A perturbative approach
to the $\eta_c \gamma$ transition form factor

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The $\eta_c \gamma$ transition form factor is calculated within a perturbative approach. For the $\eta_c$-meson, a wave function of the Bauer-Stech-Wirbel type is used where the two free parameters, namely the decay constant $f_{\eta_c}$ and the transverse size of the wave function, are related to the Fock state probability and the width for the two-photon decay $\Gamma[\eta_c \rightarrow \gamma \gamma]$. The $Q^2$ dependence of the $\eta_c \gamma$ transition form factor is well determined.

Key words: eta/c (2980), transition form factor, hard scattering

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1 Introduction

In 1995 the CLEO collaboration has presented their preliminary data on pseudoscalar meson-photon transition form factors (see Fig. 1) at large momentum transfer $Q^2$ for the first time [1]. Since then these form factors attracted the interest of many theoreticians and it can be said that the CLEO measurement has strongly stimulated the field of hard exclusive reactions. One of the exciting aspects of the $\pi \gamma$ form factor is that it possesses a well-established asymptotic behavior [2,3], namely $F_{\pi \gamma} \rightarrow \sqrt{2} f_{\pi}/Q^2$ where $f_{\pi} (= 131$ MeV) is the decay constant of the pion. At the upper end of the measured $Q^2$ range the CLEO data [1,4] only deviate by about 15% from that limiting value. Many theoretical papers are devoted to the explanation of that little difference. The perhaps most important result of these analyses, as far as they are based upon perturbative approaches (see e.g. [5,6]), is the rather precise determination of the pion’s light-cone wave function. It turns out that the

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pion’s distribution amplitude, i.e. its wave function integrated over transverse
momentum, is close to the asymptotic form \( \sim x(1-x) \). This result has far-
reaching consequences for the explanation of many hard exclusive reactions in
which pions participate (see, for instance, \cite{8–10}).

\[
\gamma^* \gamma e^+e^- \leftrightarrow \pi, \eta, \eta', \eta_c
\]

Fig. 1. Meson-Photon transition form factors in \( e^+e^- \) collisions.

The situation is more complicated for the other cases, the \( \eta\gamma \) and the \( \eta'\gamma \)
form factors. One has to determine not only the corresponding wave functions
but as well the decay constants and the \( SU(3)_F \) octet-singlet mixing angle for
pseudoscalars. With the help of a few plausible assumptions a determination
of these quantities from the \( \eta\gamma \) and \( \eta'\gamma \) transition form factors seems possible
\cite{6}.

There is a fourth form factor of the same type, namely the \( \eta_c\gamma \) form factor
which is neither experimentally nor theoretically known. Since a measurement
of that form factor up to a momentum transfer of about 10 GeV\(^2\) seems feasible
\cite{11}, a theoretical analysis and prediction of it is desirable. The purpose of this
paper is the presentation of such an analysis. In analogy to the \( \pi\gamma \) case \cite{5,6}
we will employ a perturbative approach on the basis of a factorization of short-
and long-distance physics \cite{2}. Observables are then described as convolutions
of a so-called hard scattering amplitude to be calculated from perturbative
QCD and universal (process-independent) hadronic light-cone wave functions,
which embody soft non-perturbative physics. The wave functions are not cal-
culable with sufficient degree of accuracy at present and one generally has to
rely on more or less well motivated model assumptions.

In the case of interest the mass of the charm quarks, the \( \eta_c \) meson is com-
posed of, already provides a large scale which allows the application of the
perturbative approach even for zero virtuality of the probing photon, \( Q^2 \to 0 \),
and, therefore, our analysis can be linked to the two-photon decay width

\[ B_2 \]

Allowing for a second term in the expansion of the pion’s distribution amplitude
upon the the eigenfunctions of the evolution kernel in order to quantify possible
deviations from the asymptotic form, we find, from the recent CLEO data \cite{11} and
within the modified hard scattering approach, a value of 0.0 ± 0.1 for the expansion
coefficient \( B_2 \) at the scale \( \mu = 1 \) GeV.
The experimental information on the latter width provides a constraint on the $\eta_c$ wave function. The valence Fock state probability $P_{c\bar{c}}$ of the $\eta_c$, which is expected to lie in the range $0.8 - 1.0$, offers a second constraint on the wave function and, for the simple ansatz we will use, determines it completely. We will show that variation of $P_{c\bar{c}}$ over the expected range has only a very mild influence on the final result, and hence our prediction for the transition form factor as a function of $Q^2$ turns out to be practically model-independent in the region of experimental interest, where potential $Q^2$ dependence from higher order QCD corrections can be neglected.

The organization of this paper is as follows: First we discuss the perturbative approach to the $\eta_c\gamma$ transition form factor, including the leading order result for the hard scattering amplitude and our ansatz for the wave function (sect. 2). In the following sect. 3 the two parameters that enter our wave function are fixed by relating them to the Fock state probability and the width for the two-photon decay. We present our results and conclusions in sect. 4.

2 The perturbative approach

In analogy to the case of the $\pi\gamma$ case we define the $\eta_c\gamma$ transition form factor as a convolution of a hard scattering amplitude $T_H$ and a non-perturbative (light-cone) wave function $\Psi$ of the $\eta_c$’s leading $c\bar{c}$ Fock state

$$F_{\eta_c\gamma}(Q^2) = \int_0^1 dx \int \frac{d^2k_\perp}{16\pi^3} \Psi(x, k_\perp) T_H(x, k_\perp, Q) .$$

Here $k_\perp$ denotes the transverse momentum of the $c$ quark defined with respect to the meson’s momentum and $x$ is the usual momentum fraction carried by the $c$ quark. In contrast to the $\pi\gamma$ case we do not include a Sudakov factor in eq. (1) and therefore we are not forced to work in the transverse configuration space. The Sudakov factor which comprises higher order QCD corrections in next-to-leading-log approximation, can be ignored for two reasons: First, due to the large mass of the $c$ quark the QCD corrections only produce soft divergences but no collinear ones, and hence, the characteristic double logs do not appear. Secondly, the Sudakov factor is only relevant in the endpoint regions ($x \to 0$ or $1$) where it provides strong suppressions of the perturbative contribution. Since, however, the $\eta_c$ wave function is expected to be strongly peaked at $x = x_0$, with $x_0 = 1/2$, and exponentially damped for $x \to 0, 1$ the endpoint regions are unimportant anyway.

The hard scattering amplitude in leading order is calculated from the Feynman diagrams shown in Fig. 2. With one photon being almost on-shell $q_1^2 \simeq 0$ and
the virtuality of the second photon denoted as $q_2^2 = -Q^2$, this leads to (with $\bar{x} = (1 - x)$)

$$T_H(x, k_\perp, Q) = \frac{e_c^2 2\sqrt{6}}{x Q^2 + (x\bar{x} + \rho^2) M_{\eta_c}^2 + k_\perp^2} + (x \leftrightarrow \bar{x}) + O(\alpha_s)$$  \hfill (2)

where $M_{\eta_c} (= 2.98 \text{ GeV})$ is the mass of the $\eta_c$ meson. $\rho$ is the ratio of the charm quark mass ($m_c$) and the $\eta_c$ mass, for which we will take the value $\rho = 0.5$. The charge of the charm quark in units of the elementary charge is denoted by $e_c$. Due to the symmetry of the wave function $\Psi(x) = \Psi(\bar{x})$, the two graphs provide identical contributions.

For the $\eta_c$ wave function we use a form adapted from Bauer, Stech and Wirbel \[14\],

$$\Psi(x, k_\perp) = \frac{f_{\eta_c}}{2\sqrt{6}} \phi(x) \Sigma(k_\perp) .$$  \hfill (3)

$f_{\eta_c}$ is the decay constant (corresponding to $f_\pi = 131 \text{ MeV}$) which plays the role of the configuration space wave function at the origin. $\phi(x)$ is the quark distribution amplitude which is parameterized as

$$\phi(x) = N_\phi(a) \ x \bar{x} \ \exp \left[ -a^2 M_{\eta_c}^2 (x - x_0)^2 \right] .$$  \hfill (4)

The normalization constant $N_\phi(a)$ is determined from the usual requirement $\int_0^1 dx \ \phi(x) = 1$. The distribution amplitude \[4\] exhibits a pronounced maximum at $x_0$ and is exponentially damped in the endpoint regions. This feature of the distribution amplitude parallels the theoretically expected and experimentally confirmed behavior of heavy hadron fragmentation functions. Furthermore, $\Sigma$ is a Gaussian shape function which takes into account the finite transverse size of the meson,

$$\Sigma(k_\perp) = 16\pi^2 a^2 \ \exp[ -a^2 k_\perp^2 ] \ , \ \int \frac{d^2k_\perp}{16\pi^3} \Sigma(k_\perp) = 1 .$$  \hfill (5)
Frequently used and for light mesons even mandatory \([15,7]\) is a form of the \(k_{\perp}\) dependence like \(\exp[-b^2 k_{\perp}^2 / x \bar{x}]\). Due to the behavior of the distribution amplitude \([4]\) any explicit appearance of \(x\) in \(\Sigma\) can be replaced by \(x_0\) to good approximation.

3 Fixing the parameters

Let us start with the determination of the \(\eta_c\) decay constant, a parameter which is not accessible in a model-independent way at present. Usually, one estimates \(f_{\eta_c}\) through a non-relativistic approach which provides a connection between \(f_{\eta_c}\) and the well-determined decay constant of the \(J/\psi\). We note, that the non-relativistic approach, which is only valid for \(Q^2 \ll M_{\eta_c}^2\), is consistent with our definition of \(f_{\eta_c}\) (see \((1-3)\)) if relativistic corrections are ignored. In the non-relativistic approach the partial widths \(\Gamma[\eta_c \to \gamma \gamma]\) and \(\Gamma[J/\psi \to e^+ e^-]\) are related to each other

\[
\Gamma[\eta_c \to \gamma \gamma] = \frac{3}{2} \frac{e^4 c^2 \alpha^2}{m_c^2} |R_S(0)|^2 \left[ 1 - 3.4 \frac{\alpha_s}{\pi} \right] \left[ 1 - \lambda_2 v^2 \right]^2,
\]

\[
\Gamma[J/\psi \to e^+ e^-] = \frac{e^2 c^2 \alpha^2}{m_c^2} |R_S(0)|^2 \left[ 1 - 5.3 \frac{\alpha_s}{\pi} \right] \left[ 1 - \lambda_1 v^2 \right]^2. \tag{6}
\]

Here \(R_S(r)\) is the common non-relativistic \(S\)-wave function of the \(J/\psi\) and \(\eta_c\) meson, \(\lambda_{1,2}\) parameterize the leading relativistic corrections, and the \(\alpha_s\) corrections have been calculated in \([10]\). The wave function at the origin \(R_S(0)\) is related to the decay constants, and in the limit \(v^2 \to 0\), \(\alpha_s \to 0\) one has \(f_{\eta_c} = f_{J/\psi} = \sqrt{3/2 m_c \pi} |R_S(0)|\) and \(\Gamma[\eta_c \to \gamma \gamma] / \Gamma[J/\psi \to e^+ e^-] \approx 3 e_c^2\). The latter decay constant is model-independently determined from the \(J/\psi\) leptonic decay width

\[
\Gamma[J/\psi \to e^+ e^-] = \frac{4 \pi e_c^2 \alpha^2 f_{J/\psi}^2}{3 M_{J/\psi}} = 5.26 \pm 0.37 \text{ keV} \tag{7}
\]

which leads to \(f_{J/\psi} = 409\) MeV. However, the \(\alpha_s\) corrections in \((8)\) are large (depending on the value of \(\alpha_s\) one prefers), and the relativistic corrections are usually large and model-dependent (e.g. Chao et al. \([15]\) find \(\lambda_1 = 5/12\), \(\lambda_2 = 11/12\) from a Bethe-Salpeter model). Estimates of the corrections typically lead to \([15,22]\) \(f_{\eta_c} / f_{J/\psi} = 1.2 \pm 0.1\) and \(\Gamma[\eta_c \to \gamma \gamma] = (5 - 7)\) keV.

The parameters entering the wave function are further constrained by the Fock state probability

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\[ 1 \geq P_{\bar{c}\bar{x}} = \int \frac{dx \, d^2k_\perp}{16\pi^3} |\Psi(x, k_\perp)|^2 \simeq \frac{f_{\eta_c}^2 a^2 \pi^2}{3} \cdot \frac{aM_{\eta_c}}{\sqrt{2}\pi} \left(1 + \frac{2}{a^2M_{\eta_c}^2}\right). \] (8)

As we said in the introduction, one expects \(0.8 \leq P_{\bar{c}\bar{x}} < 1\) for a charmonium state (for smaller values of \(P_{\bar{c}\bar{x}}\) one would not understand the success of non-relativistic potential models for these states). Since the perturbative contribution to the \(\eta_c\gamma\) form factor only mildly depends on the value of \(P_{\bar{c}\bar{x}}\), as it will turn out below, we use \(P_{\bar{c}\bar{x}} = 0.8\) as a constraint for the transverse size parameter \(a\). For \(f_{\eta_c} = 409\) MeV this leads to \(a = 0.97\) GeV\(^{-1}\), a value that is consistent with estimates for the radius \(\langle r^2 \rangle = 3a^2 \simeq (0.4\) fm\(^2\) or the quark velocity \(v^2 = 3/(Ma)^2 \simeq 0.3\) from potential models [21].

The two photon decay width \(\Gamma[\eta_c \rightarrow \gamma\gamma]\), the experimental value of which still suffers from large uncertainties [17], can be directly related to the \(\eta_c\gamma\) transition form factor at \(Q^2 = 0\)

\[
\Gamma[\eta_c \rightarrow \gamma\gamma] = \frac{\pi\alpha^2 M_{\eta_c}^3}{4} |F_{\eta_c\gamma}(0)|^2 = \begin{cases} 
7.5^{+1.6}_{-1.4} \text{ keV} & \text{(direct)} \\
(4.0 \pm 1.5 \text{ keV}) \cdot \frac{\Gamma_{\eta_c}}{13.2 \text{ MeV}} & \text{(BR)}
\end{cases} \tag{9}
\]

One may use this decay rate as a normalization condition for \(F_{\eta_c\gamma}(Q^2 = 0)\) and present the result in the form \(F_{\eta_c\gamma}(Q^2) / F_{\eta_c\gamma}(0)\). In this way the perturbative QCD corrections at \(Q^2 = 0\) to the \(\eta_c\gamma\) transition form factor, which are known to be large (see eq. (6)), are automatically included, and also the uncertainties in the present knowledge of \(f_{\eta_c}\) do not enter our predictions.

4 Results and Conclusions

Let us now turn to numerical estimates of the \(\eta_c\gamma\) transition form factor. The left hand side of Fig. 3 shows that form factor for two different values of the Fock state probability \(P_{\bar{c}\bar{x}}\). As already mentioned, we observe that the dependence on \(P_{\bar{c}\bar{x}}\) is weak. On the right hand side of Fig. 3 we present the result for the transition form factor \(Q^2 F_{\eta_c\gamma}\) scaled to a partial width \(\Gamma[\eta_c \rightarrow \gamma\gamma]\) of 6 keV.

For the values of the meson mass and the transverse size parameter \(a\) that we are dealing with (i.e. \((aM_{\eta_c})^2 = 9\)) it makes also sense to consider the peaking approximation in which the hard scattering amplitude is evaluated at the position of the maximum of the distribution amplitude. The peaking approximation is formally equivalent to the replacement of the distribution amplitude (4) by a \(\delta\) function at \(x = x_0\) (into which it collapses in the limit \((aM_{\eta_c}) \to \infty\)). This approximation is numerically quite reliable and allows one to discuss the qualitative features of the model results in a rather simple
Fig. 3. Left: The results $F_{\eta c\gamma}(Q^2)/F_{\eta c\gamma}(0)$ for different values of the Fock state probability $P_{cc}$ as well as the approximation (10) (with $\langle k_1^2 \rangle \to 0$) with and without $\alpha_s$ corrections. Right: The predictions for $Q^2 F_{\eta c\gamma}(Q^2)$ scaled to $\Gamma[\eta_c \to \gamma\gamma] = 6$ keV in the leading order of the perturbative approach (for $P_{qq}=0.8$). The dashes indicate the $Q^2$ region where QCD corrections may alter the predictions slightly.

By means of the uncertainty principle, $(aM_{\eta c})^2 \gg 1$ can be turned into $\langle k_1^2 \rangle \ll M_{\eta c}^2$, and hence one may also neglect the $k_1^2$ dependence in the hard scattering amplitude (collinear approximation). Including $1/aM_{\eta c}$ corrections to both, the peaking approximation and the collinear approximation, and using for the mean transverse momentum the relation $1/a^2 = 2\langle k_1^2 \rangle$ (see (5)) one arrives at the approximate result for $Q^2 \lesssim M_{\eta c}^2$

$$F_{\eta c\gamma}(Q^2) \approx \frac{4 e^2 f_{\eta c}}{Q^2 + M_{\eta c}^2 + 2\langle k_1^2 \rangle} \approx \frac{F_{\eta c\gamma}(0)}{1 + Q^2/(M_{\eta c}^2 + 2\langle k_1^2 \rangle)}.$$  

(10)

which agrees with the perturbative result to order $(1/aM_{\eta c})^2$. Eq. (10) reveals that, to a very good approximation, the predictions for the $\eta_c\gamma$ form factor are rather insensitive to the details of the wave function. Only the mean transverse momentum following from it is required.

To assess the quality of the approximation (10) we compare it for the special case of $\langle k_1^2 \rangle = 0$ to the full result from the perturbative approach in Fig. 3 (left hand side). We observe that, with increasing $Q^2$, the two results growingly deviate from each other, at $Q^2 = 10$ GeV$^2$ the difference amounts to 10%. If one uses our estimated value of $\langle k_1^2 \rangle$ in (10) the deviation from the full result is further reduced and amounts only to 4% at $Q^2 = 10$ GeV$^2$. This little difference is likely smaller than the expected experimental errors in a future measurement of the $\eta_c\gamma$ form factor (see [11]). These considerations nicely illustrate that the $Q^2$ dependence of the $\eta_c\gamma$ form factor is well determined. The main uncertainty of the prediction resides in the normalization, i.e. the $\eta_c$ decay constant or the value of the form factor at $Q^2 = 0$. 

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Eq. (10) resembles the Brodsky-Lepage interpolation formula proposed for the $\pi\gamma$ transition form factor [22] as well as the prediction from the vector meson dominance model (VDM). Our value of $\sqrt{M_{\eta_c}^2 + 2\langle k_{\perp}^2 \rangle}$ is 3.15 GeV which is very close to the value of the $J/\psi$ mass that one would have inserted in the VDM ansatz [4]. In the VDM the $\eta_c\gamma$ form factor at $Q^2 = 0$ is given by $F_{\eta_c\gamma}^{\text{VDM}}(0) = e_c g_{J/\psi\eta_c\gamma} f_{J/\psi}/M_{J/\psi}$ where the $J/\psi\eta_c\gamma$ coupling constant can be obtained from the radiative decay $J/\psi \rightarrow \eta_c\gamma$ [17,23]. One finds $F_{\eta_c\gamma}^{\text{VDM}}(0) = 0.048$ MeV$^{-1}$ and hence $\Gamma_{\text{VDM}}^{\eta_c \rightarrow \gamma\gamma} = 2.87$ keV which appears to be somewhat small as compared to the experimental values quoted in (9). Inclusion of a similar contribution from the $\psi'$ pole does not improve the VDM result since the $\psi'$ contribution is very small. In the case of two virtual photons $q_1^2 \neq 0$ the perturbative prediction $F(q_1^2, q_2^2) \propto 1/(-q_1^2 - q_2^2 + M_{\eta_c}^2 + 2\langle k_{\perp}^2 \rangle)$ differs substantially from the VDM.

Let us briefly discuss, how $\alpha_s$ corrections may modify the leading order result for the $\eta_c\gamma$ form factor: One has to consider two distinct kinematic regions. First, if $Q^2 \lesssim M_{\eta_c}^2$ one can neglect the evolution of the wave function, and one is left with the QCD corrections to the hard scattering amplitude $T_H$, which have been calculated in the peaking and collinear approximation to order $\alpha_s$ in [24]. For the scaled form factor the $\alpha_s$ corrections at $Q^2$ and at $Q^2 = 0$ cancel to a high degree, and even at $Q^2 = 10$ GeV$^2$ the effect of the $\alpha_s$ corrections is less than 5% (see left side of Fig. 3).

Secondly, for $Q^2 \gg M_{\eta_c}^2$, one can neglect the quark and meson masses and arrives at the same situation as for the pions. The $\alpha_s$ corrections to the hard scattering amplitude and the evolution of the wave function with $Q^2$ are known [2,24,25]. For very large values of $Q^2$ the asymptotic behavior of the transition form factor is completely determined by QCD, since any meson distribution amplitude evolves into the asymptotic form $\phi(x) \rightarrow \phi_{\text{as}}(x) = 6 x \bar{x}$,

$$F_{\eta_c\gamma}(Q^2) \rightarrow \frac{2e_c^2 f_{\eta_c}}{Q^2} \int_0^1 dx \frac{\phi(x)}{x} \rightarrow \frac{8 f_{\eta_c}}{3 Q^2}, \quad (Q^2 \rightarrow \infty) \quad (11)$$

The value of the moment $\langle x^{-1} \rangle = \int dx \phi(x)/x$ evolves from 2.5 to the asymptotic value 3. We note that the asymptotic behavior of the peaking approximation (10) is $16/9 f_{\eta_c}/Q^2$. The deviation from (11) demonstrates the inaccuracy of the peaking approximation for broad distribution amplitudes.

A precise measurement of the strength of the $\eta_c\gamma$ transition form factor may serve to determine the decay constant $f_{\eta_c}$ (see, e.g. [10]). Though attention

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3 Considering the uncertainty in the mean transverse momentum and in the $c$-quark mass (see [2]), we estimate the uncertainty in the effective pole position following from (10) to amount to about 5%.
must be paid to the fact that the obtained value of $f_{\eta_c}$ is subject to large QCD corrections (about of the order 10-15% for $Q^2 \lesssim 10$ GeV$^2$) which should be taken into account for an accurate extraction of the $\eta_c$ decay constant.

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