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Light front approach to axial meson photon transition form factors: probing the structure of $\chi_{c1}(3872)$

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Abstract. We propose to study the structure of the enigmatic $\chi_{c1}(3872)$ axial vector meson through its $\gamma^*_L\gamma \to \chi_{c1}(3872)$ transition form factor. We use our recently derived light-front wave function representation of the form factor for the lowest $c\bar{c}$ Fock-state. We found that the reduced width of the state is well within the current experimental bound recently published by the Belle collaboration. This strongly suggests a crucial role of the $c\bar{c}$ Fock-state in the photon-induced production. Our predictions for the Q^2 dependence can be tested by future single tagged e^+e^- experiments, giving further insights into the short-distance structure of this meson.

1 Introduction

The $\chi_{c1}(3872)$ (or $X(3872)$) axial vector meson state discovered by the Belle collaboration some 20 years ago [1] still poses a number of puzzles. Its mass is close to the $D^0 D^{*0}$ threshold which suggests a picture based on a very weakly bound meson molecule (for a review, see e.g. Ref.[2] and references therein). On the other hand, in high-energy proton-proton collisions, its production at large transverse momenta proceeds at rates comparable to the quarkonium $\psi'(2S)$ [3–5]. This appears counterintuitive for such a weakly bound, very large, strongly interacting system. Indeed, our recent calculations [6] suggest, that a compact $c\bar{c}$ component may play a decisive role in the production mechanism. Here, the production in a virtual photon-photon mode suggests itself as a much cleaner environment to study the role of the possible $c\bar{c}$ component. Here the photon virtuality serves as a handle to zoom in on the short-distance structure of the meson. First results in e^+e^- collisions have been reported by the Belle Collaboration [7]. Here, we give a brief review of our recent work [8].

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2 $\gamma^*\gamma^*$ transition form factors for the $J^{PC} = 1^{++}$ state

In the coupling of two virtual photons to an axial vector meson, three invariant form factors appear. The relevant $\gamma^*\gamma^*$-meson amplitude can be written in covariant form as [9, 10]:

$$\begin{aligned}\frac{1}{4\pi\alpha_{\rm em}}\mathcal{M}_{\mu\nu\rho} &= i\Big(q_1 - q_2 + \frac{Q_1^2 - Q_2^2}{(q_1+q_2)^2}(q_1+q_2)\Big)_\rho \tilde{G}_{\mu\nu}\,\frac{M}{2X}F_{\rm TT}(Q_1^2,Q_2^2) \\ &+ ie^L_\mu(q_1)\tilde{G}_{\nu\rho}\,\frac{1}{\sqrt{X}}F_{\rm LT}(Q_1^2,Q_2^2) + ie^L_\nu(q_2)\tilde{G}_{\mu\rho}\,\frac{1}{\sqrt{X}}F_{\rm TL}(Q_1^2,Q_2^2)\,. \qquad (1)\end{aligned}$$

Here we have introduced the mass M of the meson, and

$$\tilde{G}_{\mu\nu} = \varepsilon_{\mu\nu\alpha\beta}q_1^\alpha q_2^\beta\,, \qquad X = (q_1\cdot q_2)^2 - q_1^2 q_2^2\,, \qquad (2)$$

as well as the polarization vectors of longitudinal photons

$$e^L_\mu(q_1) = \sqrt{\frac{-q_1^2}{X}}\Big(q_{2\mu} - \frac{q_1\cdot q_2}{q_1^2}q_{1\mu}\Big), \qquad e^L_\nu(q_2) = \sqrt{\frac{-q_2^2}{X}}\Big(q_{1\nu} - \frac{q_1\cdot q_2}{q_2^2}q_{2\nu}\Big)\,. \qquad (3)$$

Above, the Lorentz indices μ,ν correspond to the photon legs, while ρ is to be contracted with the meson's polarization vector. We have denoted $Q_i^2 = -q_i^2$ for the photon virtualities, and are only interested in the spacelike (and on-shell) region $Q_i^2 \geq 0$. A spin-1 particle cannot decay into two photons (by the Landau-Yang "theorem"), which means that $F_{\rm TT}(0,0) = 0$. On the other hand, to avoid a kinematical singularity, the combination

$$f_{\rm LT}(Q^2) = \frac{F_{\rm LT}(Q^2,0)}{Q} \qquad (4)$$

has a definite limit at $Q^2 \to 0$. Its value $f_{\rm LT}(0)$, therefore, serves to quantify the strength of the two-photon coupling to the axial vector and gives rise to the so-called "reduced width":

$$\tilde{\Gamma} = \frac{\pi\alpha_{\rm em}^2 M}{3}\,f_{\rm LT}^2(0)\,.$$

We thus need at least **one virtual photon** to produce an axial vector in photon-photon collisions. This excludes ultraperipheral heavy ion collisions, where photons are quasi-real. Electron scattering gives us access to finite Q^2 and a whole polarization density matrix of virtual photons. Here, feasible options are (see the diagram in the left panel of figure 1):

1. single tag e^+e^- collisions. Here the tagged lepton couples to the virtual photon, while photons from the lepton "lost in the beampipe" are quasireal [7].

2. electron-proton or electron-ion scattering. Here especially heavy ions such as Gold, the large charge $Z = 79$ of which give rise to a large quasireal photon flux enhanced by Z^2, are of interest. For the example of η_c production, see [11].

2.1 Light front representation of transition form factors

We evaluate the $\gamma^*\gamma^* \to \chi_{c1}$ amplitude in the Drell-Yan frame where $q_{1\mu} = q_{1+}n^+_\mu + q_{1-}n^-_\mu$ and $q_{2\mu} = q_{2-}n^-_\mu + q^\perp_{2\mu}$, using the light front plus-component of the electromagnetic current, (compare the diagram in the right panel of figure 1):

$$\langle\chi_{c1}(\lambda)|J_+(0)|\gamma^*_L(Q^2)\rangle = 2q_{1+}ee_c\,\sqrt{N_c}\int\frac{dzd^2\boldsymbol{k}}{z(1-z)16\pi^3}\sum_{\sigma,\bar\sigma}\Psi^{\lambda*}_{\sigma\bar\sigma}(z,\boldsymbol{k})\,(\boldsymbol{q}_2\cdot\nabla_{\boldsymbol{k}})\Psi^{\gamma_L}_{\sigma\bar\sigma}(z,\boldsymbol{k},Q^2)\,. \qquad (5)$$

Table 1. The reduced width of the $\chi_{c1}(2P)$ state for several models of the charmonium wave functions with specific c-quark mass.

$c\bar{c}$ potential	m_c (GeV)	$f_{\rm LT}(0)$	$\tilde{\Gamma}_{\gamma\gamma}$ (keV)
harmonic oscillator	1.4	0.041	0.36
power-law	1.334	0.033	0.24
Buchmüller-Tye	1.48	0.029	0.18
logarithmic	1.5	0.025	0.14
Cornell	1.84	0.018	0.07
BLFQ [13]	1.6	0.044	0.42

The form factor $f_{\rm LT}$ when expressed through the $c\bar{c}$ Fock state light front wave function (LFWF) then takes the form

$$\frac{f_{\rm LT}(Q^2)}{Q^2+M_\chi^2} = -2\sqrt{2N_c}\,e_c^2 \int \frac{dz d^2\boldsymbol{k}}{16\pi^3} \frac{k_x + ik_y}{[\boldsymbol{k}^2+\epsilon^2]^2} \sqrt{z(1-z)} \Big\{ \Psi^{(+1)*}_{\uparrow\downarrow}(z,\boldsymbol{k}) + \Psi^{(+1)*}_{\downarrow\uparrow}(z,\boldsymbol{k}) \Big\} . \quad (6)$$

We note that the fully transverse form factor for the case of a quark-antiquark state is obtained as:

$$F_{\rm TT}(Q^2,0) = -\frac{Q^2}{M} f_{\rm LT}(Q^2) .$$

Regarding the LFWF of the meson, we adopt two options. The first one is based on solutions of the radial Schrödinger equation in the meson rest frame and a prescription on how to transform the obtained wave function into a radial LFWF. The spin-orbit part is obtained by means of a Melosh transformation, see Ref.[10] for details. A second approach is based on a solution of the bound state problem directly on the light front [12, 13], labelled BLFQ.

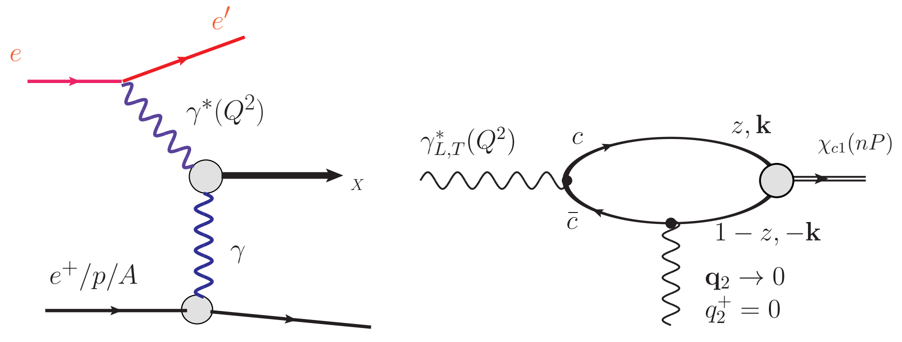

Figure 1. Left: a typical $\gamma^*\gamma$ fusion process in the large angle scattering of an electron off a positron, proton, or nucleus. Right: the $\gamma_L^*\gamma_T \to \chi_{c1}$ transition form factor in the kinematics of the Drell–Yan frame.

Modelling the $\chi_{c1}(3872)$ as a $2P$ $c\bar{c}$ state, we obtain the values of the reduced width shown in table 1, and the form factor $f_{\rm LT}(Q^2)$ shown in figure 2. In the case of $\chi_{c1}(3872)$, the values obtained for a 2^3P_1 charmonium are well within the range of the first Belle data, compare the updated value of Ref.[14]:

$$0.024\,\text{keV} < \tilde{\Gamma}(\chi_{c1}(3872)) < 0.615\,\text{keV} . \quad (7)$$

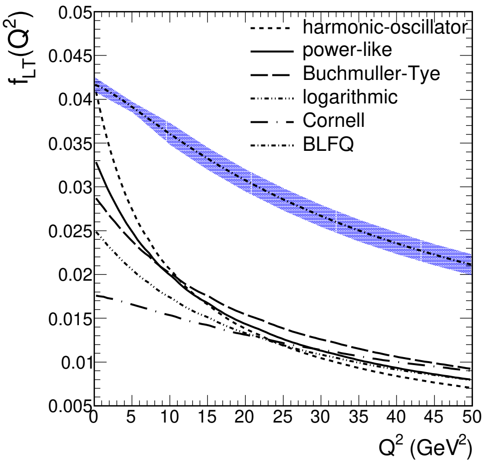

Figure 2. The form factor $f_{\rm LT}(Q^2)$ for different models of the LFWF of the $\chi_{c1}(3872)$.

This suggests an important role of the $c\bar{c}$ Fock state for production in the $\gamma^*\gamma$ mode. (Of course, there is still room for additional contributions.) Electroproduction of $\chi_{c1}(1P), \chi_{c1}(3872)$ in the Coulomb field of a heavy nucleus may give access to the form factor $f_{\rm LT}(Q^2)$. This is additional information on the structure. We know how to calculate it for $c\bar{c}$ states.

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