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Study of $e^+e^- \to e^+e^-\eta'$ in the double-tag mode at BABAR

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We study the process $e^+e^- \to e^+e^-\eta'$ in the double-tag mode and measure for the first time the $\gamma^\star\gamma^\star \to \eta'$ transition form factor $F_{\eta'}(Q_1^2, Q_2^2)$ in the momentum-transfer range $2 < Q_1^2, Q_2^2 < 60$ GeV^2. The analysis is based on a data sample corresponding to an integrated luminosity of around 469 fb^{-1} collected at the PEP-II e^+e^- collider with the BaBar detector at center-of-mass energies near 10.6 GeV.

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1. Introduction

We report on the measurement of the $\gamma^\star\gamma^\star \to \eta'$ transition form factor (TFF) by using the two-photon-fusion reaction $e^+e^- \to e^+e^-\eta'$. The TFF is defined via the amplitude for the $\gamma^\star\gamma^\star \to \eta'$ transition

$$T = -i4\pi\alpha\varepsilon_{\mu\nu\beta\gamma}\varepsilon_1^\mu\varepsilon_2^\nu q_1^\beta q_2^\gamma F_{\eta'}(Q_1^2,Q_2^2), \tag{1.1}$$

where α is the fine structure constant, $\varepsilon_{\mu\nu\alpha\beta}$ is the totally antisymmetric Levi-Civita tensor, $\varepsilon_{1,2}$ and $q_{1,2}$ are the polarization vectors and four-momenta, respectively, of the space-like photons, $Q_{1,2}^2 = -q_{1,2}^2$, and $F_{\eta'}(Q_1^2,Q_2^2)$ is the transition form factor.

We measure the differential cross section of the process $e^+e^- \to e^+e^-\eta'$ in the double-tag mode, in which both scattered electrons[1] are detected (tagged). The tagged electrons emit highly off-shell photons with momentum transfers $q_{e^+}^2 = -Q_{e^+}^2 = (p_{e^+} - p'_{e^+})^2$ and $q_{e^-}^2 = -Q_{e^-}^2 = (p_{e^-} - p'_{e^-})^2$, where $p_{e^\pm}$ and $p'_{e^\pm}$ are the four-momenta, respectively, of the initial- and final-state electrons. We measure for the first time $F_{\eta'}(Q_1^2,Q_2^2)$ in the kinematic region with two highly off-shell photons $2 < Q_1^2, Q_2^2 < 60$ GeV^2. The η' transition form factor $F_{\eta'}(Q^2,0)$ in the space-like momentum transfer region and in the single-tag mode was measured in several previous experiments [1, 2, 3, 4, 5]. The most precise data at large Q^2 were obtained by the CLEO [4] experiment, and then by the BaBar [5] experiment, in the momentum transfer ranges $1.5 < Q^2 < 30$ GeV^2 and $4 < Q^2 < 40$ GeV^2, respectively. Many theoretical models exist for the description of the TFFs of pseudoscalar mesons, $F_P(Q_1^2,0)$ and $F_P(Q_1^2,Q_2^2)$ (see for example Refs. [9, 6, 8, 7]). Measurement of the TFF at large Q_1^2 and Q_2^2 allows the predictions of models inspired by perturbative QCD (pQCD) to be distinguished from those of the vector dominance model (VDM) [10, 12, 11]. In the case of only one off-shell photon, both classes of models predict the same asymptotic dependence $F_P(Q^2,0) \sim 1/Q^2$ as $Q^2 \to \infty$, while for two off-shell photons the asymptotic predictions are quite different, $F(Q_1^2,Q_2^2) \sim 1/(Q_1^2+Q_2^2)$ for pQCD, and $F(Q_1^2,Q_2^2) \sim 1/(Q_1^2Q_2^2)$ for the VDM model.

2. Data set and event selection

The data used in this analysis were collected with the BaBar detector at the PEPII asymmetric-energy e^+e^- collider, at the SLAC National Accelerator Laboratory. A total integrated luminosity of 468.6 fb^{-1} [20] is used. The decay chain $\eta' \to \pi^+\pi^-\eta \to \pi^+\pi^-2\gamma$ is used to reconstruct the η' meson candidate. Two photon candidates are combined to form an η candidate. We apply a kinematic fit to the two photons, with an η mass constraint to improve the precision of their momentum measurement. An η' candidate is formed from a pair of oppositely charged pion candidates and an η candidate. The final selection uses tagged electrons and is based on variables in the c.m. frame of the initial e^+ and e^-. The total momentum of the reconstructed $e^+e^-\eta'$ system ($P^\star_{e^+e^-\eta'}$[2]) must be less than 0.35 GeV/c. The total energy of the $e^+e^-\eta'$ system must be in the range of 10.30–10.65 GeV. To reject background from QED events, requirements on the energies of the detected electron and positron are applied. The distribution of the η candidate mass versus the η' one for the selected data and simulated signal samples is shown in Fig. 1. A clustering of events in the central region of

[1]Unless otherwise specified, we use the term "electron" for either an electron or a positron.

[2]The superscript asterisk indicates a quantity calculated in the e^+e^- c.m. frame

the data distribution corresponds to the two-photon η' production. To further suppress background we require that the invariant mass of the η candidate be in the range 0.50–0.58 GeV/c^2, as shown by the horizontal lines in Fig. 1.

Data events that pass all selection criteria are divided into five ($Q^2_{e^-}$, $Q^2_{e^+}$) regions, as illustrated on Fig. 2 for events with $0.945 < M_{\pi^+\pi^-\eta} < 0.972$ GeV/c^2. Because of the symmetry of the process under the exchange of the e^- with the e^+, regions 3 and 4 each include two disjunct regions, mirror symmetric with respect to the diagonal. The number of signal events (N_{events}) in each ($Q^2_{e^-}$, $Q^2_{e^+}$) region is obtained from a fit to the $\pi^+\pi^-\eta$ invariant mass spectrum with a sum of signal and background distributions. The total number of signal events is $46.2^{+8.3}_{-7.0}$. The total systematic uncertainty related to the description of the background and signal is 3.7% and the total systematic uncertainty of the detection efficiency is 11%. Following the methods developed in the single-tag analysis of Ref. [5], we have studied possible sources of peaking background.

3. Cross section, form factor and Summary

The cross section in the entire range of momentum transfer $2 < Q_1^2, Q_2^2 < 60$ GeV^2 is $\sigma = 11.4^{+2.8}_{-2.4}$ fb, where the uncertainty is statistical. The systematic uncertainty includes the uncertainty in the number of signal events associated with background subtraction (Sec. 2), the uncertainty in the detection efficiency, the uncertainty in the calculation of the radiative correction (1%) [24], and the uncertainty in the integrated luminosity (1%) [20]. The total systematic uncertainty (12%) is the sum in quadrature of all the systematic contributions. The model uncertainty is described in [26].

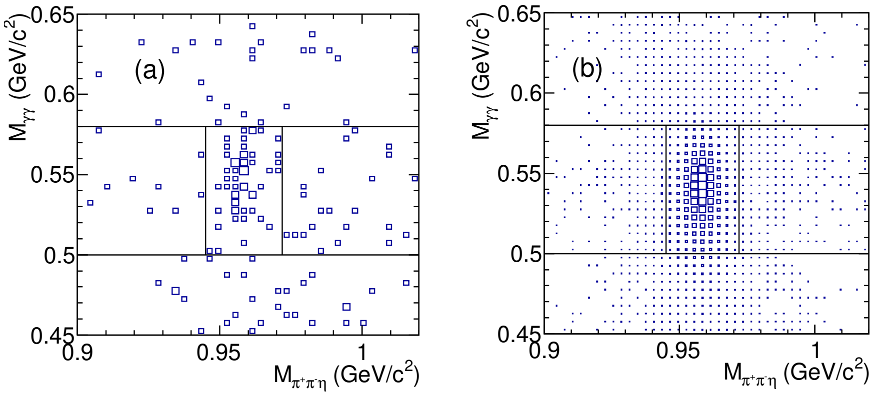

Figure 1: Distribution of the η candidate mass ($M_{\gamma\gamma}$) versus the η' candidate mass ($M_{\pi^+\pi^-\eta}$) for data (a) and signal MC simulation (b). The horizontal lines indicate the boundaries of the selection condition applied. The vertical lines correspond to the restriction $0.945 < M_{\pi^+\pi^-\eta} < 0.972$ GeV/c^2 that is used for the plot of $Q^2_{e^-}$ versus $Q^2_{e^+}$ distribution in Fig. 2.

The obtained values of the transition form factor are published in [26] and are represented in Fig. 3 by the triangles. The error bars attached to the triangles indicate the statistical uncertainties. The quadratic sum of the systematic and model uncertainties is shown by the shaded rectangles.

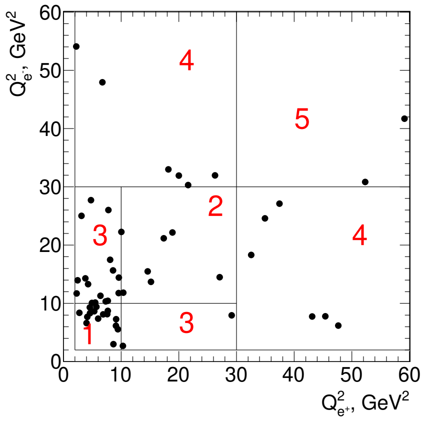

Figure 2: The $Q^2_{e^-}$ versus $Q^2_{e^+}$ distribution for data events. The lines and numbers indicate the five regions used for the study of the dynamics of TFF a function of $Q^2_{e^-}$ and $Q^2_{e^+}$.

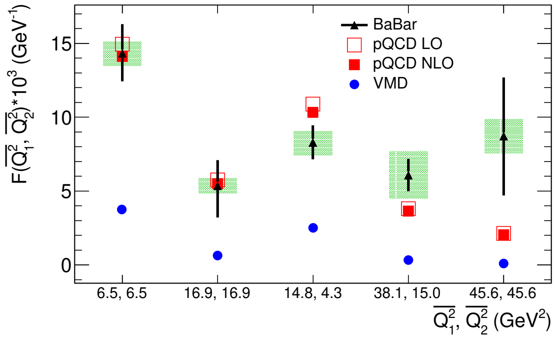

Figure 3: Comparison of the measured $\gamma^\star\gamma^\star \to \eta'$ transition form factor (triangles, with error bars representing the statistical uncertainties) with the LO (open squares) and NLO (filled squares) pQCD predictions and the VDM predictions (circles).

The open and filled squares in Fig. 3 correspond to the LO and NLO pQCD predictions, respectively. The NLO correction is relatively small. The measured TFF is, in general, consistent with the QCD prediction. The circles in Fig. 3 represent the predictions of the VDM model, which exhibits a clear disagreement with the data.

So, we have studied for the first time the process $e^+e^- \to e^+e^-\eta'$ in the double-tag mode and have measured the $\gamma^\star\gamma^\star \to \eta'$ transition form factor in the momentum-transfer range $2 < Q_1^2, Q_2^2 < 60$ GeV^2. The measured values of the form factor are in agreement with the pQCD prediction and contradict the prediction of the VDM model. We are grateful for the extraordinary contributions of our PEPII colleagues in achieving the excellent luminosity and machine conditions and we have received support from the Russian Foundation for Basic Research (grant No. 18-32-01020).

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