Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Two photon physics at BESIII

To cite this article: Yuping Guo and on behalf ofBESIII Collaboration 2019 *J. Phys.: Conf. Ser.* **1137** 012008

Two photon physics at BESIII

Yuping Guo on behalf of BESIII Collaboration

Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55128, Mainz, Germany

E-mail: guo@uni-mainz.de

Abstract. The anomalous magnetic momentum of the muon, $a_\mu = (g-2)$, has been considered as one of the variables with which to test the completeness of the Standard Model. It has been precisely measured experimentally and calculated theoretically, but there is a 3 to 4 standard deviations between measurement and calculation. The dominant contribution to the uncertainty in the theoretical calculation comes from the hadronic part, including hadronic vacuum polarization and hadronic light-by-light scattering. The two-photon fusion process at electron-positron colliders can be used to measure the space-like transition form factors, which will served as an input or constraint to the calculation of the hadronic light-by-light contribution to a_μ. Studies of the form factors using two-photon processes for π^0, η, and η', as well as the cross-section of $\gamma\gamma^* \to \pi^+\pi^-$ are presented.

1. Introduction

The direct measurement of the muon anomaly from the BNL experiment yields $(11659208.9 \pm 6.3) \times 10^{-10}$, with a statistical precision of 0.54 ppm [1]. It has been calculated in the Standard Model (SM) with similar precision[2, 3, 4]. The difference between the measurement and theoretical calculation is 3 to 4 standard deviations. A new experiment, begun in 2017 at Fermilab [5], as well as the planned experiment at J-PARC [6], aim to reduce the uncertainty of measurement by a factor of four; an improvement of the SM prediction is urgently needed. The SM prediction is dominated by the QED contribution, which has been calculated up to 5-loop in perturbation theory, with a precision of 0.0007 ppm [7]. The weak contribution is small; it has been calculated to 2-loop, with the measured Higgs mass taken into account [8], and its uncertainty is well under control. The hadronic contribution is the current limitation of the precision of the SM calculation. It can be decomposed into a hadronic vacuum polarization (HVP) contribution and a hadronic light-by-light (HLbL) contribution. Although the absolute value from HLbL is only about 1.5% of HVP, their uncertainties are at the same level. So improvements from both are needed.

The HVP contribution can be related to the hadronic cross-section via a dispersion relation, thus improving the accuracy of the cross-section measurement can directly improve the precision of the HVP contribution. The situation for the HLbL contribution is much complicated. So far, there are only estimates from hadronic models. The validation of these models usually is done with the meson transition form factor (TFF). And there is no reliable method to estimate the uncertainty of these models. Recently, data-driven dispersive approaches have been developed by two independent groups [9, 10, 11]. By using the meson TFF and the helicity partial waves of the two-photon cross-section as input, this dispersive approach build a direct relation between the HLbL contribution and experimentally measurable variables. This allows a more precise prediction of both the central value and the uncertainty. The dominant contribution from HLbL comes from pseudoscalar meson exchange, followed by the meson loop contribution. These input variables can be measured in the time-like regime through the meson Dalitz decay process or radiative process from e^+e^- annihilation, or in the space-like regime through two-photon process at e^+e^- machine.

2. The BESIII experiment

The BESIII detector is a magnetic spectrometer [12] located at the Beijing Electron Position Collider (BEPCII). 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), 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 (MUC) interleaved with steel. The acceptance of charged particles and photons is 93% over 4π solid angle. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for 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 is 110 ps. The position resolution in MUC is about 2 cm.

The BESIII experiment has collected large data samples at center-of-mass (CM) energies from 2.0 GeV to 4.6 GeV, including 1.3×10^9 events at the J/ψ peak, 448.1×10^6 events at tne $\psi(2S)$ peak, 2.9 fb^{-1} at $\psi(3770)$ peak, more than 15 fb^{-1} at CM energies above 4.0 GeV, and a set of data samples at 151 CM energies covers the whole energy region used for measurements of R, τ physics, and form factor measurement.

3. Sapce-like transition form factor measurement

Figure 1 shows the typical Feynman diagram for two-photon process, where q_1 and q_2 refer to the momentum of the two photons emitted from the lepton lines. The meson TFF can be

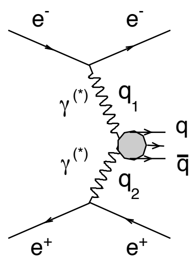

Figure 1. The Feynman diagram for the two-photon fusion process.

measured through the two-photon process with three techniques depending on the number of leptons detected in the detector. In the untag case, only hadronic productions is detected. By requiring both leptons to parallel the beam directions, the virtuality of both photons is very small ($q^2_{1,\,2} \simeq 0$), and they can be considered as quasi-real. In the single tagged case, one of the leptons is detected in the detector, while the other is required to be scattered along the beam direction. In this case, the photon emitted from the tagged lepton is far off-shell with $q_1^2 \equiv -Q^2$, while the untagged one is quasi-real, with $q_2^2 \simeq 0$. The TFF as a function of Q^2, $F_{M\gamma^*\gamma^*}(q_1^2, q_2^2) \equiv F_{M\gamma^*\gamma}(Q^2)$ can be measured. In the double tagged case, all final state particles are detected, and the TFF $F_{M\gamma^*\gamma^*}(q_1^2, q_2^2)$ is accessible. This is the input variable needed for the

IOP Conf. Series: Journal of Physics: Conf. Series **1137** (2019) 012008 doi:10.1088/1742-6596/1137/1/012008

data-driven calculation of the calculation of the HLbL contribution to a_μ. The double tagged method is limited by statistics as the cross-section of the two-photon process strongly peaks at small angle, so most of the current measurements are done with untagged or single tagged methods. The studies presented here are all performed in single tagged method.

4. Transition form factor measurements of pseudoscalar mesons

Theoretical calculation shows the dominate contribution from HLbL to a_μ comes from the neutral pseudoscalar exchange contribution, π^0, η, η', $\cdots$ [2, 3, 4]. The models used to calculate the meson exchange contribution are constrained or tested with the respective TFF. The TFFs in the space-like region have been measured by the BaBar [13, 14] and Belle [15] experiments, as well as CELLO [16] and CLEO [17] experiments in 1990s. The results from these experiments are shown in Fig. 2. B-factory measurements have provided high precision for $Q^2 \geq 4$ GeV^2. CLEO measurement provided data for $Q^2 \geq 1.5$ GeV^2, and for $Q^2 \leq$ 1.5GeV^2, the only measurement comes from CELLO experiment but with poor accuracy.

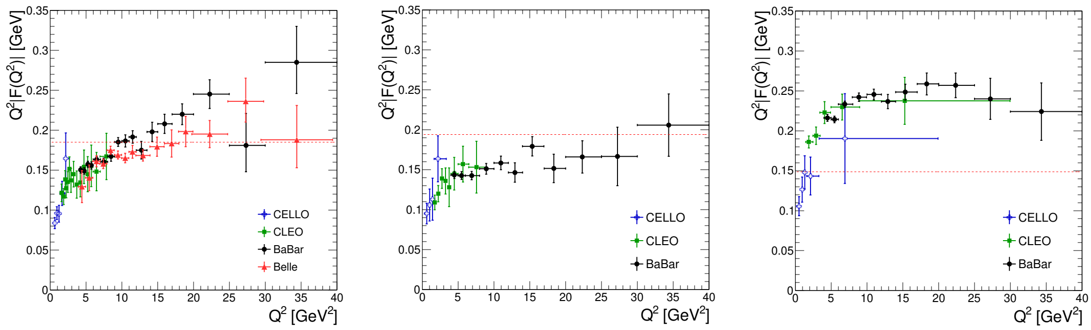

Figure 2. (Colours online) The TFF measured from the CELLO [16], CLEO [17], BaBar [13, 14], and Belle [15] experiments for π^0 (left), η (middle), and η' (right).

Using a dispersive approach, the pseudoscalar contribution has been evaluated as in Ref [18]. In this representation, the contribution can be factorized as a two-dimensional integral of the universal weight functions times the form factor dependent functions. The weight functions are model-independent, and peak in the region of photon momenta below 1.0 GeV for the case of π^0 and 1.5 GeV for the cases of η and η'. This means the main contribution comes from the small Q^2 region, and the precision of the TFF measured in this region is important for the control of the uncertainty from the dispersive estimation of the pseudoscalar contribution to HLbL.

The BESIII experiment runs at much lower CM energies than the B-factories, and thus has the advantage that the measurements can get access to the most relevant Q^2 region. The data sample collected at the $\psi(3770)$ peak has been used to measure the TFFs of the π^0, η, and η'.

4.1. Transition form factor of π^0

We use $\gamma\gamma$ final state to reconstruct the π^0. Events with only one lepton and 2 to 4 photons reconstructed in the detector volume are considered as signal candidates. Using momentum conservation, the untagged lepton is required to parallel the beam. Backgrounds mainly come from the radiative Bhabha scattering events, where the hard radiative photon combined with soft photons form a fake π^0. These events has been suppressed with conditions put on the helicity angle of the π^0 candidates and the polar angle difference of the two photons from the π^0 in the laboratory frame. A further requirement on $\frac{\sqrt{s}-E^*_{l\pi^0}-p^*_{l\pi^0}}{\sqrt{s}}$ is applied, where $E^*_{l\pi^0}$ and $p^*_{l\pi^0}$ are the sum of the energy and three-momentum of the tagged lepton and π^0 in the two-photon CM frame. This requirement suppresses events with large initial state radiation, leading to incorrect reconstruction of Q^2, as well as backgrounds from charmonium decays with hadrons in the final states. Events after these selections show a clear π^0 peak in the $\gamma\gamma$ invariant mass spectrum.

The number of π^0 events is extracted by performing fits to the $\gamma\gamma$ invariant mass distributions in bins of Q^2. With the reconstruction efficiency obtained from a signal Monte Carlo (MC) simulation using the *ekhara* generator [19] and the luminosity of the data sample, the differential cross section $d\sigma/dQ^2$ is calculated. The TFF as a function of Q^2 is extracted by dividing out the point like cross-section. With the $\psi(3770)$ data sample, the BESIII measurement of the π^0 TFF covers the region $0.3 \leq Q^2$ [GeV^2] ≤ 3.1. The precision for $Q^2 < 1.5$ GeV^2 is unprecedented, compatible to the CLEO [17] result in the region above. The preliminary result is shown in Fig. 3.

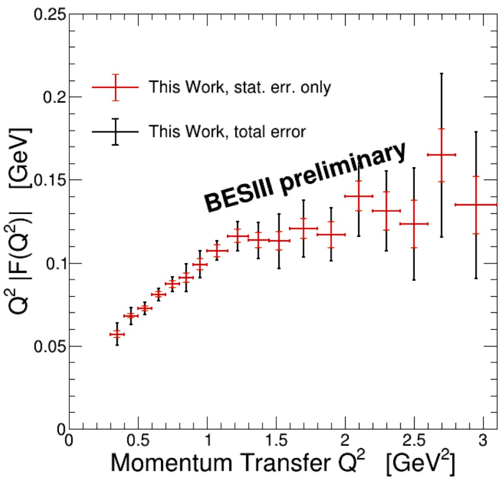

Figure 3. (Colours online) Preliminary π^0 TFF measurement from BESIII.

With an analysis strategy similar to that used in the π^0 TFF measurement, the TFFs of the η and η' are measured, as well. The decay modes used are $\eta \to \pi^+\pi^-\pi^0$ and $\eta' \to \pi^+\pi^-\eta$, respectively. The TFFs can be extracted in the region $0.3 \leq Q^2$ [GeV^2] ≤ 3.5 with a precision comparable to the previous results from CELLO [16] and CLEO [17] experiments. Adding more decay modes and including more data samples at CM energies above 4.0 GeV, the precision of these TFF measurements can be improved significantly.

5. Measurement of $\gamma\gamma^* \to \pi^+\pi^-$

Meson loops ($\pi\pi$, KK, $\cdots$) also make important contributions to HLbL scattering. A dispersive analysis for these final states is needed due to the fact that these resonance has finite hadronic decay width, as well as non-resonant contributions. Experimental measurements of $\gamma^{(*)}\gamma^{(*)} \to \pi\pi$, $\gamma^{(*)}\gamma^{(*)} \to \pi\eta$, $\cdots$, are important checks of the validity of the dispersive approach.

The $\pi^+\pi^-$ final state was measured by MarkII [20], CELLO [21] and Belle [22] experiments, but none used a tagging method. Both CELLO and Belle measurements started from an invariant $\pi^+\pi^-$ mass around 0.8 GeV$/c^2$. The only measurement at the $\pi^+\pi^-$ mass threshold was made by the MarkII experiment with large uncertainties and a gap in the region between $0.4 - 0.7$ GeV$/c^2$.

At BESIII, we select single tagged events, where signal events are selected by requiring exact three charged tracks reconstructed in the detector, two of which are identified as pions and the remaining identified as as electron or positron. The dominant background contributions come from $e^+e^- \to e^+e^-\mu^+\mu^-$ and $e^+e^- \to e^+e^-\pi^+\pi^-$(not from two photon process). The cross-section of the QED background, present from π - μ misidentification, is about 6 times larger than that of the signal. This interaction is well-understood from the studies at LEP. MC generators developed for the LEP energy scale [23, 24] have been validated in the BESIII energy region. Background contributions remaining after separating pions and muons with a multi-variable analysis are subtracted using MC simulations. Backgrounds with the same final states as signal events are mainly from radiative Bhabha scattering, where the radiative photon couples to a vector meson, such as ρ and ω in the case of $\pi^+\pi^-$ final states. These events peak in the $\pi^+\pi^-$ invariant mass spectrum and can be subtracted by fitting to that spectrum.

The remaining events are pure $\gamma\gamma^* \to \pi^+\pi^-$ events. From the $\pi^+\pi^-$ invariant mass spectrum, a clear $f_2(1270)$ signal is observed, as well as an accumulation of events in the $f_0(980)$ mass region. The clean signal sample allows a measurement of the differential cross-section in bins of Q^2, the $\pi^+\pi^-$ invariant mass (W), and the pion helicity angle (cosθ^*). This is the first measurement of the two-photon $\pi^+\pi^-$ process with a single tagged method. The measurement can provide data points for Q^2 region from 0.1 GeV^2 to 4.0 GeV^2, W from the $\pi^+\pi^-$ invariant mass threshold to 2.0 GeV/c^2, and full cosθ^* coverage $|\cos\theta^*| < 1.0$.

6. Summary

The two-photon project at BESIII yields TFF measurement for pesudoscalar mesons, as well as an helicity amplitude measurement for the $\pi^+\pi^-$ final state in the Q^2 region most relevant for the calculation of the HLbL contribution to a_μ. The TFF of π^0 measured at BESIII is unprecedented in the Q^2 region from 0.3 GeV^2 to 1.5 GeV^2. The first single tagged $\gamma\gamma^* \to \pi^+\pi^-$ analysis can provide measurement in the small Q^2 region, as well as in the low $\pi^+\pi^-$ invariant mass region down to the threshold with full coverage of cosθ^*. These measure are important inputs to the calculation of the HLbL contribution to a_μ using a dispersive approach.

References

[1] G W *et al.* (Muon g-2 Collaboration) 2006 *Phys. Rev.* D **73** 072003
[2] Davier M, Hoecker A, Malaescu B and Zhang Z 2017 *Eur. Phys. J.* C **77** 827
[3] Keshavarzi A, Nomura D and Teubner T 2018 *Phys. Rev.* D **97** 114025
[4] Jegerlehner F 2018 *Eur. Phys. J. Web Conf.* **166** 00022
[5] http://muon-g-2.fnal.gov.
[6] http://g-2.kek.jp/portal/index.html
[7] Aoyama T, Hayakawa M, Kinoshita T and Nio M 2012 *Phys. Rev. Lett.* **109** 111808
[8] Gnendiger C, Stöckinger D and Stökinger-Kim H 2013 *Phys. Rev.* D **88** 053005
[9] Colangelo G, Hoferichter M, Procura M and Stoffer P 2014 *J. High Energy Phys.* **2014** 091
[10] Colangelo G, Hoferichter M, Kubis B, Procura M and Stoffer P *Phys. Lett.* B **738** 6
[11] Pauk V and Vanderhaeghen M 2014 *Phys. Rev.* D **90** 113012
[12] Ablikim M *et al.* (BESIII Collaboration) 2010 *Nucl. Instrum. Meth.* A **614** 345
[13] Aubert B *et al.* (BaBar Collaboration) 2009 *Phys. Rev.* D **80** 052002
[14] del Amo Sanchez P *et al.* (BaBar Collaboration) 2011 *Phys. Rev.* D **84** 052001
[15] Uehara S *et al.* Belle Collaboration 2012 *Phys. Rev.* D **86** 092007
[16] Behrend H J *et al.* (CELLO Collaboration) 1991 *Z. Phys.* C **49** 401
[17] Gronberg J *et al.* (CLEO Collaboration) 1998 *Phys. Rev.* D **57** 33
[18] Nyffeler A 2016 *Phys. Rev.* D **94** 053006
[19] Czyz H, Ivashyn S, Korchin A and Shekhovtsova O 2012 *Phys. Rev.* D **85** 094010
[20] Boyer J *et al.* 1990 *Phys. Rev.* D **42** 1350
[21] Behrend H *et al.* (CELLO Collaboration) 1992 *Z. Phys.* C **56** 381
[22] Mori T *et al.* (Belle Collaboration) 2007 *Phys. Rev.* D **75** 051101(R)
[23] Berends F A, Daverveldt P H and Kleiss R 1986 *Comput. Phys. Commun.* **40** 285
[24] Berends F A, Daverveldt P H and Kleiss R 1986 *Comput. Phys. Commun.* **40** 271