the recent decades enormous efforts have been made to reach a precision in the order of 10^{-10} in the direct experimental measurement [2], as well as in the Standard Model prediction

⋆e-mail: redmer@uni-mainz.de

of a_μ. However, there remains a discrepancy of 3 to 4 standard deviations between the measured and the calculated values of a_μ [3, 4]. The potential origin of this difference has triggered a lot of activity, since, even if not being significant enough to claim a discovery, it could be considered as a hint for New Physics.

New experiments have been proposed to remeasure a_μ with a four times better precision [5, 6]. These proposals have triggered numerous efforts to improve the Standard Model prediction on the same level. While the dominating QED contribution has been calculated including corrections up to the tenth order [7], and the weak contribution also being well understood by means of perturbation theory [8], the error of the prediction of a_μ is completely dominated by the hadronic contributions. The main challenge is that QCD cannot be handled by perturbative methods at the relevant energy regime.

The largest hadronic contribution a_μ^{hVP} is due to the hadronic vacuum polarization. It can be handled within a dispersive framework, which requires hadronic cross sections measured at e^+e^- colliders as experimental input [4]. Various laboratories world wide have measured $\sigma(e^+e^- \to \text{hadrons})$ in scan experiments and exploiting the technique of Initial State Radiation (ISR). These results can be used to significantly reduce the uncertainty of a_μ related to hadronic vacuum polarization in the near future.

Another hadronic contributions comes from hadronic Light-by-Light scattering (hLbL), a_μ^{hLbL}. It cannot be as easily related to experimental observables as a_μ^{hVP}. Calculations of the hLbL process are possible at lowest energies by means of chiral perturbation theory, or at high energies, using perturbative QCD. The energy scale relevant for the magnetic moment of the muon is the intermediate regime, which cannot be addressed by perturbative means. In order to evaluate the hLbL, different hadronic models have been developed and are used for the calculation of a_μ^{hLbL}. Two more frequently quoted examples for these models are provided by Prades, de Rafael and Vainshtain [9], which is referred to as the "Glasgow Consensus", and by Jegerlehner and Nyffeler [3]. The different models agree on the dominating processes in their evaluation of hLbL, which comes from the transitions of the pseudoscalar mesons π^0, η and η' [10]. The validity of the models can, thus, be tested with measurements of the momentum transfer dependence of the respective TFF. The uncertainties of the resulting values of a_μ^{hLbL} are, however, strongly model dependent.

In order to reduce the model dependency of the prediction of a_μ^{hLbL}, data driven approaches are being developed. Their goal is to provide a more reliable estimate of the uncertainty of a_μ^{hLbL} by describing the dominating processes based on dispersive analyses [11, 12] and experimental information. Important inputs to these calculations are the TFF of π^0, of two pions and the pion polarizabilities.

Only few experiments investigated the momentum dependence of space-like TFF of light mesons. At e^+e^- machines the information can be accessed via the meson production in two-photon collision. However, the kinematics of two-photon reactions result in a maximum of the differential cross section at smallest scattering angles of the two leptons. Detectors designed to study the annihilation reactions of the beam particles do not cover smallest scattering angles. The design of the beam pipes and the need for magnets close to the interaction point to bring the beams to collision prevents the installation of detectors. Instead, a technique referred to as "single-tag measurement" is applied. Only one of the two scattered leptons and the complete hadronic system, which was produced, is reconstructed in the detector volume. The other lepton is assumed to have escaped detection at smallest scattering angles, i.e. it has been scattered along the beam axis. The assumption can be tested with the polar angle of the missing momentum of the detected particles. Since the momentum transfer of the undetected lepton is small, the exchanged photon is quasi-real and the TFF depends only on a single momentum transfer: $F(Q_1^2, Q_2^2 \approx 0) = F(Q^2)$.

The most recent results on the momentum dependence of TFF are provided by the B-factories [13–16]. Their studies of the π^0, η, η', and more recently the $\pi^0\pi^0$ system cover momentum transfers Q^2

from 4 GeV^2 to 40 GeV^2. The results, especially for the TFF of the π^0 at $Q^2 > 10$ GeV^2, triggered a discussion on the applicability of pQCD in this energy range, which is often referred to as the Belle-BaBar-puzzle. For the determination of a_μ^{hLbL}, however, these data are less important. Here, the Q^2-dependence of the TFF at approximately 1.5 GeV^2 is most relevant [17]. At these energies only measurements from the CELLO and CLEO experiments [18, 19] are available, which have rather low statistics.

The need for additional precision data on the momentum dependence of TFF, in order to improve the calculations of hLbL and, thus, to improve the prediction of a_μ, is a key motivation of the $\gamma\gamma$ physics program at BESIII. The BESIII experiment can contribute in the region of low momentum transfer and can provide data on the TFF dependence with high statistical accuracy.

2 The BESIII detector at BEPCII

The BESIII experiment [20] is located at the symmetric e^+e^- collider BEPCII, which is operated at the IHEP in Beijing (China). Data can be collected at center-of-mass energies from 2.0 GeV to 4.6 GeV. The BESIII detector setup consists of a large drift chamber surrounding the Beryllium beam pipe, a time-of-flight system, and an electromagnetic calorimeter, which are placed inside the bore of a superconducting solenoid, providing a 1.0 T magnetic field. The flux-return yoke is instrumented and serves as muon counter. The detector covers 93% of the solid angle. Momenta of charged particles and photon energies are measured with a resolution of 0.5% and 2.5% at 1 GeV, respectively.

The BESIII collaboration has collected $1.31 \times 10^9 e^+e^- \to J/\psi$ events, more than $500 \times 10^6 e^+e^- \to \psi(2S)$ events, 2.9 fb^{-1} at the $\psi(3770)$ peak, and more than 10 fb^{-1} in the center-of-mass region above 4 GeV, which are devoted to studies of the charmonia and charmonium-like states [21–23]. Additional data have been acquired for a τ-mass scan and a high statistics R-scan. Based on these data, the BESIII collaboration pursues a physics program [24], which focuses on charmonium spectroscopy, charm physics, light hadron spectroscopy, τ physics, and R-measurements.

The investigations in the field of $\gamma\gamma$ physics make use of all larger data sets, whereas the data taken at $\sqrt{s} = 3.773$ GeV constitute one of the largest individual samples. It is used to study the TFF of π^0, η and η'.

3 Electromagnetic Transition Form Factors of π^0, η and η'

The analysis of the TFF of π^0, η and η' is based on a single-tag technique. The two-photon reaction $e^+e^- \to \mathcal{P}e^+e^-$ with $\mathcal{P} = \pi^0, \eta, \eta'$ is reconstructed by measuring only one of the two scattered leptons and the decay products of the produced mesons $\mathcal{P}$ in the detector. The missing momentum of the measured particles is taken as the four-momentum of the undetected lepton. As it is undetected, its scattering angle smaller is required to be less than 8°, which corresponds to a distance from the beam axis equal to the radius of the beam pipe at the end of the detector.

The π^0 meson is reconstructed from its dominating decay into two photons. The main source of background in the event selection are QED processes, such as radiative Bhabha scattering. Hard radiative photons detected along with soft photons from any secondary process can reproduce the invariant mass of a pion. A set of three conditions has been worked out to successfully reduce the background contribution. First, a limit on the helicity angle of the photons is applied, which is defined as the angle between one of the photons in the rest frame of the pion and the direction of motion of the pion in the laboratory frame. Another condition to suppress radiative Bhabha scattering is imposed by setting a threshold on the scattering angle of the pion candidate. Finally, a minimum polar angle difference of the two photons is required in the laboratory frame to suppress contributions from cluster splitting. Another source of background comes from incompletely detected hadronic final states. Decays of $\psi(3770)$ into pairs of D mesons, the radiative return to $\psi(2S)$ and J/ψ, and, most dominantly, states from the from the $q\bar{q}$ continuum contribute. A condition, designed by the BaBar collaboration [13] to suppress initial state radiation (ISR) in two-photon production, turned out also to suppress this kind of background. Making use of four-momentum conservation to calculate the energy of a potential, unregistered ISR photon, it is also sensitive to the energy imbalance induced by incompletely reconstructed hadronic final states. Event candidates fulfilling all selection criteria show clear signal peaks, not only of the π^0, but also of the η meson in the invariant mass distribution of the two photons.

The differential distribution of the momentum transfer of the tagged lepton is used to extract the TFF of the π^0 and study its momentum dependence. In a first step, the remaining background is subtracted. The background contribution in each bin in Q^2 is estimated from the corresponding invariant mass spectrum of the two photon system. The pion signal content is determined from a fit to the spectrum and the number of signal events above a continuous background are considered as the background free content of the individual bin in Q^2. The background free Q^2 distribution is converted to the distribution of the differential cross section by normalizing it to the reconstruction efficiency and the integrated luminosity. Finally, the TFF is extracted by dividing out the point-like cross section, which is obtained from a Monte Carlo simulation, based on the Wess-Zumino-Witten term [25, 26].

The data taken by the BESIII collaboration at the $\psi(3770)$ peak allow to measure the TFF of the π^0 at momentum transfers in the region between 0.3 GeV^2 and 3.1 GeV^2. The interval matches the kinematic region, which has been identified as most relevant input for the calculations on hadronic Light-by-Light scattering [17]. The statistical accuracy obtained with the analysis scheme described above is unprecedented for $\mathrm{Q}^2 \leq 1.5$ GeV^2; for larger momentum transfers it is compatible with the accuracy of the CLEO [19] result. The evaluation of the systematic uncertainties is being finalized. The method applied for background subtraction has been identified as the largest source of uncertainty. The publication of the final result is expected soon.

An improved understanding of the contribution of the π^0 TFF to a_μ^{hLbL} is, however, only sufficient on the level of the current experimental precision of the direct measurement of a_μ. In view of the announced measurements and their planned four-fold improvement in accuracy, it is necessary to include and to improve the understanding of the contributions of η and η' as well [17].

A dedicated measurement of the respective TFF has been started at BESIII, based on the decay modes $\eta \to \pi^0\pi^+\pi^-$ and $\eta' \to \eta\pi^+\pi^-$. Taking into account the subsequent decays of π^0 and η into two photons, both decay modes yield the same final state. Analogously to the investigation of the π^0 TFF, analysis strategy follows the single-tag technique in order to study the momentum dependence of the TFF. The dominating background contributions involve on the one hand decays of ω and ϕ mesons into three pions in the analysis of the η and η' TFF and on the other hand incompletely reconstructed decays of η' mesons in the analysis of the η TFF. Both kinds of background contributions are efficiently suppressed by kinematically fitting the decay systems to the masses of η and η', respectively.

Similar to the investigation of the momentum dependence of the TFF of the π^0, the TFF of η and η' can be studied based on the data taken at $\sqrt{s} = 3.773$ GeV, for momentum transfers between $0.3 \leq \mathrm{Q}^2\ [\mathrm{GeV}]^2 \leq 3.5$. The statistical accuracy, which is achieved with the analysis strategy described above, is compatible with the published results of the CELLO and CLEO experiments [18, 19]. However, in contrast to these published results, the current analysis of the BESIII data makes only use of a single decay channel. The accuracy achieved by the CELLO and CLEO collaborations combines the results of several different decay channels. Extending the analysis by adding more decay channels, as well as analyzing the remaining data sets will improve the BESIII result significantly.

4 Electromagnetic Transition Form Factors of $\pi\pi$

In addition to the production of single, pseudoscalar mesons, the BESIII collaboration also started the investigation of multi-meson production in two-photon collisions. The aim is to gain additional information on scalar and tensor states, which decay into $\pi\pi$, $\pi\eta$, and $\eta\eta$ systems. The motivation to study the two pion system is twofold. From point of view of spectroscopy, it is possible to extract resonance parameters and also to study pion rescattering effects at low invariant masses of the $\pi\pi$ system. Additionally, the investigation is also motivated by its relevance as input for the data-driven, dispersive calculations for the contribution of hLbL to a_μ.

Previous measurements of the production of two pseudoscalars in two-photon collisions focused on the spectroscopy of intermediate states [27–31]. The published results are based on the untagged technique, where both leptons are scattered close to the beam axis and, thus, escape detection. Due to the behavior of the differential cross section in two-photon collisions, the event rate is largest in this kinematic configuration, which makes it preferable for spectroscopy. The mass range covered by most of the different experiments is restricted to invariant masses larger than approximately 500 MeV/c^2. A few data points at lower masses have been provided by the MARKII experiment.

Recently, the Belle collaboration published the first investigation of the momentum dependence of the TFF in the two-pion system [16]. The $\pi^0\pi^0$ system was studied for momentum transfers between $3 \leq Q^2[\mathrm{GeV}^2] \leq 30$, for invariant masses of the pion pairs between $0.5 \leq m_{\pi^0\pi^0}[\mathrm{GeV/c}^2] \leq 2.1$, and with complete coverage of the helicity angle. In a partial wave analysis the $|D_0|^2$, $|D_2|^2$, and $|S|^2$ wave amplitudes have been determined, and the TFF of the $f_0(980)$ resonance and the three possible helicity states of the $f_2(1270)$ resonance were measured and compared to different predictions [32, 33].

At BESIII a measurement of the $\pi^+\pi^-$ pair production in two-photon collisions is performed. The analysis follows the single-tag strategy, successfully used in the analysis of single pseudoscalar meson production. Further analysis conditions are designed to efficiently suppress the two dominating sources of background. On the one hand, the two-photon production of muon pairs require a special focus on the μ/π separation, and on the other hand there is a contribution of time-like pion pairs production, which stems from radiative Bhabha scattering, where the photon is virtual and couples to a ρ-meson, which in turn decays into two pions.

The QED background of muon production is well understood from the $\gamma\gamma$ physics studies at LEP [34, 35]. Reliable Monte Carlo generators exist, which are currently used to subtract the QED contributions from data. At the same time, the application of an artificial neural network is prepared. Being trained based on the Monte Carlo distributions, it will allow to suppress the background from muon pairs production with an improved statistical accuracy. The method particle identification has already been successfully applied in the measurement of hadronic cross sections [36]. The background involving the ρ-meson is subtracted by fitting the clearly visible peak in the $\pi^+\pi^-$ invariant mass with the Kühn-Santamaria parameterization [37]. The remaining events allow to study the production of $\pi^+\pi^-$ in bins of the momentum transfer Q^2, the pion invariant mass, and the pion helicity angle $\cos\theta^*$. This is the first measurement in the invariant mass region of $2m_\pi \leq M_{\pi\pi}[\mathrm{GeV}] \leq 2.0$ and the momentum transfer region of $0.2 \leq Q^2[\mathrm{GeV}^2] \leq 2.0$ with a full coverage of the helicity angle.

5 Double-tagged Measurements

In double-tagged measurements both of the scattered leptons are registered in the detector. Since the design of common detector setups at e^+e^- colliders focuses on the investigation of final states produced in the annihilation of the beam particles, in a double-tagged measurement the leptons can be registered at large angles only, usually at angles larger 20° with respect to the beam axis. Thus, the momentum transfer of each lepton is large. The cross section of two-photon reactions, however, becomes vanishingly small for two large virtualities. Currently, experimental information on TFFs depending on two virtualities $F(Q_1^2, Q_2^2)$ is not available. The knowledge of TFF with arbitrary virtuality is vital for a reliable error estimate of a_μ^{hLbL}.

First exploratory studies for a double-tagged measurement of the π^0 TFF have been started at BESIII. The aim is to exploit the large data sets, originally collected for charm physics and charmonium-like spectroscopy, which in total correspond to more than 10 fb^{-1}. Based on an analysis chain using only simple conditions on energy and momentum conservation, a part the data have been studied and a π^0 signal has been observed. The signal-to-background ratio is very low, but more sophisticated analysis techniques should be able to improve it. Efficiency studies based on Monte Carlo distributions show that a direct measurement of $F(Q_1^2, Q_2^2)$ is possible for $0.5 \leq Q_i^2\ [\text{GeV}]^2 \leq 1.5$, with $i = 1, 2$. Due to the limited data set, the result of this analysis, regardless of the reconstruction efficiency, which can be achieved in a final, optimized analysis, can provide only limited information on the doubly-virtual TFF. Nevertheless, it is expected to have a significant impact on the uncertainty of a_μ^{hLbL} [38].

The statistics, which has been collected by the BESIII collaboration should provide sufficient accuracy for a meaningful confrontation with hadronic models. As pointed out recently by Nyffeler [38], certain models differ significantly in their Q^2 behavior of the TFF. For example, the momentum transfer dependence of the TFF in VMD and in the LMD+V model [17] differs by a damping factor of Q^2. The relative difference between the two models could be as large as 25% for $F(1\text{GeV}^2, 1\text{GeV}^2)$. This sizable effect could be resolved by a measurement at BESIII.

Another aspect of double-tagged measurements is related to the production mechanism in two-photon collisions. The general term for the cross section can be separated into individual terms depending on the transverse or longitudinal polarization of the individual photons, the relative parallel or perpendicular polarization of the two photons and the helicity of the two-photon system [1]. Another parameter is the angle of the plane of the leptons in the rest frame of the two photons. It can be used to separate multi-meson and tensor contributions to the TFF. Its determination requires good knowledge of all four-momenta in the final state, especially of both scattered leptons. In single-tag measurements there is, however, a large uncertainty on the azimuthal angle of the untagged lepton, which is propagated when determining the momentum transfer, i.e. the virtuality of the photons. Double-tagged measurements, in turn, suffer from a vanishing cross section, due to the limitations of conventional detector setups.

A remedy for the efficiency gaps at small angles is the installation of special tagging detectors close to the beam pipe. In this way, double-tagged measurements are not longer restricted to events with two large virtualities of the exchanged photons. Tagging detectors have already been installed at different facilities [39, 40]. Also at BESIII, a first tagging detector has been installed. It is made from spare parts of the KLOE calorimeter [41, 42], which is a sampling calorimeter made from lead an scintillating fibers. Due to spatial limitations, the tagger only covers polar angles from 1 to 10 mrad. First data have been taken and demonstrate that the tagging detector can also be used to measure photons emitted by initial state radiation. Motivated by the additional use and by the expected aging effects of the scintillating fibers in the high rate environment close to the collision region of the accelerator, it has been decided to replace the current detector design by crystal calorimeters, which will be installed in both hemispheres of the BESIII setup. These calorimeters will consist of two arrays of three by four LYSO crystals. The length of the arrays corresponds to approximately 12.2 radiation lengths. Monte Carlo simulations have been performed to optimize the setup. It was found that the energy resolution is mostly limited by the shower leakages due to the small volume of the detector. Currently, the crystals and the readout electronics are tested at the electron accelerator MAMI located at the Institute for Nuclear Physics of Mainz University, Germany. The installation of the detectors is planned for 2019.

6 Summary and Outlook

The need for new, high precision data on electromagnetic transition form factors of pseudoscalar mesons as input to the calculations of the contribution of hadronic Light-by-light scattering to the anomalous magnetic moment of the muon is one of the main motivations of the two-photon physics program at BESIII. Single-tag measurements are performed to study the momentum dependence of the respective TFF. The investigation of the π^0 TFF provides results for momentum transfers between 0.3 GeV^2 and 3.1 GeV^2, where the statistical accuracy is unprecedented for $0.3 \leq \mathrm{Q}^2\ [\mathrm{GeV}]^2 \leq 1.5$ and compatible with previous measurements for larger values of Q^2.

The TFF of η and η' has been studied reconstructing only a single decay mode. The result covers the same kinematic region as the studies of the π^0 TFF, however the statistical accuracy does not exceed previous measurements. Considering additional decays of η and η' will significantly improve the final result.

The analysis of $\pi^+\pi^-$ in two-photon collisions will provide the first single-tag measurement at low invariant masses and small momentum transfers, with the full coverage of the pion helicity angle. In addition to the investigation of the TFF for different helicities, also rescattering effects, expected at small invariant masses of the pion pairs, can be studied. The analysis is being extended to the neutral channels $\pi^0\pi^0, \pi^0\eta$ and $\eta\eta$.

In addition to the single-tag studies, a first investigation on the possibility of double-tagged measurements has been started. The outcome of first precursor studies demonstrates the feasibility and gives a hint on the impact of a final result, which will be the first direct and model independent parameterization of the TFF of π^0.

The great potential of the BESIII experiment, to contribute valuable information on the field of $\gamma\gamma$ physics is currently being extended by the installation of tagging detectors. These add new prospects to the physics program, allowing to measure the scattered leptons with small momentum transfer, which, so far, escaped detection.

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