

Investigation of $\gamma^*\gamma^* \rightarrow \eta'$ at the BESIII Experiment

Maurice Anderson^{1,*} on behalf of the BESIII Collaboration

¹Institute for Nuclear Physics, Johannes Gutenberg University Mainz

Abstract. In this analysis, the production of pseudoscalar η' mesons via two virtual spacelike photons is studied ($\gamma^*\gamma^* \rightarrow \eta'$). Double-tagged measurements are conducted at the BESIII experiment in Beijing, China, in which both virtual photons possess nonzero virtualities Q_1^2 and Q_2^2 . The Monte Carlo generator Ekhara 3.0 is used to simulate the expected signal event distribution. By measuring the double differential cross section at BESIII, the transition form factor (TFF) can be determined for $Q_1^2, Q_2^2 < 2 \text{ GeV}^2$. The TFF of pseudoscalar mesons serves as essential input for calculating the hadronic light-by-light contribution to the theoretical Standard Model prediction of the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$.

1 Introduction

The $g - 2$ puzzle refers to a sizable discrepancy of up to 5.1σ significance between the experimental measurements [1] of the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$ and the theoretical Standard Model (SM) prediction [2]. As recent theory calculations using lattice-QCD [3] and measurements of the CMD-3 collaboration [4] challenge the significance of the $g - 2$ discrepancy, it has become apparent that the precision of the SM prediction must further be improved in order to validate the need for possible physics beyond the SM. The primary sources of systematic error are the hadronic vacuum polarization (HVP) and the hadronic light-by-light (HLbL) contributions. This analysis aims to support the $g - 2$ Theory Initiative's plan to double the current precision and thus achieve a relative uncertainty of 10% for the HLbL contribution [2] by measuring the transition form factor (TFF) $\mathcal{F}_{\gamma^*\gamma^* \rightarrow \eta'}(Q_1^2, Q_2^2)$ of the pseudoscalar meson η' .

The HLbL contribution is dominated by the single exchange of the lightest pseudoscalar mesons, as depicted in Fig. 1a. In recent years, dispersive approaches have been proposed [6–8], in which experimental data on the pseudoscalar TFF are used to determine the corresponding contribution to a_μ^{HLbL} . The TFF of pseudoscalar mesons like η' can be determined experimentally at e^+e^- colliders by measuring the meson production cross section in two-photon scattering, as shown in Fig. 1b, where γ^* denotes a spacelike, virtual photon. The virtuality Q^2 of the photon corresponds to the squared four-momentum transfer of the emitting lepton:

$$Q^2 = -q^2 = -(p - p')^2 \approx 4EE' \sin^2(\theta/2). \quad (1)$$

Here, p and p' denote the lepton four-momenta before and after scattering, while E and E' are their respective energy components. θ is the scattering angle, i.e. the angle between $\vec{p}$ and $\vec{p}'$.

*e-mail: manderso@students.uni-mainz.de

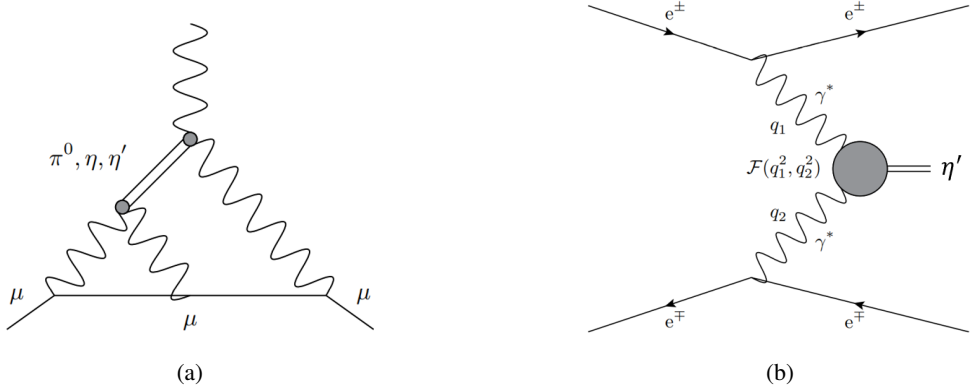


Figure 1: (a) Pseudoscalar meson-pole HLbL contribution. (b) Two-photon scattering process $\gamma^*\gamma^* \rightarrow \eta'$ in e^+e^- collisions [5].

Since the TFF parameterizes the deviation of the production cross section from the pointlike description given by QED, the η' TFF can be experimentally determined by dividing the measured cross section of the $\gamma^*\gamma^* \rightarrow \eta'$ process by the cross section of a pointlike meson σ_{point} . The pointlike cross section is calculated by using the Monte Carlo (MC) software Ekhara 3.0 [9] to generate η' events with a constant TFF normalized to 1, known as the Wess-Zumino-Witten term [10, 11].

The Q_1^2, Q_2^2 distribution of the process $\gamma^*\gamma^* \rightarrow \eta'$ can be accessed, according to Eq. 1, by measuring the energies and angles of the scattered leptons. Measuring the momentum transfers of both leptons is referred to as a double-tagged measurement. Due to the typical acceptance of detectors at e^+e^- colliders starting only from $\theta \approx 20^\circ$, it can be seen from Eq. 1 that rather large values of Q^2 can be measured. However, this process, in which both leptons scatter at large angles with nonzero momentum transfers, has a very small cross section. Thus, in order to study a double-tagged measurement with a large amount of statistics, a data set with a high integrated luminosity needs to be analyzed.

The only existing double-tagged measurement of the η' TFF is reported by the BABAR Collaboration, in which a combined integrated luminosity of 468.6 fb^{-1} was used and a total of $46.2^{+8.3}_{-7.0}$ signal events were discovered [12]. In the BABAR analysis, the η' TFF was measured for two highly off-shell photons with $2 \text{ GeV}^2 < Q_1^2, Q_2^2 < 60 \text{ GeV}^2$. Complementary to the BABAR measurement, this study uses data collected at BESIII to determine $\mathcal{F}_{\gamma^*\gamma^* \rightarrow \eta'}(Q_1^2, Q_2^2)$ for $Q_{1,2}^2 < 2 \text{ GeV}^2$. Furthermore, this momentum transfer window is advantageous because Ref. [8] concludes that more than 90% of the total η' contribution to a_μ^{HLbL} is expected from TFF information at Q^2 values below 2 GeV^2 .

2 BESIII Experiment

Located at the Institute of High Energy Physics (IHEP) in Beijing, China, the Beijing Spectrometer III (BESIII) detector [13] records symmetric e^+e^- collisions provided by the BEPCII storage ring [14] in the center-of-mass energy range from 2 to 5 GeV. The peak luminosity of $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ is achieved at $\sqrt{s} = 3.77 \text{ GeV}$, where the Mandelstam variable $s = (p_{e^+} + p_{e^-})^2$ denotes the squared center-of-mass energy of the e^+e^- system. The physics program of the BESIII collaboration spans various topics such as light hadron and charmonium spectroscopy, open-charm physics, QCD tests, and τ -mass measurements.

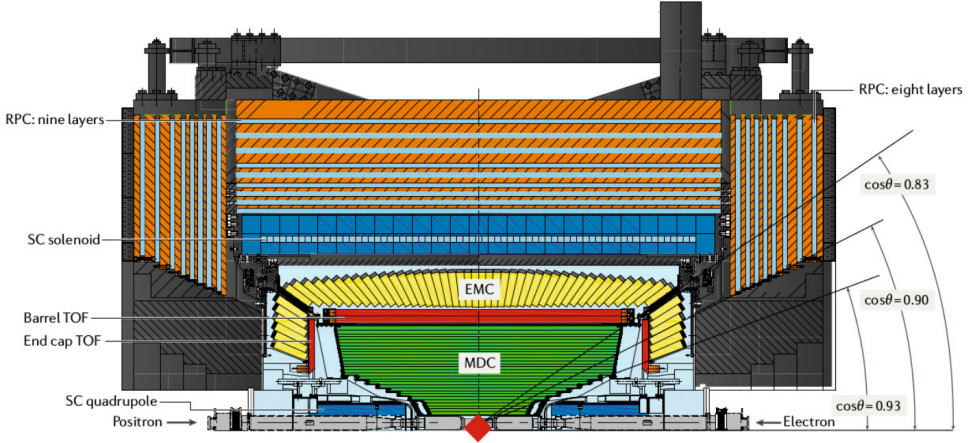


Figure 2: This is a schematic illustration of the upper half of the BESIII detector. The MDC is colored green, the TOF is red, the EMC is yellow, the superconducting solenoid is blue, and the MUC is orange [15].

The BESIII detector is composed of four concentric cylindrical layers: a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), a CsI(Tl) electromagnetic calorimeter (EMC), and a muon counter (MUC). The inner three detector layers cover 93% of the full solid angle and are enclosed by a 1 T superconducting solenoidal magnet.

Since 2009, BESIII has collected more than 35 fb^{-1} in data [16]. This study plans to analyze a total of 14 data sets of BESIII, each collected at a different $\sqrt{s}$ between 3773 MeV and 4600 MeV. At the time of this feasibility study, the accumulated integrated luminosity of these 14 data sets corresponds to $(13.5233 \pm 0.0005_{\text{stat.}} \pm 0.0373_{\text{sys.}}) \text{ fb}^{-1}$ [17–19]. The BESIII data sets are compared to MC simulated events generated with the polar angle restriction of the BESIII detector: $20^\circ < \theta < 160^\circ$. The MC events of the signal process are created according to a 3-octet TFF model using the exclusive event generator Ekhara 3.0, which is specialized in simulating the production of the light pseudoscalar mesons π^0 , η , and η' in two-photon collisions [9]. The simulation in this analysis does not include any next-to-leading order (NLO) or vacuum polarization radiative corrections.

The signal process $e^+e^- \rightarrow e^+e^-\eta'$ can occur via the s -channel ($e^+e^- \rightarrow \gamma^* \rightarrow \gamma^*\eta' \rightarrow e^+e^-\eta'$) or the t -channel ($e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-\eta'$). As this study aims to measure the TFF of the $\gamma^*\gamma^* \rightarrow \eta'$ process, only the spacelike t -channel events are desired. Fig. 3 presents the Q_1^2 , Q_2^2 distribution of simulated t -channel signal MC events. In order to later subtract the s -channel events from the data and extract the measured t -channel signal events, a MC simulation is performed in which η' decay events are generated for both s - and t -channels, allowing for an interference of the channels.

The subsequent decays of the η' mesons are simulated using the BesEvtGen generator [20, 21]. The generated MC events are reconstructed using the BESIII Offline Software System (BOSS) [22]. Possible background contributions to the event selection are studied with inclusive MC samples including Bhabha scattering ($e^+e^- \rightarrow e^+e^-$), hadronic continuum processes, hadronic charmonium transitions, and radiative return to the state $\psi(2S)$.

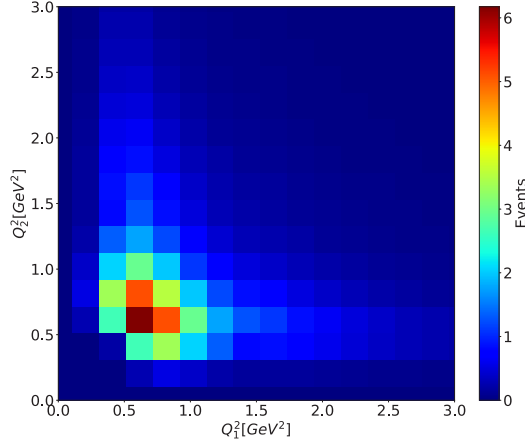


Figure 3: Q_1^2, Q_2^2 distribution of t -channel MC events, combining all 14 data sets at different $\sqrt{s}$ values.

3 Double-Tagged Analysis

The η' mesons are identified via their two most frequent decay channels. The following two processes describe the production and decay of the η' mesons, which are studied in this analysis:

$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-\eta' \rightarrow e^+e^-\pi^+\pi^-\eta \rightarrow e^+e^-\pi^+\pi^-\gamma\gamma \quad (2)$$

and

$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-\eta' \rightarrow e^+e^-\pi^+\pi^-\gamma. \quad (3)$$

The decay channel of η' in Eq. 2 occurs with a total branching fraction of $(16.7 \pm 0.2)\%$, while the decay channel of η' in Eq. 3 has a branching fraction of $(29.5 \pm 0.4)\%$ [23]. Both of these processes produce four tracks in the MDC of BESIII, corresponding to one scattered e^+ , one scattered e^- , one π^+ , and one π^- particle. Since a double-tagged measurement is desired, a reconstructed event is only accepted for further analysis if a total of exactly four tracks exists. These tracks are additionally subjected to a vertex fit and must have a point of closest approach to the interaction point within 10 cm along the beam axis and less than 1 cm in the transverse plane.

Pions and electrons are distinguished using their $E_{\text{EMC}}/p_{\text{MDC}}$ values, i.e. the ratio between energy deposited in the EMC and momentum measured in the MDC. This ratio is expected to be $E_{\text{EMC}}/p_{\text{MDC}} > 0.8$ for electrons, as they deposit all their energy in the EMC. In contrast, pions do not create electromagnetic (EM) showers in the EMC and therefore have a smaller ratio $E_{\text{EMC}}/p_{\text{MDC}} < 0.8$. To distinguish EM showers of photons from reconstruction artifacts originating from incompletely reconstructed tracks, a signal in the EMC that is more than 10° away from the extrapolated impact point of the nearest track on the EMC surface is judged as a photon signal. In both final states of interest ($\pi^+\pi^-\gamma\gamma$ and $\pi^+\pi^-\gamma$), at least one photon exists. Thus, events with no identified photon candidates are discarded.

For this analysis, if at least two photons are observed, a kinematic fit with five constraints (5C) is performed to select the process $\eta' \rightarrow \pi^+\pi^-\eta \rightarrow \pi^+\pi^-\gamma\gamma$. If at least one photon is detected, a kinematic fit with four constraints (4C) is performed to select the process $\eta' \rightarrow$

$\pi^+\pi^-\gamma$. Both the 4C and 5C kinematic fits require energy-momentum conservation. For the fifth constraint of the 5C fit, the invariant mass of the two photon candidates is required to equal the invariant mass of the η meson. Due to this fifth constraint, the process $\eta' \rightarrow \pi^+\pi^-\eta$ will be used to refer to the decay channel $\eta' \rightarrow \pi^+\pi^-\eta \rightarrow \pi^+\pi^-\gamma\gamma$ for the remainder of this analysis. Since some events can trigger both a successful 4C and 5C fit, events belonging to $\eta' \rightarrow \pi^+\pi^-\eta$ are distinguished from events belonging to $\eta' \rightarrow \pi^+\pi^-\gamma$ by comparing the reduced χ^2 of each fit. If $\chi^2_{5C}/5$ is less than $\chi^2_{4C}/4$, the event is identified as belonging to the $\eta' \rightarrow \pi^+\pi^-\eta$ process. Conversely, if $\chi^2_{4C}/4$ is less than $\chi^2_{5C}/5$, the event is identified as belonging to the $\eta' \rightarrow \pi^+\pi^-\gamma$ process.

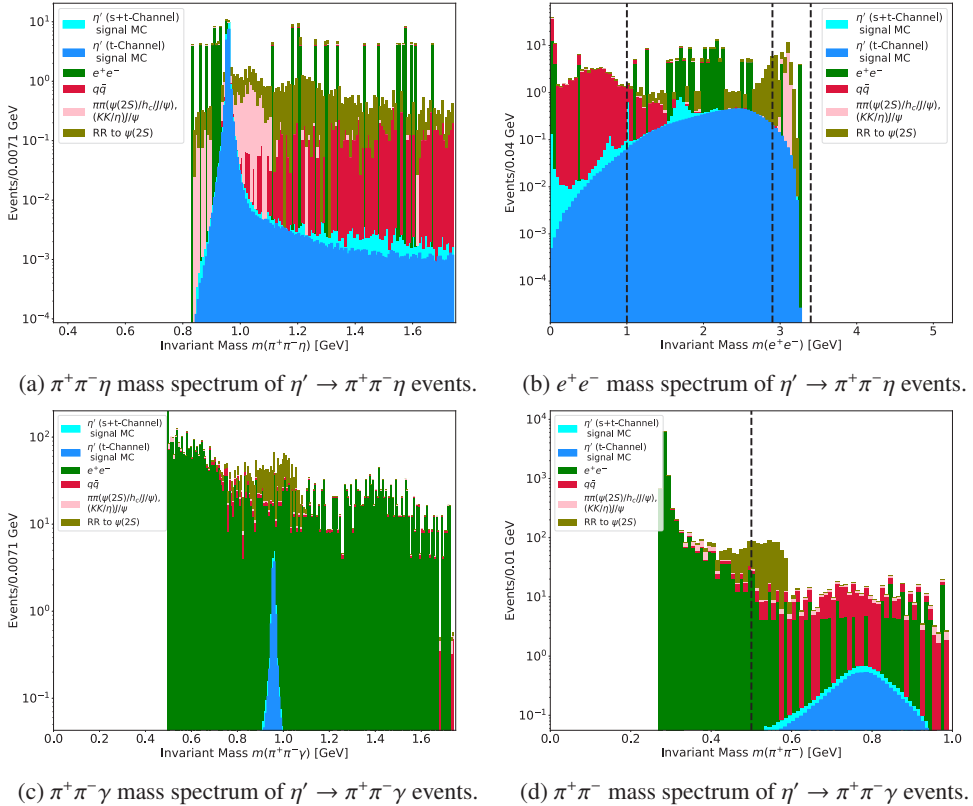


Figure 4: Mass spectra for the $\eta' \rightarrow \pi^+\pi^-\eta$ and $\eta' \rightarrow \pi^+\pi^-\gamma$ processes after the initial event selection and before the background suppression. The dotted black lines indicate the limits of event removal.

As a proof of concept, the results of the initial event selection for signal MC and background MC samples are only explicitly provided for $\sqrt{s} = (4178.0 \pm 0.1_{\text{stat.}} \pm 0.8_{\text{sys.}}) \text{ MeV}$. At the time of this feasibility study, this is the $\sqrt{s}$ at which the largest individual data set in that energy region has been measured at BESIII. For events of the $\eta' \rightarrow \pi^+\pi^-\eta$ process, Fig. 4a presents the $\pi^+\pi^-\eta$ invariant mass spectrum, where a clear signal peak of t -channel signal MC events (in dark blue) and the combined s - and t -channel signal MC events (in cyan) can be identified. To remove contributions of the background MC samples, one can examine the e^+e^- mass spectrum (see Fig. 4b), which reveals background processes such as $q\bar{q}$ production (shown in red), radiative returns to $\psi(2S)$ (shown in olive), and hadronic charmonium

transitions (HCT) such as $e^+e^- \rightarrow \pi^+\pi^- J/\psi \rightarrow \pi^+\pi^- e^+e^-$ (shown in pink). To avoid these background processes, events with $m(e^+e^-) < 1.0 \text{ GeV}$ and $2.9 \text{ GeV} < m(e^+e^-) < 3.4 \text{ GeV}$ are removed. Only 8.26% of signal events are removed with this $m(e^+e^-)$ restriction, according to the t -channel MC.

In the $\pi^+\pi^-\gamma$ invariant mass spectrum (see Fig. 4c), the background is dominated by a uniform distribution of Bhabha scattering events (shown in green). In the e^+e^- mass spectrum, the same restrictions as in the $\eta' \rightarrow \pi^+\pi^-\eta$ decay channel are applied to remove the majority of $q\bar{q}$, radiative return to $\psi(2S)$, and HCT background events. This suppression removes only 7.73% of signal events, according to the t -channel MC. A large amount of Bhabha scattering events can be removed by placing restrictions in the $\pi^+\pi^-$ mass spectrum (see Fig. 4d). Here, events with $m(\pi^+\pi^-) < 0.5 \text{ GeV}$ are removed from the selection, resulting in the loss of an additional 2.38% of t -channel signal events.

4 Summary

In conclusion, using the MC generator Ekhara 3.0 to simulate the signal event distribution, this analysis has shown the feasibility of a double-tagged measurement of the process $\gamma^*\gamma^* \rightarrow \eta'$ at BESIII to ultimately determine the TFF in dependence of both photon virtualities. Background processes can be suppressed by applying the aforementioned event selection criteria and mass spectrum restrictions to all 14 data sets of interest. According to the MC simulation of the signal t -channel process (see Fig. 3), for $Q_1^2, Q_2^2 < 2 \text{ GeV}^2$, a total of 43.5 ± 6.6 signal events are expected. Thus, this double-tagged analysis has the potential of reaching a signal event yield comparable to the $46.2^{+8.3}_{-7.0}$ events measured by BABAR [12]. An even greater signal event yield can be achieved by analyzing the additional data from the recently concluded $\psi(3770)$ data-taking at BESIII, which accumulated a total integrated luminosity of $(20.275 \pm 0.077) \text{ fb}^{-1}$ at $\sqrt{s} = 3.773 \text{ GeV}$ [24, 25].

The double differential cross section $d^2\sigma_{\text{data}}/dQ_1^2 dQ_2^2$ can be measured using the Q_1^2, Q_2^2 distribution of signal events and the reconstruction efficiency. Fig. 3 reveals that, due to the geometric limitation of the BESIII detector, only a small fraction of signal events with $Q_{1,2}^2 < 0.3 \text{ GeV}^2$ are measured for $\theta > 20^\circ$. Thus, for the calculation of the cross section, the future analysis will restrict itself to signal MC events generated in a region of defined momentum transfer $Q_{1,2}^2 > 0.3 \text{ GeV}^2$, in which the reconstruction efficiency is reasonably large. Finally, the TFF can be determined from the measured cross section in dependence of Q_1^2 and Q_2^2 .

References

- [1] D.P. Aguillard et al. (Muon g-2), Phys. Rev. Lett. **131**, 161802 (2023), 2308.06230
- [2] T. Aoyama et al., Phys. Rept. **887**, 1 (2020), 2006.04822
- [3] S. Borsanyi et al., Nature **593**, 51 (2021), 2002.12347
- [4] F.V. Ignatov et al. (CMD-3) (2023), 2302.08834
- [5] M. Lellmann, *Study of Neutral-Pion Pair Production in Two-Photon Scattering at BE-SIII* (2019), Master of Science Thesis
- [6] M. Knecht, A. Nyffeler, Phys. Rev. D **65**, 073034 (2002), hep-ph/0111058
- [7] G. Colangelo, M. Hoferichter, M. Procura, P. Stoffer, JHEP **09**, 074 (2015), 1506.01386
- [8] A. Nyffeler, Phys. Rev. D **94**, 053006 (2016), 1602.03398
- [9] H. Czyz, P. Kiszka, Comput. Phys. Commun. **234**, 245 (2019), 1805.07756
- [10] J. Wess, B. Zumino, Phys. Lett. B **37**, 95 (1971)

- [11] E. Witten, Nucl. Phys. B **223**, 422 (1983)
- [12] J.P. Lees et al. (BaBar), Phys. Rev. D **98**, 112002 (2018), 1808.08038
- [13] M. Ablikim et al. (BESIII), Nucl. Instrum. Meth. A **614**, 345 (2010), 0911.4960
- [14] C. Yu et al., *BEPCII Performance and Beam Dynamics Studies on Luminosity*, in *7th International Particle Accelerator Conference* (2016), p. TUYA01
- [15] I. Balossino, F. Cossio, R. Farinelli, L. Lavezzi, Symmetry **14**, 905 (2022)
- [16] H.B. Li et al. (BESIII), *Physics in the τ -charm Region at BESIII*, in *Snowmass 2021* (2022), 2204.08943
- [17] M. Ablikim (BESIII), Chin. Phys. C **37**, 123001 (2013), 1307.2022
- [18] M. Ablikim et al. (BESIII), Chin. Phys. C **39**, 093001 (2015), 1503.03408
- [19] M. Ablikim et al. (BESIII), Chin. Phys. C **46**, 113002 (2022), 2203.03133
- [20] R.G. Ping, Chin. Phys. C **32**, 599 (2008)
- [21] D.J. Lange, Nucl. Instrum. Meth. A **462**, 152 (2001)
- [22] W. Li et al., Proc. Int. Conf. Comput. High Energy and Nucl. Phys. **225** (2006)
- [23] R.L. Workman et al. (Particle Data Group), PTEP **2022**, 083C01 (2022)
- [24] M. Ablikim et al. (BESIII), Phys. Lett. B **753**, 629 (2016), [Erratum: Phys.Lett.B 812, 135982 (2021)], 1507.08188
- [25] M. Ablikim et al. (BESIII) (2024), 2406.05827