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STUDIES OF THE REACTION $e^+e^- \to e^+e^-\chi_{c_i}(\to \gamma J/\psi(\to \mu^+\mu^-))$ AT BELLE II WITH THE MONTE CARLO GENERATOR EKHARA*

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The Belle II experiment with the integrated luminosity of 50 ab^{-1} will allow for an access to information never available before. In this paper, we concentrate on studies of the χ_{c_i}–γ^*–γ^* form factors using the Monte Carlo event generator EKHARA. The precise experimental knowledge of the form factors can differentiate between various models giving predictions for the electronic widths $\Gamma(\chi_{c_{1,2}} \to e^+e^-)$, even without direct measurements of these widths.

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1. Introduction

The modeling of the χ_{c_i} decays into e^+e^- is far from satisfactory. The predictions of the models [1–5] rely on the modeling of the χ_c–γ^*–γ^*, χ_{c_i}–J/ψ^*–γ^* and χ_{c_i}–ψ'^*–γ^* form factors, yet the only experimental information on these form factors comes from the $\chi_{c_i} \to \gamma\gamma$, $\chi_{c_i} \to J/\psi\gamma$ and $\psi' \to \chi_{c_i}\gamma$ decays where these form factors are evaluated at the masses of the corresponding particles. These form factors enter the loop integrals and the predictions for the χ_c electronic widths do depend on the details of the modeling, which were never checked experimentally. This is the reason of the wide spread of the model predictions shown in Table I. The situation can change, if at the already running Belle II experiment [6] a decision will be taken to measure the χ_{c_i}–γ^*–γ^* form factors. Almost full integrated luminosity of the planned 50 ab^{-1} is necessary to make these studies with a decent precision.

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TABLE I

Presented predictions of the electronic widths: $\Gamma(\chi_{c_{1,2}} \to e^+e^-)$ comes from recently published models.

	[1]	[2]	[3]	[4]	[5]
$\Gamma\,(\chi_{c_1} \to e^+e^-)$ [eV]	0.37	0.43	0.09	0.367	0.1
$\Gamma\,(\chi_{c_2} \to e^+e^-)$ [eV]	3.86	4.25	0.07	0.137	—

To study this possibility in details and to help in the future data analysis, the Monte Carlo event generator EKHARA [9, 10] was updated. Seven new channels have been implemented. Three to calculate cross sections of the reactions $e^+e^- \to e^+e^-\chi_{c_i}$, $i = 0, 1, 2$, three to study also the subsequent decays of the χ_{c_i} into $\gamma J/\psi(\to \mu^+\mu^-)$, and one were the code simulates the simultaneous production of all the χ_{c_i} with their decay to the identical final state $\gamma J/\psi(\to \mu^+\mu^-)$.

The electronic widths of the χ_{c_1} and χ_{c_2} can be measured at the BESSIII experiment [7] by scanning the energy range around these resonances if the electronic widths are in the upper bulk of the predictions [2]. If this is not done, the only option to scrutinise the models is to measure the χ_{c_i}–γ^*–γ^* form factors at Belle II.

2. The model implemented in the Monte Carlo generator EKHARA

In the last update (version 2.2) of the Monte Carlo generator EKHARA [1], a model developed in [2], extended to describe also χ_{c_0} properties, was implemented. The details can be found in [2] and [1]. Here, we present only the main assumptions.

The amplitudes $A_{0,1,2}$ for the reactions $\chi_{c_{0,1,2,}} \to \gamma(p_1)\gamma(p_2)$ predicted within this specific model read

$$\begin{aligned} A_0 &= \sqrt{\tfrac{1}{6}}c_\gamma \frac{1}{M_{\chi_{c_0}}}\left[I_1^0\left(M^2_{\chi_{c_0}} + p_1\cdot p_2\right) - 2I_2^0\right] , \\ A_1 &= -\frac{i}{2}c_\gamma\left[I_1^1 + I_2^1\right] , \qquad A_2 = -c_\gamma\sqrt{2}M_{\chi_{c_2}}I_2^2 , \end{aligned} \tag{1}$$

where

$$F_{\mu\nu} = \epsilon_\mu p_\nu - \epsilon_\nu p_\mu , \qquad I_1^0 = F^1_{\mu\nu}F^{2\mu\nu} , \qquad I_2^0 = p_1^\nu F^1_{\mu\nu}F^{2\mu\alpha}p_{2\alpha} ,$$
$$I_1^1 = F^1_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}F^2_{\alpha\gamma}p_2^\gamma\epsilon_\beta , \quad I_2^1 = F^2_{\mu\nu}\epsilon^{\mu\nu\alpha\beta}F^1_{\alpha\gamma}p_1^\gamma\epsilon_\beta \quad \text{and} \quad I_2^2 = \epsilon^{\mu\alpha}F^{1\beta}_{\mu}F^2_{\alpha\beta} .$$

We assume that the Lorentz structure of the amplitudes, as well as the functional form of the form factors are identical also for χ_{c_i}–γ–J/ψ and χ_{c_i}–γ–ψ' interactions, while the coupling constants are allowed to be different. It means that one has to replace c_γ in Eq. (1) with $c_{J/\psi}$ or $c_{\psi'}$ given below

$$\begin{aligned}
c_\gamma &= \frac{4e^2}{\sqrt{m}}\left(a + \frac{f a_J}{M^2_{J/\psi}} + \frac{f' a_{\psi'}}{M^2_{\psi'}}\right)\frac{1}{\left(M^2_{\chi_{c_i}}/2 + b_i^2/4 + b_i M_{\chi_{c_i}}/2\right)^2}\,,\\
c_{J/\psi} &= \frac{4ea_J}{\sqrt{m}}\frac{1}{\left(M^2_{\chi_{c_i}}/2 + b_i^2/4 + bM_{\chi_{c_i}}/2 - M^2_{J/\psi}/2\right)^2}\,,\\
c_{\psi'} &= \frac{4ea_{\psi'}}{\sqrt{m}}\frac{1}{\left(M^2_{\chi_{c_i}}/4 + m^2 - M^2_{\psi'}/2\right)^2}\,,
\end{aligned} \tag{2}$$

where $a = \sqrt{\frac{1}{4\pi}}3Q^2\Phi'(0)(Q = 2/3)$ is proportional to the derivative of the wave function at the origin, a_J is the coupling constant of J/ψ–χ_{c_i}–γ, $a_{\psi'}$ is the coupling constant of ψ'–χ_{c_i}–γ, $b_i = 2m - M_{\chi_{c_i}}$ are the binding energies, m is the effective charm quark mass, $f = \sqrt{\frac{3\Gamma_{J/\psi\to e^+e^-}M^3_{J/\psi}}{4\pi\alpha^2}}$ and $f' = \sqrt{\frac{3\Gamma_{\psi'\to e^+e^-}M^3_{\psi'}}{4\pi\alpha^2}}$.

6 parameters: a, m, a_J, a^0_J, $a_{\psi'}$ and $a^0_{\psi'}$ were fitted by using Minuit package to the 8 experimental variables: $\Gamma(\chi_{c_{0,2}} \to \gamma\gamma)$, $\Gamma(\chi_{c_{0,1,2}} \to J/\psi\gamma)$ and $\Gamma(\psi' \to \chi_{c_{0,1,2}}\gamma)$ with $\chi^2 = 0.943$. The model parameters obtained in the fits in [2] and in [1] are shown in Table II.

TABLE II

The model parameters implemented in the EKHARA generator [1] compared to [2].

a [GeV$^{5/2}$]	m [GeV]	a_J [GeV$^{5/2}$]	a^0_J [GeV$^{5/2}$]	$a_{\psi'}$ [GeV$^{5/2}$]	$a^0_{\psi'}$ [GeV$^{5/2}$]	Model
0.0786	1.69	0.150	—	−0.070	—	[2]
0.0796	1.67	0.129	0.073	−0.078	0.122	[1]

3. Testing χ_{c_i} properties at Belle II

In the simulations, a setup close to the Belle II experiment was used. Energy of the initial positron and electron beams are 4 GeV and 7 GeV respectively, the crossing angle is equal to 83 mrad. The number of expected events is obtained assuming integrated luminosity of 50 ab^{-1}. Polar angles of the observed particles are in the range from 17° to 150°. To suppress the non-resonant QED background, we require that the virtual masses of χ_{c_i} and J/ψ are in the range of 10 widths from their physical masses.

The implementation was cross checked using two independent codes obtained independently with the helicity and the trace method.

3.1. The production of the χ_{c_i} states in the reactions $e^+e^- \to e^+e^-\chi_{c_i}$

With the complete angular range covered by a detector, the expected number of events, predicted within the model described in Section 2, is about 140M for χ_{c0} and χ_{c2}, while only 4.3 M for χ_{c1} (it is caused by a fact

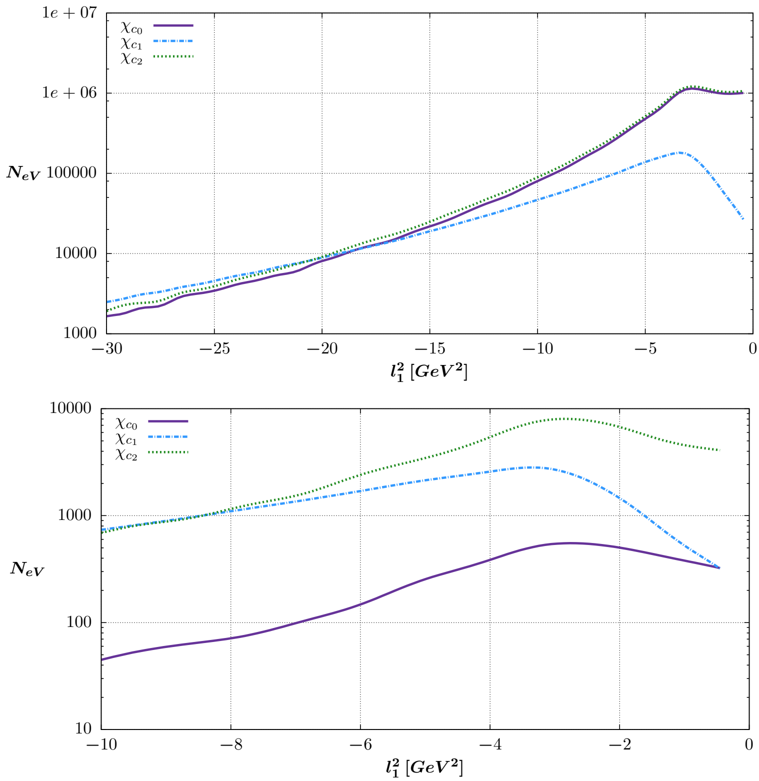

Fig. 1. The distributions of the expected number of events for the χ_{c_i} production (top) and the decay (bottom). For the production (decay), we require that the polar angles of the final positron (positron, γ, μ^+ and μ^-) were in the range of 17°–150°. $l_1^2 = (p_1 - q_1)^2$ is the invariant mass of a virtual photon with p_1 and q_1 being four momenta of the initial and the final positron, respectively. Bins of the length of 0.91 GeV^2 were used to obtain this plots.

that the $\Gamma(\chi_{c_1} \to \gamma\gamma) = 0$). For the polar angle of the observed positron in the range of 17°–150°, we obtained 6.7 M, 1.4 M and 7.2 M events for χ_{c0}, χ_{c1} and χ_{c2}, respectively. The distribution of expected number of events is shown in Fig. 1 (top). When both positron and electron are observed in the range of 17°–150°, one expects about 200 k events for each mode. These numbers show that the Belle II experiment can access information about χ_{c_i}–γ^*–γ^* form factors.

3.2. The production of the χ_{c_i} *with a subsequent decay into* $\gamma J/\psi(\to \mu^+\mu^-)$

The amplitudes describing the reactions $e^+e^- \to e^+e^-\chi_{c_i}(\to \gamma J/\psi(\to \mu^+\mu^-))$ for $i = 0, 1, 2$ in principle interfere. Yet, the interference between them can be safely neglected as the cross sections calculated from a single amplitude drop rapidly when the invariant mass is slightly off-resonance (see Fig. 2).

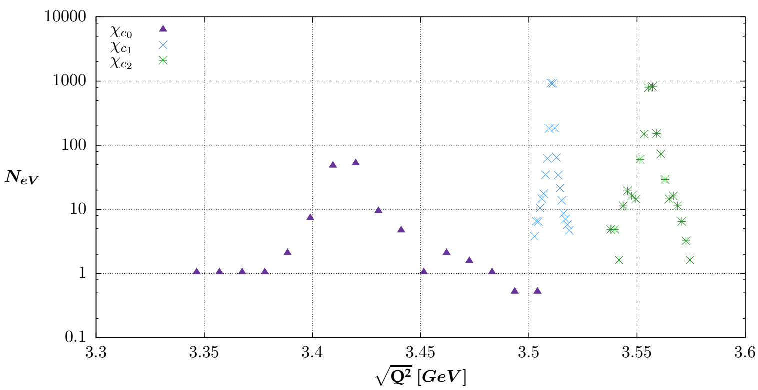

Fig. 2. The distributions of the expected number of events in the processes $e^+e^- \to e^+e^-\chi_{c_i}(\to \gamma J/\psi(\to \mu^+\mu^-))$ as a function of the invariant mass of the $\mu^+\mu^-\gamma$ system Q^2, $i = 0, 1, 2$.

For this particular decay channel, the number of single tag events, when all final particles except the electron are observed in the angular range of 17°–150°, is about 3.1 k for χ_{c0}, 22 k for χ_{c1} and 44 k for χ_{c2}. Thus, the testing of the χ_{c_i}–γ^*–γ form factors will be possible using only this channel.

3.3. The estimation of the QED background

To estimate the non-resonant QED background, the HELAC-PHEGAS generator [8] was used. The polar angles of the observed particles were in the range between 17° and 150° in the laboratory frame, while the ranges of the invariant masses of $\mu^+\mu^-\gamma$ and $\mu^+\mu^-$ systems were chosen to accommodate 99% of the signal.

For the cross sections of the reactions $e^+e^- \to e^+e^-\chi_{c_{1,2}}(\to \gamma J/\psi(\to \mu^+\mu^-))$, the interference between the background and the signal can be safely neglected because the background-to-signal ratio is equal to 0.2% (0.1%) for χ_{c_1} and 0.7% (1.7%) for χ_{c_2} with single (double) tag events. For the χ_{c_0} the situation is different. The background-to-signal ratio is equal to 110% and 220% for the single and the double tag events respectively, mostly due to the low signal and the big width of the χ_{c_0} as compared to the $\chi_{c_{1,2}}$ widths. The effects of the interference between the background and the signal for χ_{c_0} have to be studied in future.

4. Conclusions

It was shown, within the considered model, that at the Belle II experiment it will be possible to study in details χ_{c_i}–γ^*–γ^* form factors. The size of the non-resonant QED background contributing to the measurements was also investigated.

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