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# The radiative decay $D^0 \rightarrow \bar{K}^{*0}\gamma$ with vector meson dominance<sup>\*</sup>

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**Abstract:** Motivated by the experimental measurements of  $D^0$  radiative decay modes, we have proposed a model to study the  $D^0 \rightarrow \bar{K}^{*0}\gamma$  decay, by establishing a link with  $D^0 \rightarrow \bar{K}^{*0}V$  ( $V = \rho^0, \omega$ ) decays through the vector meson dominance hypothesis. In order to do this properly, we have used the Lagrangians from the local hidden gauge symmetry approach to account for  $V\gamma$  conversion. As a result, we have found the branching ratio  $\mathcal{B}[D^0 \rightarrow \bar{K}^{*0}\gamma] = (1.55 - 3.44) \times 10^{-4}$ , which is in fair agreement with the experimental values reported by the Belle and BaBar collaborations.

**Keywords:** radiative decay, vector meson dominance, local hidden gauge symmetry

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## 1 Introduction

Heavy hadron weak decays have become an important source of information not only in the quest for new physics beyond the standard model, but also to understand in a deeper way the hadron dynamics behind those processes [1]. In Ref. [1] a thorough review is given of reactions involving B and D weak decays, as well as of heavy baryons, which show that one can separate the part involving the weak and the primary strong process and another part that has to do with the final state interaction of hadrons which are formed in the primary step. Selection of different related reactions allows one to cancel the first part in ratios of mass distributions, and observables are then obtained which are basically related to the interaction of hadrons and the formation of resonances.

Weak radiative decays also promise to provide information along these lines. Although comparatively

smaller in number, there are already many modes reported for B weak radiative decays [2–7] (see a recent compilation of data in Ref. [8]). On the other hand, theoretical predictions associated with those ratios differ at least by 2 orders of magnitude, requiring more investigation in order to shed light on this issue [9–13].

From the perspective followed in Ref. [1], some B radiative decays, corresponding to radiative weak-annihilation decays, were studied in Ref. [14], where accurate results for their branching ratios were obtained. More concretely, since the long-distance effects might be dominant in those decays, the authors presented a mechanism where a link between  $B \rightarrow J/\psi V$  and the  $B \rightarrow J/\psi\gamma$  decay was established by means of the vector meson dominance hypothesis (VMD) [15]. The implementation of VMD was done using the Lagrangians from local hidden gauge symmetry [16–18]. The results found in Ref. [14] were in good agreement with the upper limits set for the branching ratios aforementioned.

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Charm radiative decays have been discussed less in the literature [12, 13, 19, 20]<sup>1)</sup>. The amount of theoretical work follows the same lines as the experimental counterpart, *i. e.* the lack of experimental results associated with radiative decays of charmed mesons does not motivate many theoretical studies, since most of them are dedicated to the search for new physics beyond the standard model [12]. It turns out that charm radiative decays are dominated by long-distance effects, which makes them less attractive to new physics practitioners. On the other hand, concerning hadronic systems, this same feature makes these charmed radiative decays an interesting issue to investigate hadron dynamics as well as to make predictions to be tested by the experimental facilities. This might be a good scenario to test the successful chiral unitary theory and other nonperturbative models related to the description of hadron dynamics.

As mentioned previously, the amount of experimental information for charm radiative decays is scarce. For instance, the first branching ratio measurement for the  $D^0 \rightarrow \bar{K}^{*0}\gamma$  radiative decay was performed in 2008 by the BaBar collaboration [21], with  $\mathcal{B}(D^0 \rightarrow \bar{K}^{*0}\gamma) = (3.28 \pm 0.20 \pm 0.27) \times 10^{-4}$ , where the first error is statistical and the second systematic. Recently, the Belle collaboration has also measured the same branching ratio [22], obtaining a different value,  $\mathcal{B}(D^0 \rightarrow \bar{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.21) \times 10^{-4}$ , although it is of the same order of magnitude as the one reported by BaBar. From the theoretical side, in Ref. [23] the authors used an extension of the standard model approach in order to separate the long and short-range contributions to the  $\mathcal{B}(D^0 \rightarrow \bar{K}^{*0}\gamma)$  branching ratio. They have estimated a range of values equal to  $\mathcal{B} = (4.6-18) \times 10^{-5}$ , with large errors. On the other hand, using a different approach, a value of the same order of magnitude as the previous one was obtained in Ref. [24]:  $\mathcal{B} = (4.5-19) \times 10^{-5}$ . In both cases, although VMD is invoked in those studies, they aim at the search for new physics and because of that the authors are more concerned with what happens to the short-range contributions from one model to the other. In Refs. [19, 20] a hybrid model is used, combining chiral perturbation theory, heavy quark effective theory and vector meson dominance, and a range of  $\mathcal{B} = (6-36) \times 10^{-5}$  is obtained. The hybrid model used in Ref. [25] gives a range of  $\mathcal{B} = (7-12) \times 10^{-5}$ . The same approach used in Ref. [12] gives  $\mathcal{B} = (0.26-4.6) \times 10^{-4}$ , while from Ref. [13], updated in Ref. [12], a value  $1.8 \times 10^{-4}$  (with no available uncertainties) is reported. In Ref. [12] a different approach, based on weak annihilation, is also used and a range  $\mathcal{B} = (0.011-1.6) \times 10^{-4}$  is obtained. In view of this, in this work we adopt a different perspective and look at what happens to the hadron dynamics in these decays,

and we shall propose a model based on the mechanism of Ref. [14] to estimate the  $D^0 \rightarrow \bar{K}^{*0}\gamma$  branching ratio. Although the short-range contributions play an important role in  $B$  meson decays, in some cases, such as that shown by the authors of Ref. [14], the long-range physics is the main ingredient and may help to provide more accurate results, as discussed in that work. Since in the charm sector the radiative decays are largely dominated by the long-range physics [22-24], we expect to get reasonably accurate results, in particular for  $D^0 \rightarrow \bar{K}^{*0}\gamma$ , where short-range terms tied to the  $c \rightarrow u\gamma$  transition are not operative [12].

The starting point in our approach is to establish a link between the  $D^0 \rightarrow \bar{K}^{*0}V$  decays, with the vector meson  $V$  related to the  $\rho$  and  $\omega$  mesons, and the radiative  $D^0 \rightarrow \bar{K}^{*0}\gamma$  decay via the VMD hypothesis. In our case, the VMD is implemented using the hidden gauge Lagrangians [16-18], describing the  $V\gamma$  conversion. In the next section, we show the details of how to do this properly and also how to get the branching ratios we are concerned with. We also present arguments that support the suppression of the short-range effects in the amplitudes contributing to the branching ratio we are interested in.

## 2 Theoretical Framework

In order to calculate the radiative decay rate of  $D^0 \rightarrow \bar{K}^{*0}\gamma$ , we follow the approach used in Ref. [14], where the authors combine vector meson dominance, through hidden gauge Lagrangians, with a novel mechanism, proposed in Ref. [26] for  $B^0(B_s^0) \rightarrow J/\psi V$ , to describe the  $B^0(B_s^0) \rightarrow J/\psi\gamma$  decays. In the following, we shall describe briefly this mechanism extended to our problem.

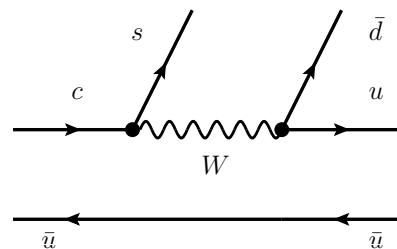


Fig. 1. The  $D^0$  meson decaying weakly into a  $\bar{K}^{*0}$  and a vector meson at the quark level: a  $c$  quark converts into an  $s$  quark by emission of a  $W$  boson, which then coalesces into a  $du$  pair, producing a  $u\bar{u}$  pair in the final state. The first pair of quark/antiquarks forms a  $\bar{K}^{*0}$  meson, while the remaining  $u\bar{u}$  can form either a  $\rho$  or an  $\omega$  meson.

The  $D^0$  meson decays weakly into a  $\bar{K}^{*0}$  meson in addition to a  $\rho^0$  or an  $\omega$  meson, denoted by  $V$ . At the

1) CP violation and determination of strong phases has also been one of the aims in the study of these radiative decays (see a recent review on this issue in Ref. [12]), but this is not the object of our study here.

quark level, this process is illustrated in Fig. 1. According to this figure, a c quark converts into a strange quark by emission of a W boson, that subsequently coalesces into a  $\bar{d}\bar{u}$  pair. As a result, we have a  $\bar{K}^{*0}$  meson, related to the  $s\bar{d}$  pair, while the remaining  $u\bar{u}$  can be related to the vector mesons,  $\rho^0$  or  $\omega$ . At this point, it is worth emphasizing that we adhere to the  $q\bar{q}$  picture for vector mesons. In fact, studies have shown that wave functions for the low-lying vector mesons are essentially dominated by  $q\bar{q}$  components [27–34]. Therefore, in terms of quarks the wave functions for vector mesons are given by<sup>1)</sup>

$$\begin{aligned}\rho^0 &= \frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d}), \\ \omega &= \frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d}).\end{aligned}$$

Since there is no  $s\bar{s}$  pair in the process of Fig. 1, we do not have a  $\phi$  meson contribution. One could have a  $\phi$  contribution through  $\omega-\phi$  mixing, but this admixture is tiny [35–38] and the contribution to radiative decay via  $\omega\rightarrow\phi\rightarrow\gamma$  is negligible versus that of the direct  $\omega\rightarrow\gamma$  transition.

To write the  $D^0\rightarrow\bar{K}^{*0}V$  amplitudes, we restrain ourselves to factorizing the weak vertices in terms of a factor  $V'_p$ , which contains weak vertices, Cabibbo angles, etc. The factor  $V'_p$  cancels, since we are interested in the ratios of decay rates. A similar assumption was made in Ref. [26], where the decay rates related to  $\bar{B}^0\rightarrow J/\psi\bar{K}^{*0}$  and  $\bar{B}_s^0\rightarrow J/\psi K^{*0}$  channels were evaluated, with results in good agreement with the experimental ones [39]. Hence, the amplitudes for the  $\bar{K}^{*0}V$  production are

$$\begin{aligned}t_{D^0\rightarrow\bar{K}^{*0}\rho^0} &= \frac{V'_p}{\sqrt{2}}, \\ t_{D^0\rightarrow\bar{K}^{*0}\omega} &= \frac{V'_p}{\sqrt{2}},\end{aligned}\quad (1)$$

where the polarization vectors in each expression above are omitted (we shall come back to the spin structure later).

Once we have determined the amplitudes associated with the production of  $\bar{K}^{*0}V$ , we have to go a step further and let the V meson convert into a photon  $\gamma$ , according to the VMD hypothesis [15]. In order to implement VMD properly, we use the Lagrangians from the local hidden

gauge approach [16–18], which for the  $V\gamma$  vertex is given by

$$\mathcal{L}_{V\gamma} = -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q \rangle, \quad (2)$$

where  $e$  is the electron charge,  $e^2/4\pi\approx 1/137$ , and  $g$  is the universal coupling in the hidden gauge Lagrangian, defined by  $g=M_V/(2f_\pi)$ , with  $f_\pi$  the pion decay constant ( $f_\pi=93$  MeV), while  $M_V$  stands for the vector meson mass (we take  $M_V=780$  MeV in this work).  $A_\mu$  is associated with the photon field and  $V^\mu$  is the matrix below

$$V_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu. \quad (3)$$

Furthermore, in Eq. (2)  $Q=\text{diag}(2/3, -1/3, -1/3)$  is the charge matrix of the u, d, and s quarks, while the symbol  $\langle \rangle$  in Eq. (2) means the trace of the  $V^\mu Q$  product. Therefore the Lagrangian of Eq. (2) now reads

$$\mathcal{L}_{V\gamma} = -M_V^2 \frac{e}{g} A_\mu \left[ \frac{\rho^\mu}{\sqrt{2}} + \frac{\omega^\mu}{3\sqrt{2}} - \frac{\phi^\mu}{3} \right]. \quad (4)$$

Equation (4) can be simplified if we define  $\tilde{V}^\mu$  as denoting the  $\rho^0$ ,  $\omega$  and  $\phi$  fields and  $C_{V\gamma}$  standing for their respective constants  $1/\sqrt{2}$ ,  $1/3\sqrt{2}$ ,  $-1/3$ . Therefore, we have

$$\mathcal{L}_{V\gamma} = -M_V^2 \frac{e}{g} A_\mu \tilde{V}^\mu C_{V\gamma}, \quad (5)$$

with  $C_{V\gamma}$  given by

$$C_{V\gamma} = \begin{cases} \frac{1}{\sqrt{2}} & \text{for } \rho^0 \\ \frac{1}{3\sqrt{2}} & \text{for } \omega \\ -\frac{1}{3} & \text{for } \phi \end{cases}. \quad (6)$$

Now that we have determined the  $\bar{K}^{*0}V$  production amplitude as well as the Lagrangian that describes the  $V\gamma$  vertex, we can write down the amplitude for the photon production, which is depicted in Fig. 2.

1) In general, the physical isoscalars  $\phi$  and  $\omega$  are mixtures of the  $SU(3)$  wave functions  $\psi_8$  and  $\psi_1$ :

$$\begin{aligned}\phi &= \psi_8 \cos\theta - \psi_1 \sin\theta, \\ \omega &= \psi_8 \sin\theta + \psi_1 \cos\theta,\end{aligned}$$

where  $\theta$  is the nonet mixing angle and:

$$\begin{aligned}\psi_8 &= \frac{1}{\sqrt{6}}(u\bar{u}+d\bar{d}-2s\bar{s}), \\ \psi_1 &= \frac{1}{\sqrt{3}}(u\bar{u}+d\bar{d}+s\bar{s}).\end{aligned}$$

For ideal mixing,  $\tan\theta=1/\sqrt{2}$  (or  $\theta=35.3^\circ$ ), the  $\omega$  meson is pure  $u\bar{u}+d\bar{d}$ , and the  $\phi$  meson becomes a pure  $s\bar{s}$  state.

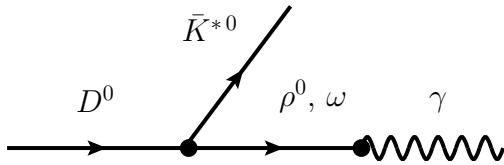


Fig. 2. Diagram associated with  $D^0 \rightarrow \bar{K}^{*0}\gamma$  decay at the hadron level.

Using Eqs. (1), (5) and (6), the decay amplitude for the diagram of Fig. 2 is

$$\begin{aligned} & -it_{D^0 \rightarrow \bar{K}^{*0}\gamma} \\ &= \left( -it_{D^0 \rightarrow \bar{K}^{*0}\rho^0} \epsilon_\mu(\rho) \frac{i}{q^2 - M_\rho^2} (-i) M_\rho^2 \frac{e}{g} \epsilon_\nu(\rho) \epsilon^\nu(\gamma) C_{\rho\gamma} \right. \\ & \quad \left. -it_{D^0 \rightarrow \bar{K}^{*0}\omega} \epsilon_\alpha(\omega) \frac{i}{q^2 - M_\omega^2} (-i) M_\omega^2 \frac{e}{g} \epsilon_\beta(\omega) \epsilon^\beta(\gamma) C_{\omega\gamma} \right) \\ & \quad \times \epsilon^\mu(\bar{K}^*), \end{aligned} \quad (7)$$

where  $\epsilon_\mu(\rho)$ ,  $\epsilon_\alpha(\omega)$  are the polarization vectors for the  $\rho^0$  and  $\omega$  mesons production, while  $\epsilon^\nu(\gamma)$  is that associated with the photon. Remembering that

$$\sum_{\text{pol.}} \epsilon_\mu(V) \epsilon_\nu(V) = -g_{\mu\nu} + \frac{p_\mu^V p_\nu^V}{M_V^2}, \quad (8)$$

and knowing that  $p^V \cdot \epsilon(V) = 0$  (Lorentz condition), with  $p_\mu^V$  the momentum of the vector meson that is equal to the photon momentum, after a bit of algebra Eq. (7) can be written as

$$t_{D^0 \rightarrow \bar{K}^{*0}\gamma} = \frac{2}{3} \frac{e}{g} V'_p \epsilon_\mu(\gamma) \epsilon^\mu(\bar{K}^*), \quad (9)$$

where we have used the approximation  $M_\rho \approx M_\omega \approx M_V$ , as usual in the hidden gauge approach.

In order to estimate the ratios, we need the decay formulas associated with the  $D^0 \rightarrow \bar{K}^{*0}\rho^0(\omega)$  and  $D^0 \rightarrow \bar{K}^{*0}\gamma$  channels. They are given by

$$\begin{aligned} \Gamma_{D^0 \rightarrow \bar{K}^{*0}\rho(\omega)} &= \frac{1}{8\pi} \frac{1}{M_D^2} \sum_{\text{pol.}} \left| t_{D^0 \rightarrow \bar{K}^{*0}\rho^0(\omega)} \right|^2 p_{\rho(\omega)}, \\ \Gamma_{D^0 \rightarrow \bar{K}^{*0}\gamma} &= \frac{1}{8\pi} \frac{1}{M_D^2} \sum_{\text{pol.}} \left| t_{D^0 \rightarrow \bar{K}^{*0}\gamma} \right|^2 p_\gamma, \end{aligned} \quad (10)$$

where  $p_{\rho(\omega)}$  and  $p_\gamma$  are the  $\rho^0(\omega)$  meson and the photon momenta in the  $D^0$  rest frame. Substituting Eqs. (1) and (9) into Eq. (10), we get the following expression for the ratio  $\Gamma_{D^0 \rightarrow \bar{K}^{*0}\gamma} / \Gamma_{D^0 \rightarrow \bar{K}^{*0}\rho^0}$

$$\frac{\Gamma_{D^0 \rightarrow \bar{K}^{*0}\gamma}}{\Gamma_{D^0 \rightarrow \bar{K}^{*0}\rho^0}} = \left( \frac{2}{3} \frac{e}{g} \right)^2 \frac{p_\gamma}{p_\rho}. \quad (11)$$

As we mentioned before, the parametrization of the weak vertex defined as  $V'_p$  does not play a role in our approach since it cancels, as can be seen by looking at the ratio in Eq. (11).

In a general context the mechanism that we have adopted here is considered as a long-range process in

Refs. [25, 40–43]. In these works, the B radiative decays involving a  $K^*$  and  $\rho$  mesons were addressed. They were separated into long and short-range processes and their contribution was estimated. As a result, the short-range contribution, considered in those works as the dominant one, was bigger (by a factor 30) for the  $B \rightarrow K^*\gamma$  process than the upper bounds for the  $B \rightarrow J/\psi\gamma$  case, indicating that the equivalent short-range contribution could not be dominant in the  $J/\psi\gamma$  case, as discussed in Ref. [14]. Furthermore, in the charm sector, it was pointed out in Ref. [25] that the short-range diagrams provided results smaller than the one related to its long-range counterpart. In our case the short-range diagram gives no contribution since there is no  $\bar{K}^{*0}(s\bar{d})$  production in the final state, as can be seen in Fig. 3(a).

In Fig. 3 we show all the diagrams associated with short and long-range processes. As we have mentioned previously, the diagram in Fig. 3(a) is related to the short-range contribution, and does not contribute in our case, which is represented by diagram (b), since it produces  $\rho^0\gamma$  or  $\omega\gamma$  but not  $\bar{K}^{*0}\gamma$ . The remaining diagrams, Fig. 3(c)–(f), are suppressed with respect to that in Fig. 3(b). This happens because they have a weak process involving two quarks of the original  $D^0$  meson and, according to the discussion in Ref. [44], these kinds of processes are penalized with respect to those involving just one quark.

According to Ref. [14] we have to take into account the polarization structure of the  $D^0 \rightarrow \bar{K}^{*0}\gamma$  vertex. In weak decay processes we can have parity violation as well as parity conservation. In order to take this feature into account in our model, we are going to follow the procedure of Ref. [14] and define both parity conserving (PC) and parity violating (PV) structures, which are often used in weak decay studies [9–11, 42]. They are

$$V_{PC} = \frac{V'_p}{\sqrt{2}} \epsilon_{\mu\nu\alpha\beta} \epsilon^\mu(\bar{K}^*) q^\nu \epsilon'^\alpha(V) q'^\beta, \quad (12)$$

$$V_{PV} = \frac{V'_p}{\sqrt{2}} \epsilon^\mu(\bar{K}^*) \epsilon'^\nu(V) (g_{\mu\nu} q \cdot q' - q'_\mu q_\nu), \quad (13)$$

where  $\epsilon'(V)$  and  $q'$  are the polarization vector and the momentum of the vector meson ( $\rho^0$  or  $\omega$ ) to be converted into  $\gamma$  through VMD. In the case of photon production in both Eqs. (12) and (13),  $\epsilon'$  and  $q'$  stand for the vector polarization and momentum of the photon, respectively.

Note that both structures are gauge invariant. In fact, when we use the Lagrangians from the local hidden gauge approach to deal with vector-vector interactions  $VV$  and also  $V\gamma$  conversion, gauge invariant amplitudes are obtained, as discussed in Refs. [16–18, 45, 46].

In order to take into account the polarization structure of the weak vertices, as discussed previously, we have

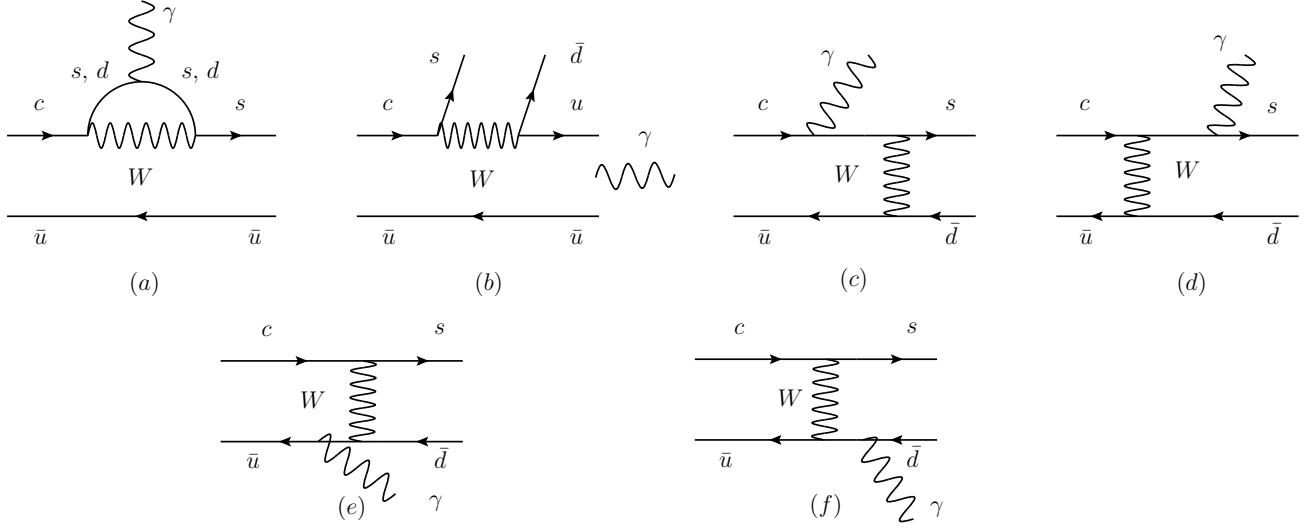


Fig. 3. Short- and long-range diagrams contributing to the  $D^0 \rightarrow \bar{K}^{*0} \gamma$  amplitude.

to sum the square of Eqs. (12) and (13) over the polarizations of the vector meson or the photon. Summing up over the polarization provides

$$\begin{aligned} \sum_{\lambda} \sum_{\lambda'} |V_{PC}|^2 &= 2[(q \cdot q')^2 - q'^2 q'^2], \\ \sum_{\lambda} \sum_{\lambda'} |V_{PV}|^2 &= 2(q \cdot q')^2 + q'^2 q'^2, \end{aligned} \quad (14)$$

where  $q'^2 = M_V^2$  for vector production or 0 in the case of photon production, while

$$q \cdot q' = \frac{1}{2}(M_{D^0}^2 - M_{\bar{K}^{*0}}^2 - M_V^2), \quad (15)$$

with  $M_V^2 = 0$  for the case of photon production.

With this, we can obtain the following ratios

$$R_{PC} = \frac{\sum_{\lambda} \sum_{\lambda'} |V_{PC}|^2 \text{ for } \gamma}{\sum_{\lambda} \sum_{\lambda'} |V_{PC}|^2 \text{ for } \rho}, \quad (16)$$

and

$$R_{PV} = \frac{\sum_{\lambda} \sum_{\lambda'} |V_{PV}|^2 \text{ for } \gamma}{\sum_{\lambda} \sum_{\lambda'} |V_{PV}|^2 \text{ for } \rho}. \quad (17)$$

Therefore, the polarization structures discussed above are taken into account in our calculation simply by plugging them into Eq. (11), which now reads

$$\frac{\mathcal{B}(D^0 \rightarrow \bar{K}^{*0} \gamma)}{\mathcal{B}(D^0 \rightarrow \bar{K}^{*0} \rho)} = \left( \frac{2e}{3g} \right)^2 \left( \frac{p_\gamma}{p_\rho} \right) R_{PC(PV)}, \quad (18)$$

where on the left-hand side we have divided the numerator as well as the denominator by  $\Gamma_{\text{total}}$  in order to convert the widths into branching fractions.

In Ref. [23] the vector meson dominance mechanism is also taken into account. No details are given but the

procedure of Ref. [25] is used. There it is calculated in terms of Wilson coefficients, with a warning that the final state interactions are relevant and not contained in the BSW Hamiltonian that they use [47].

In Ref. [24] a light front dynamics formalism is employed. Neutral vector meson production is evaluated from the theoretical framework and then VMD is implemented through conversion to  $\gamma$ , as we do in our work. In our case we take the input of neutral vector production from experiment. There is also another technical difference. The  $\rho, \omega, \phi$  propagators in the  $V\gamma$  conversion are taken as  $[q^2 - m_V^2 + i m_V \Gamma_V]^{-1}$  in Ref. [24] with  $q^2 = 0$  from the photon produced, and  $\Gamma_V$  is taken as the on shell width of the corresponding vector mesons. We, instead, adhere to a field theoretical approach in which the width of the  $\rho$  propagator, for instance, would be implemented attaching a  $\pi\pi$  loop to the  $\rho$  line, but with  $q^2 = 0$  this loop does not generate an imaginary part. In other words, in this approach one should take  $\Gamma_\rho(q^2 = 0)$  which is zero. So, our propagators are strictly  $[-m_V^2]^{-1}$ , as one can see in Eq. (7).

### 3 Results

In order to estimate our results, we use the following values for the meson masses:  $M_\rho \approx M_\omega \approx M_V = 780$  MeV,  $M_{\bar{K}^*} = 891.6$  MeV and  $M_{D^0} = 1864.8$  MeV. Furthermore, we also use as an input for  $\Gamma_{D^0 \rightarrow \bar{K}^* \rho(\omega)}$  an average value from the following experimental results, extracted from the PDG [39], which in our approach should be equal. We have

$$\begin{aligned} \mathcal{B}[D^0 \rightarrow \bar{K}^{*0} \rho^0] &= (1.58 \pm 0.35) \times 10^{-2}, \\ \mathcal{B}[D^0 \rightarrow \bar{K}^{*0} \omega] &= (1.10 \pm 0.5) \times 10^{-2}. \end{aligned} \quad (19)$$

These results are compatible, within errors, providing an average value of  $(1.4 \pm 0.4) \times 10^{-2}$ . Therefore, from Eq. (18), using the values defined above, we get the following result for the branching fraction associated with the  $D^0 \rightarrow \bar{K}^{*0}\gamma$  channel:

$$\mathcal{B}[D^0 \rightarrow \bar{K}^{*0}\gamma] = (3.44 \pm 1.0) \times 10^{-4}, \text{ for PV,} \quad (20)$$

$$\mathcal{B}[D^0 \rightarrow \bar{K}^{*0}\gamma] = (1.60 \pm 0.5) \times 10^{-4}, \text{ for PC,} \quad (21)$$

where the uncertainties are obtained from the experimental errors. The average experimental value in the PDG [39] is

$$\mathcal{B}[D^0 \rightarrow \bar{K}^{*0}\gamma]_{\text{exp}} = (4.1 \pm 0.7) \times 10^{-4}. \quad (22)$$

We can see that the theoretical result with *PV* is compatible with the experimental number. The one with *PC* is somewhat smaller. An equal mixture of both the *PC* and *PV* modes would give

$$\mathcal{B}[D^0 \rightarrow \bar{K}^{*0}\gamma] = (2.5 \pm 1.1) \times 10^{-4}, \quad (23)$$

which is compatible with the experimental value within errors. We do not consider other systematic errors tied to our theoretical approach, but simply state that with the uncertainties tied to our ignorance of the weight of the *PC* and *PV* parts (Eqs. (12) and (13)) and the experi-

mental uncertainties, the agreement of our results with experiment is fair.

In Ref. [23] the authors have used a model related to the extensions of the standard model in order to look for new physics in the charm rare decays. They have done calculations for the long-range distance  $D \rightarrow V\gamma$  amplitudes (see Table IV of that reference), where for the  $D^0 \rightarrow \bar{K}^{*0}\gamma$  a ratio of about  $(4.6 - 18) \times 10^{-5}$  was obtained. Using a different approach called the light-front quark model, a similar result was found in Ref. [24]. The value obtained in this latter work for the same ratio was  $(4.5 - 19) \times 10^{-5}$ . Note that both results are smaller than our result, given by Eqs. (20), (21) and (23), as well as the experimental one. Note also that the range of allowed values is much bigger than in our case, and the lower bound is about one order of magnitude smaller than our results. The dispersion in the theoretical results and the large uncertainties of those works are also common to other approaches like the hybrid models,  $(0.26 - 4.6) \times 10^{-4}$  from Ref. [12],  $(6 - 36) \times 10^{-5}$  from Refs. [19, 20],  $(7 - 12) \times 10^{-5}$  from Ref. [25], or weak annihilation  $(0.011 - 1.6) \times 10^{-4}$  from Ref. [12].

In Table 1, for completeness, we show our results compared with those of other groups.

Table 1. Theoretical and experimental results for the branching ratio  $\mathcal{B}(D^0 \rightarrow \bar{K}^{*0}\gamma)$ .

theoretical works ( $10^{-4}$ )	experimental results ( $10^{-4}$ )	this work ( $10^{-4}$ )
Ref. [23] (BSM <sup>1)</sup> approach): (0.46–1.8)	Ref. [21] (Babar Collaboration): 3.28 $\pm$ 0.20 $\pm$ 0.21	
Ref [24] (Light-front QM <sup>2)</sup> ): (0.45–1.9)	Ref. [22] (Belle Collaboration): 4.66 $\pm$ 0.21 $\pm$ 0.21	(1.55–3.44)
Ref. [12] (hybrid model): (0.26–4.6)	Ref. [39] (PDG average) 4.1 $\pm$ 0.7	
Refs. [19, 20] (hybrid model): (0.6–3.6)		
Ref. [25] (BSM approach): (0.7–1.2)		
Ref. [12] (Weak Annihilation): (0.011–1.6)		

<sup>1)</sup> Beyond Standard Model.

<sup>2)</sup> Quark Model.

## 4 Conclusions

Using a mechanism adopted in Ref. [14], we have established a link between the  $D^0 \rightarrow \bar{K}^{*0}V$ , with  $V = \rho^0, \omega$  mesons, and  $D^0 \rightarrow \bar{K}^{*0}\gamma$  radiative decays. Concretely, after calculating the amplitude for  $V$  meson production, we use the vector meson dominance hypothesis to convert the vector mesons produced in our mechanism into a photon. This was done using the Lagrangians from the local hidden gauge approach, which provides a gauge invariant amplitude when the vector polarization structure is taken into account. Thus, we have obtained an expression in which both parity violation and conservation contributions are considered. As a result, we have obtained a value for the branching ratio  $\mathcal{B}[D^0 \rightarrow \bar{K}^{*0}\gamma]$  in a fair agreement with the experimental value quoted in the PDG [39], while other estimations using different

approaches provide results with large uncertainties, with some values one or two orders of magnitude smaller than our findings.

We should mention that our evaluation is done using as input the experimental rates for  $D^0 \rightarrow \bar{K}^{*0}\rho^0(\omega)$ . Alternative calculations that use other experimental information to fix unknown parameters of the theory [12, 13, 19, 20, 23–25] lead to larger uncertainties. Note that other terms, like loop corrections, that in other approaches must be calculated explicitly, are incorporated effectively in our approach when using the empirical values of the  $D^0 \rightarrow \bar{K}^{*0}\rho^0(\omega)$  rates [14]. In this sense, once one shows that short-range terms in the process studied do not contribute, or are small, the method used here proves to be rather accurate for evaluating this kind of radiative decay.

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