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# Excited Heavy-Light Systems and Hadronic Transitions

M. Di Pierro and E. Eichten

Fermilab, Batavia, IL 60510, USA

## Abstract

A detailed study of orbital and radial excited states in  $D$ ,  $D_s$ ,  $B$  and  $B_s$  systems is performed. The chiral quark model provides the framework for the calculation of pseudoscalar meson ( $\pi$ ,  $K$ , ...) hadronic transitions among heavy-light excited and ground states. To calculate the excited states masses and wavefunctions, we must resort to a relativistic quark model. Our model includes the leading order corrections in  $1/m_{(c,b)}$  (e.g. mixing). Numerical results for masses and light hadronic transition rates are compared to existing experimental data. The effective coupling of the chiral quark model can be determined by comparing with independent results from lattice simulations ( $g_A^8 = 0.53 \pm 0.11$ ) or fitting to known widths ( $g_A^8 = 0.82 \pm 0.09$ ).

# 1 Introduction

Although heavy quark spectroscopy is now a rather mature subject, a number of interesting issues remain. In particular, the detailed properties of the excitation spectrum of heavy-light mesons ( $D, D_s, B, B_s$ ) and their light hadronic transitions are yet to be fully understood. Experimentally, much of this excitation spectrum remains to be observed. Only the ground state S-waves and a few of the  $j_l = 3/2$  P-waves are presently well established. However, many of these states will be accessible in the present and future B factories: CLEO, BaBar, Belle, CDF, D0, BTeV and LHC B. Besides furthering our understanding of QCD dynamics, the detailed study of these excited states may have practical benefits. For example, triggering on excited states may provide an efficient method of same side B tagging in hadron colliders. Tagging is essential to the study of CP violation in the B system.

The theoretical tools available to determine the properties of excited states in heavy-light systems include Heavy Quark Effective Theory (HQET) and low energy chiral effective theory [1]. Unfortunately, these tools are not sufficient to determine the detailed properties of these states. Lattice gauge theory is the only existing technique which allows the systematic study of all the aspects of QCD in heavy-light systems. Detailed studies of the P-wave excited heavy-light states within the quenched approximation already exist [2]. Future lattice studies will provide more insight into the nature of QCD dynamics as well as the masses and static properties of heavy-light hadrons.

It is clear that a model to estimate the hadronic transitions from excited state to ground states would also be very useful. Such a formalism has been developed and applied extensively to transitions in heavy-heavy ( $\bar{Q}Q'$ ) systems [3]. However, heavy-light mesons are more difficult because the light quark is subject to the full nonperturbative QCD dynamics. One possible approach to providing a framework for these hadronic transitions is to use the chiral quark model [4]. This has been suggested by Goity and Roberts [5].

In this paper we closely follow the work done in Refs. [5, 6, 7]. To compute the masses and wavefunctions of the excited states we use a Dirac equation for the light quark in the potential generated by the heavy quark (including first order corrections in the heavy quark expansion and mixing effects). We then use these masses and wavefunctions to compute the hadronic decay amplitudes of excited heavy mesons in the context of a chiral quark model [4].

The main differences between the present and preceding works are in the

choice for the parameters of the chromoelectric potential and in the inclusion of mixing effects both in the spectrum and in the decay amplitudes. Moreover we use our results for the radial wavefunctions of the excited mesons to make a comparison with recent lattice results. From the comparison we extract an estimation for  $g_A^8$ , the effective coupling of the quark to the pseudoscalar mesons. We find  $g_A^8 = 0.53 \pm 0.11$

We present numerical results for the low-lying spectrum (excited states up to the 3S states). We also compute the pseudoscalar meson hadronic transitions for these states as a function of the chiral quark model effective coupling constant. Comparing our results with recent experimental width measurements we estimate this effective coupling  $g_A^8 = 0.82 \pm 0.09$ .

In Section 2, we discuss our determination of the spectrum of excited states. Our notation, the choice of the potential, inclusion of mixing and other order  $1/m_h$  corrections are explained. Details of the masses and wavefunctions are presented for the low-lying excitation spectrum. Comparison is made with present experimental data. Our treatment of hadronic decays is described in Section 3. The analytic results are summarized in Eqs. (32-34). Explicit expressions for the coupling coefficients appearing in these equations are given in Appendix A. Also in Section 3, details of the partial rates for the 1S and 1P states in the  $D, D_s, B$  and  $B_s$  systems are presented. Again comparison is made with present experimental data. A complete list of remaining results for masses and partial decay widths is reported in Appendix B.

## 2 Spectrum

### 2.1 Basic Model and Notation

The general Hamiltonian of the heavy-light system can be expanded in powers of  $(1/m_h)$

$$\mathcal{H} = \mathcal{H}^{(0)} + \frac{1}{m_h} \mathcal{H}^{(1)} + \frac{1}{m_h^2} \mathcal{H}^{(2)} + \dots \quad (1)$$

However, even within the heavy quark limit, the general form of the zeroth order Hamiltonian,  $\mathcal{H}^0$ , still involves the full nonperturbative QCD dynamics for the remaining degrees of freedom (including light quark pair creation and gluonic degrees of freedom). At present it can not be solved analytically. We are forced to resort to use a relativistic potential model for  $\mathcal{H}^0$ .

We model the most general heavy-light meson (in the  $D, D_s, B, B_s$  family),  $H$ , as a bound state of a light quark ( $q$ ) and a heavy quark ( $h$ ). The heavy quark is treated as a static source of chromoelectric field and the only quantum number associated with it is its spin. The light quark is treated relativistically and its state is described by the wavefunction  $\psi_{n,\ell,j,m}(r, \theta, \varphi)$ . In analogy with the hydrogen atom, we introduce the following quantum numbers:

- $n$ , the number associated with the radial excitations;
- $\ell$ , the orbital angular momentum;
- $j$ , the total angular momentum of the light quark;
- $m$ , the component of  $j$  along the  $\hat{z}$  axis;
- $J$ , the total angular momentum of the system;
- $M$ , the component of  $J$  along the  $\hat{z}$  axis;
- $S$ , the spin of the heavy quark along the  $\hat{z}$  axis;

The parameters of our model are the masses of the light quarks ( $m_q$  for  $q = u, d$  or  $s$ ), the masses of the heavy quarks ( $m_h$  for  $h = c$  or  $b$ ) and the chromoelectric potential of the heavy quark ( $V(r)$ ).

The total wavefunction of the system can be decomposed as follows

$$\Psi_{n,\ell,j,J,M}(r, \theta, \varphi) = \sum_{S \in \{-\frac{1}{2}, +\frac{1}{2}\}} C_{j,m;\frac{1}{2},S}^{J,M} \psi_{n,\ell,j,m}(r, \theta, \varphi) \otimes \xi_S \quad (2)$$

where  $C_{j,m;\frac{1}{2},S}^{J,M}$  are the usual Clebsh-Gordan coefficients and  $\xi_S$  is a two component spinor representing the heavy quark. Eq. (2) is a solution of the following eigenvalue problem

$$\mathcal{H}\Psi_{n,\ell,j,J,M} = E_{n,\ell,j,J}\Psi_{n,\ell,j,J,M} \quad (3)$$

where  $\mathcal{H}$  is the Hamiltonian of the system. The energy levels in Eq. (3) do not depend on  $M$  because of rotational invariance.

We rewrite Eq. (2) introducing the most general parameterization for the four spin components of the light quark wavefunction

$$\Psi_{n,\ell,j,J,M}(r, \theta, \varphi) = \sum_{S \in \{-\frac{1}{2}, +\frac{1}{2}\}} C_{j,m;\frac{1}{2},S}^{J,M} \begin{pmatrix} i f_{n,\ell,j}^0(r) k_{\ell,j,m}^+ Y_{m-\frac{1}{2}}^\ell(\theta, \varphi) \\ i f_{n,\ell,j}^0(r) k_{\ell,j,m}^- Y_{m+\frac{1}{2}}^\ell(\theta, \varphi) \\ f_{n,\ell,j}^1(r) k_{2j-\ell,j,m}^+ Y_{m-\frac{1}{2}}^{2j-\ell}(\theta, \varphi) \\ f_{n,\ell,j}^1(r) k_{2j-\ell,j,m}^- Y_{m+\frac{1}{2}}^{2j-\ell}(\theta, \varphi) \end{pmatrix} \otimes \xi_S \quad (4)$$

Here  $Y_m^\ell(\theta, \varphi)$  are spherical harmonics that encode the angular dependence while  $f_{n,\ell,j}^0(r)$ ,  $f_{n,\ell,j}^1(r)$  are real functions that encode that radial dependence.  $k_{\ell,j,m}^+$  and  $k_{\ell,j,m}^-$  are fixed, up to an overall phase, by imposing a normalization condition. Our choice of the phase is such that

$$k_{\ell,j,m}^\pm = \begin{cases} +\sqrt{\frac{\ell \pm m + \frac{1}{2}}{2\ell+1}} & \text{for } j = \ell + \frac{1}{2} \\ \pm\sqrt{\frac{\ell \mp m + \frac{1}{2}}{2\ell+1}} & \text{for } j = \ell - \frac{1}{2} \end{cases} \quad (5)$$

## 2.2 Choice of the potential

Within our basic framework,  $\mathcal{H}^{(0)}$  is given by the relativistic Dirac Hamiltonian

$$\mathcal{H}^{(0)} = \gamma^0(-i\not{\partial} + m_q) + V(r) \quad (6)$$

and the rotational-invariant potential is the sum of a constant factor ( $M_h$ ), a scalar part ( $V_s$ ) and (the zeroth component of) a vector part ( $V_v$ )

$$V(r) = M_h + \gamma^0 V_s(r) + V_v(r) \quad (7)$$

The constant  $M_h$  is a an overall energy shift that depends on the heavy quark flavor and, in general, it is not equal to  $m_h$ , as often assumed in the literature. For this reason we consider  $m_h$  and  $M_h$  two independent parameters of the model.

Asymptotic freedom suggests that at short distances the potential is dominated by a vector part that asymptotically approaches a Coulomb potential,  $V \sim V_v \sim 1/r$ . On the other hand lattice simulations indicate that at

large distances the potential is confining, scalar and asymptotically linear,  $V \sim V_s \sim r$ .

The naive assumption about a short distance Coulomb-like divergent behavior of the potential is doomed because it gives rise to ultraviolet divergences (as discussed in Ref. [8] and Ref. [9]). In this context the divergence arises in the  $1/m_h$  correction to the energy and it is due to the inconsistency of a static point-like source (the heavy quark) within a relativistic framework. One solution is assuming that the heavy quark is static but not point-like, therefore the potential that it generates is a convolution of the Coulomb-like potential and the square of the heavy quark wavefunction (peaked around the center of mass of the system and smeared within some small length scale  $\lambda^{-1}$ ).

More generally, one is allowed to cure this divergence by regulating the potential close to the origin (on a length scale of the order  $\lambda^{-1}$ ). Different choices for the regulator are allowed and they do not affect the physics we want to describe, providing that  $\lambda^{-1}$  is small enough. The values of the parameters that appear in the Hamiltonian, on the contrary, depend on this choice since they run with  $\lambda$ . In fact, to obtain the same spectrum, different choices for the regulator imply different fitting parameters.

We chose to regulate the vector potential by assuming a Gaussian shape for the wavefunction of the heavy quark,  $\Phi(x) = \exp(-x^2\lambda^2/2)$ , and with this choice

$$V_v(r) = -\frac{4}{3} \int |\Phi(x)|^2 \frac{\alpha_s}{|\mathbf{r} - \mathbf{x}|} d^3x = -\frac{4}{3} \frac{\alpha_s}{r} \text{erf}(\lambda r) \quad (8)$$

For the scalar potential we assume a simple linear form

$$V_s(r) = br + c \quad (9)$$

We observe that  $c$  is not a physical parameter since it can be absorbed into the definition of  $m_q$ . For this reason  $c$  will be omitted from now on.

Summarizing, the nine parameters of our model are

$$\alpha_s, \lambda, b, m_u, m_s, m_c, M_c, m_b, M_b \quad (10)$$

where  $m_u \equiv m_d$  and  $m_s$  are mass parameters for the light  $u, d$  and  $s$  quarks respectively, equivalent to constituent quark masses shifted by the constant amount  $c$  of eq. (9), which is undetermined in our model.  $m_c$  is the mass of the  $c$  quark with  $M_c$  the corresponding energy shift. Analogously for the  $b$  quark.

### 2.3 $1/m_h$ correction

For any given set of input parameters we solve the eigenvalue problem, Eq. (3), using the Hamiltonian of Eq. (6) and the potential specified by Eqs. (7), (8) and (9). In this way we determine the radial wavefunctions  $f_{n,\ell,j}^0$  and  $f_{n,\ell,j}^1$  associated to the energy levels  $E_{n,\ell,j}^{(0)}$ . We then compute  $1/m_h$  corrections to the energy levels in first order perturbation theory

$$E_{n,\ell,j,J} = E_{n,\ell,j}^{(0)} + \frac{1}{m_h} \delta E_{n,\ell,j,J}^{(1)} \quad (11)$$

where, ignoring for the moment the mixing of the states,

$$\delta E_{n,\ell,j,J}^{(1)} = \sum_M \int \Psi_{n,\ell,j,J,M}^\dagger(x) \mathcal{H}^{(1)} \Psi_{n,\ell,j,J,M}(x) d^3x \quad (12)$$

The analytical expression for  $\mathcal{H}^{(1)}$  has been derived in Ref. [6] using the Bethe-Salpeter formalism. In terms of the radial wavefunctions (after the analytical integration of the angular part), we rewrite  $\delta E^{(1)}$  as a sum of three contributions

$$\delta E_{n,\ell,j,J}^{(1)} = A_{n,\ell,j,J} + B_{n,\ell,j,J} + C_{n,\ell,j,J} \quad (13)$$

These terms are respectively:

- The kinetic energy

$$A_{n,\ell,j,J} = -\frac{1}{2} \int_0^\infty \left[ f_{n,\ell,j}^0 \left( \partial_r^2 + \frac{2}{r} \partial_r - \frac{\ell^2 + \ell}{r^2} \right) f_{n,\ell,j}^0 \right. \quad (14)$$

$$\left. f_{n,\ell,j}^1 \left( \partial_r^2 + \frac{2}{r} \partial_r - \frac{\bar{\ell}^2 + \bar{\ell}}{r^2} \right) f_{n,\ell,j}^1 \right] r^2 dr \quad (15)$$

with  $\bar{\ell} = 2j - \ell$ .

- A shift due to spin-orbit interaction

$$B_{n,\ell,j,J} = \int_0^\infty V_v \left[ f_{n,\ell,j}^1 \left( \partial_r - \frac{\ell}{r} \right) f_{n,\ell,j}^0 - f_{n,\ell,j}^0 \left( \partial_r + \frac{\ell+2}{r} \right) f_{n,\ell,j}^1 \right] r^2 dr \quad (16)$$

for  $j = \ell + \frac{1}{2}$ , or

$$B_{n,\ell,j,J} = \int_0^\infty V_v \left[ f_{n,\ell,j}^1 \left( \partial_r + \frac{\ell+1}{r} \right) f_{n,\ell,j}^0 - f_{n,\ell,j}^0 \left( \partial_r - \frac{\ell-1}{r} \right) f_{n,\ell,j}^1 \right] r^2 dr \quad (17)$$

for  $j = \ell - \frac{1}{2}$ .

- The hyperfine splitting

$$C_{n,\ell,j,J} = (-1)^{J-\ell} \frac{2j+1}{2J+1} \int_0^\infty (\partial_r V_v) f_{n,\ell,j}^0 f_{n,\ell,j}^1 r^2 dr \quad (18)$$

## 2.4 Mixing

In Eqs.(11) and (12) we assumed that the Hamiltonian was diagonal. This is not the case because the  $\frac{1}{m_h}$  interaction term in the Hamiltonian mixes states. In general correction terms can mix any states with the same total angular momentum,  $J$ , and parity,  $P$ . However, there are only two types of sizable mixings. Large mixing can occur for pairs of states  $\Psi_{n,\ell,j,J,M}$  and  $\Psi_{n',\ell',j',J,M}$  with: (1)  $n = n'$ ,  $\ell = \ell'$  and  $j + \frac{1}{2} = j' - \frac{1}{2} = \ell = J$  (i.e. mixing within a given  $n$  and  $l$  multiplet); or (2)  $n + 1 = n'$ ,  $\ell + 2 = \ell'$  and  $j + \frac{1}{2} = j' - \frac{1}{2} = \ell = J$  (e.g. S-D mixing). The off-diagonal term in the Hamiltonian that mixes such pairs of states has the form

$$\begin{aligned} \epsilon &= \frac{1}{m_h} \sum_M \int \Psi_{n,\ell,j,J,M}^\dagger(x) \mathcal{H}^{(1)} \Psi_{n',\ell',j',J,M}(x) d^3x \\ &= (-1)^{J-\ell} \frac{1}{m_h} \frac{\sqrt{J(J+1)}}{2J+1} \int_0^\infty (\partial_r V_v) [f_{n,\ell,j}^0 f_{n',\ell',j'}^1 + f_{n,\ell,j}^1 f_{n',\ell',j'}^0] r^2 dr \end{aligned} \quad (19)$$

and it induces a mixing in the wavefunctions and in the energy levels

$$\begin{pmatrix} \psi_{n,\ell,j,m} \\ \psi_{n',\ell',j',m} \end{pmatrix}^{\text{phys.}} = \begin{pmatrix} 1 & +\frac{\epsilon}{2\Delta} \\ -\frac{\epsilon}{2\Delta} & 1 \end{pmatrix} \begin{pmatrix} \psi_{n,\ell,j,m} \\ \psi_{n',\ell',j',m} \end{pmatrix} + \mathcal{O}(\epsilon^2) \quad (20)$$

$$\begin{pmatrix} E_{n,\ell,j,J} \\ E_{n',\ell',j',J} \end{pmatrix}^{\text{phys.}} = \begin{pmatrix} E_{n,\ell,j,J} + \frac{\epsilon^2}{2\Delta} \\ E_{n',\ell',j',J} - \frac{\epsilon^2}{2\Delta} \end{pmatrix} + \mathcal{O}(\epsilon^2) \quad (21)$$

with  $\Delta = (E_{n,\ell,j,J} - E_{n',\ell',j',J})/2$ .

We find that the effect of mixing is generally negligible except for the  $P$  waves, where the mixing among wavefunctions can be of the order of 10%. In Tables 1-4 we report the value of  $\phi = \frac{100}{2}\epsilon/\Delta$  for each excited state. It measures, in percent, the contribution of the mixing to the wavefunction.



$H (n^J L_J)$	$m_{\text{exp.}}$	$E^0$	$E^{\text{phys.}}$	$\phi(\%)$
$D (1^{\frac{1}{2}} S_0)$	1.865	1.895	1.868	
$D (1^{\frac{1}{2}} S_1)$	2.007	1.895	2.005	
$D (1^{\frac{1}{2}} P_0)$		2.282	2.377	
$D (1^{\frac{3}{2}} P_1)$	2.422	2.253	2.417	-10.92
$D (1^{\frac{3}{2}} P_2)$	2.459	2.253	2.460	
$D (1^{\frac{1}{2}} P_1)$		2.282	2.490	10.92
$D (2^{\frac{1}{2}} S_0)$		2.447	2.589	
$D (2^{\frac{1}{2}} S_1)$		2.447	2.692	2.17
$D (1^{\frac{5}{2}} D_2)$		2.504	2.775	-5.41
$D (1^{\frac{3}{2}} D_1)$		2.553	2.795	-2.17
$D (1^{\frac{5}{2}} D_3)$		2.504	2.799	
$D (1^{\frac{3}{2}} D_2)$		2.553	2.833	5.41
$D (2^{\frac{1}{2}} P_0)$		2.683	2.949	
$D (2^{\frac{3}{2}} P_1)$		2.679	2.995	-10.70
$D (2^{\frac{3}{2}} P_2)$		2.679	3.035	1.79
$D (2^{\frac{1}{2}} P_1)$		2.683	3.045	10.70
$D (1^{\frac{7}{2}} F_3)$		2.709	3.074	-3.17
$D (1^{\frac{7}{2}} F_4)$		2.709	3.091	
$D (1^{\frac{5}{2}} F_2)$		2.760	3.101	-1.79
$D (1^{\frac{5}{2}} F_3)$		2.760	3.123	3.17
$D (3^{\frac{1}{2}} S_0)$		2.823	3.141	
$D (3^{\frac{1}{2}} S_1)$		2.823	3.226	

Table 1: Tabulated spectrum for  $D$  mesons.  $E^0$  denotes the lowest order energies.  $E^{\text{phys.}}$  includes all the order  $1/m_h$  corrections. (All units in GeV). The mixings between lowest order states are denoted by  $\phi$ .

$H (n^j L_J)$	$m_{\text{exp.}}$	$E^0$	$E^{\text{phys.}}$	$\phi(\%)$
$D_s (1^{\frac{1}{2}} S_0)$	1.969	1.988	1.965	
$D_s (1^{\frac{1}{2}} S_1)$	2.112	1.988	2.113	
$D_s (1^{\frac{1}{2}} P_0)$		2.374	2.487	
$D_s (1^{\frac{3}{2}} P_1)$	2.535	2.353	2.535	-11.62
$D_s (1^{\frac{3}{2}} P_2)$	2.573	2.353	2.581	
$D_s (1^{\frac{1}{2}} P_1)$		2.374	2.605	11.62
$D_s (2^{\frac{1}{2}} S_0)$		2.540	2.700	
$D_s (2^{\frac{1}{2}} S_1)$		2.540	2.806	1.97
$D_s (1^{\frac{5}{2}} D_2)$		2.606	2.900	-6.11
$D_s (1^{\frac{3}{2}} D_1)$		2.648	2.913	-1.97
$D_s (1^{\frac{5}{2}} D_3)$		2.606	2.925	
$D_s (1^{\frac{3}{2}} D_2)$		2.648	2.953	6.11
$D_s (2^{\frac{1}{2}} P_0)$		2.777	3.067	
$D_s (2^{\frac{3}{2}} P_1)$		2.775	3.114	-10.58
$D_s (2^{\frac{3}{2}} P_2)$		2.775	3.157	1.81
$D_s (2^{\frac{1}{2}} P_1)$		2.777	3.165	10.58
$D_s (1^{\frac{7}{2}} F_3)$		2.812	3.203	-3.60
$D_s (1^{\frac{7}{2}} F_4)$		2.812	3.220	
$D_s (1^{\frac{5}{2}} F_2)$		2.857	3.224	-1.81
$D_s (1^{\frac{5}{2}} F_3)$		2.857	3.247	3.60
$D_s (3^{\frac{1}{2}} S_0)$		2.917	3.259	
$D_s (3^{\frac{1}{2}} S_1)$		2.917	3.345	

Table 2: Tabulated spectrum for  $D_s$  mesons. (All units in GeV). Notation as in Table 1.

$H (n^j L_J)$	$m_{\text{exp.}}$	$E^0$	$E^{\text{phys.}}$	$\phi(\%)$
$B (1^{\frac{1}{2}} S_0)$	5.279	5.288	5.279	
$B (1^{\frac{1}{2}} S_1)$	5.325	5.288	5.324	
$B (1^{\frac{3}{2}} P_1)$		5.646	5.700	-6.00
$B (1^{\frac{1}{2}} P_0)$		5.675	5.706	
$B (1^{\frac{3}{2}} P_2)$		5.646	5.714	
$B (1^{\frac{1}{2}} P_1)$		5.675	5.742	6.00
$B (2^{\frac{1}{2}} S_0)$		5.840	5.886	
$B (2^{\frac{1}{2}} S_1)$		5.840	5.920	0.69
$B (1^{\frac{5}{2}} D_2)$		5.897	5.985	-1.96
$B (1^{\frac{5}{2}} D_3)$		5.897	5.993	
$B (1^{\frac{3}{2}} D_1)$		5.946	6.025	-0.69
$B (1^{\frac{3}{2}} D_2)$		5.946	6.037	1.96
$B (2^{\frac{1}{2}} P_0)$		6.076	6.163	
$B (2^{\frac{3}{2}} P_1)$		6.072	6.175	-9.11
$B (2^{\frac{3}{2}} P_2)$		6.072	6.188	0.50
$B (2^{\frac{1}{2}} P_1)$		6.076	6.194	9.11
$B (1^{\frac{7}{2}} F_3)$		6.102	6.220	-0.99
$B (1^{\frac{7}{2}} F_4)$		6.102	6.226	
$B (1^{\frac{5}{2}} F_2)$		6.153	6.264	-0.50
$B (1^{\frac{5}{2}} F_3)$		6.153	6.271	0.99
$B (3^{\frac{1}{2}} S_0)$		6.216	6.320	
$B (3^{\frac{1}{2}} S_1)$		6.216	6.347	

Table 3: Tabulated spectrum for  $B$  mesons. (All units in GeV). Notation as in Table 1.

$H (n^j L_J)$	$m_{\text{exp.}}$	$E^0$	$E^{\text{phys.}}$	$\phi(\%)$
$B_s (1^{\frac{1}{2}} S_0)$	5.369	5.381	5.373	
$B_s (1^{\frac{1}{2}} S_1)$	5.417	5.381	5.421	
$B_s (1^{\frac{1}{2}} P_0)$		5.767	5.804	
$B_s (1^{\frac{3}{2}} P_1)$		5.746	5.805	-7.19
$B_s (1^{\frac{3}{2}} P_2)$		5.746	5.820	
$B_s (1^{\frac{1}{2}} P_1)$		5.767	5.842	7.19
$B_s (2^{\frac{1}{2}} S_0)$		5.933	5.985	
$B_s (2^{\frac{1}{2}} S_1)$		5.933	6.019	0.64
$B_s (1^{\frac{5}{2}} D_2)$		5.999	6.095	-2.31
$B_s (1^{\frac{5}{2}} D_3)$		5.999	6.103	
$B_s (1^{\frac{3}{2}} D_1)$		6.041	6.127	-0.64
$B_s (1^{\frac{3}{2}} D_2)$		6.041	6.140	2.31
$B_s (2^{\frac{1}{2}} P_0)$		6.170	6.264	
$B_s (2^{\frac{3}{2}} P_1)$		6.168	6.278	-9.81
$B_s (2^{\frac{3}{2}} P_2)$		6.168	6.292	0.51
$B_s (2^{\frac{1}{2}} P_1)$		6.170	6.296	9.81
$B_s (1^{\frac{7}{2}} F_3)$		6.205	6.332	-1.15
$B_s (1^{\frac{7}{2}} F_4)$		6.205	6.337	
$B_s (1^{\frac{5}{2}} F_2)$		6.250	6.369	-0.51
$B_s (1^{\frac{5}{2}} F_3)$		6.250	6.376	1.15
$B_s (3^{\frac{1}{2}} S_0)$		6.310	6.421	
$B_s (3^{\frac{1}{2}} S_1)$		6.310	6.449	

Table 4: Tabulated spectrum for  $B_s$  mesons. (All units in GeV). Notation as in Table 1.

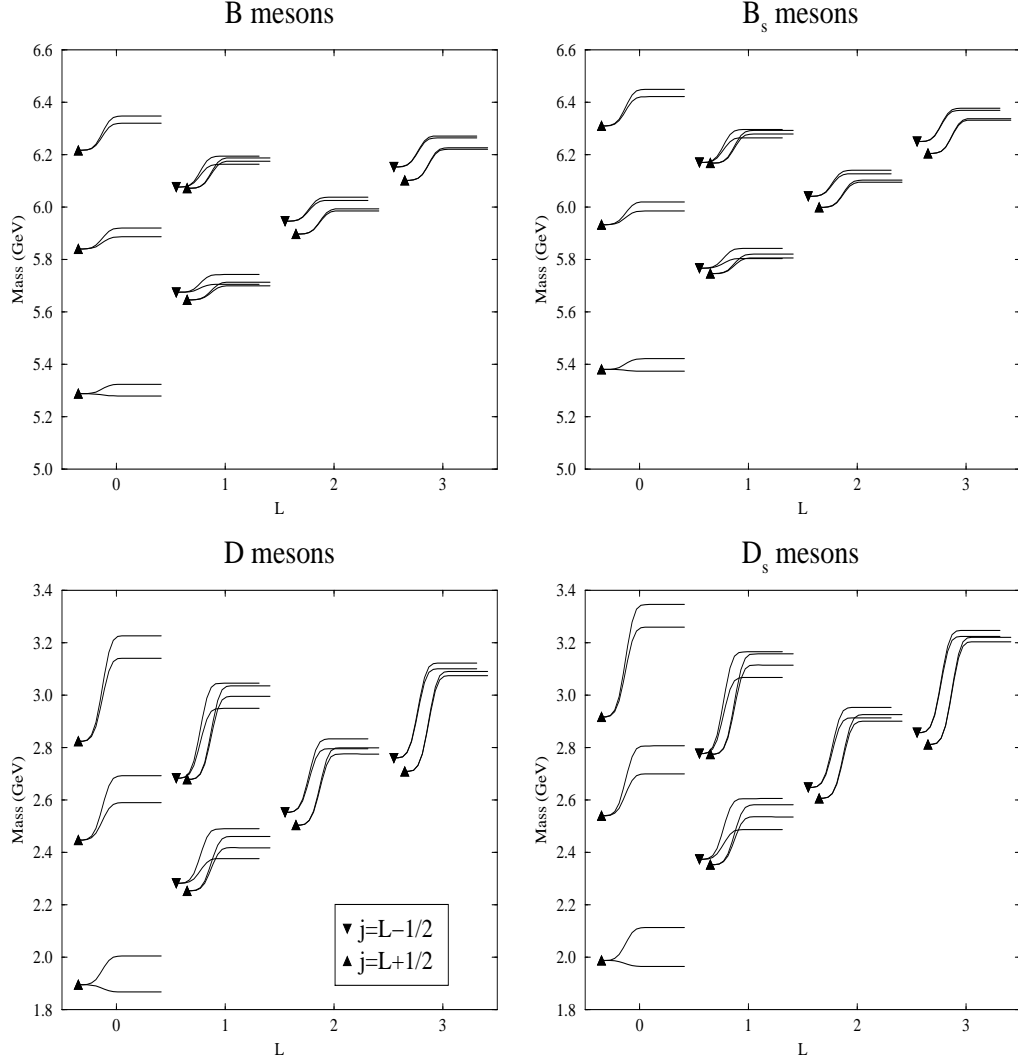


Figure 1: Computed spectrum of excited states in the  $\{D, D_s, B, B_s\}$  family. The plot shows the spectrum before and after  $1/m_h$  corrections (including mixing). These corrections are responsible for the hyperfine splitting. The horizontal axis is the orbital angular momentum of the meson ( $\ell$ ). For each value of  $\ell$  and  $j$  there is a doublet of states ( $J = j - \frac{1}{2}$  and  $J = j + \frac{1}{2}$ , with lower and higher energy respectively).

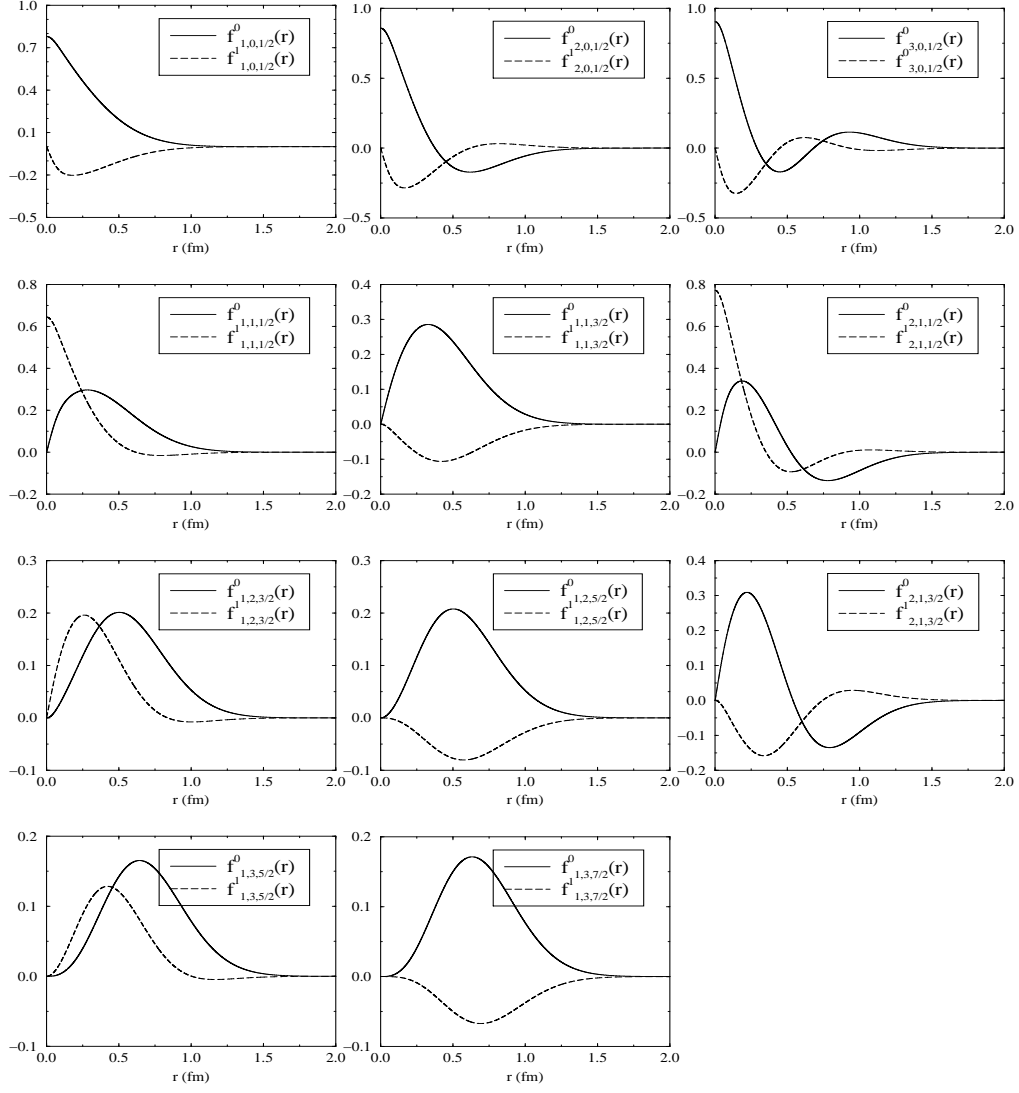


Figure 2: Radial wavefunctions for some excited states (for non-strange mesons). The continuum (dashed) line refers to the  $f^0(r)$  ( $f^1(r)$ ) function. These plots do not include the mixing contribution.

## 2.5 Determination of the parameters and predictions

The nine parameters of our model, Eq.(10), are determined numerically as follows: We define a function  $\mathcal{F}$  of the input parameters that finds eigenvalues and eigenfunctions of Eq. (3) using a fourth order Runge-Kutta formula, corrects the energy levels by including the  $1/m_h$  perturbative corrections (including mixing effects) and returns

$$\chi^2 = \sum_{\text{observed states}} \left( \frac{E_{n,\ell,j,J}^{\text{phys.}} - m_{n,\ell,j,J}}{\delta m_{n,\ell,j,J}} \right)^2 \quad (22)$$

where  $E_{n,\ell,j,J}^{\text{phys.}}$  are the computed energy levels and  $m_{n,\ell,j,J} \pm \delta m$  are the measured masses (with their experimental error) of the corresponding particles.

We then minimize  $\mathcal{F}$  in its nine dimensional domain. We repeat this procedure with different sets of starting parameters until we are confident that we have found the absolute minimum. The experimental data used for the “observed states” in the fit are reported in the third column of Tables 1-4.

Our best fit gives the following values for the parameters

$\alpha_s$	0.339
$\lambda$	2.823 GeV
$b$	0.257 GeV <sup>2</sup>
$m_u$	0.071 GeV
$m_s$	0.216 GeV
$m_c$	1.511 GeV
$M_c$	1.292 GeV
$m_b$	4.655 GeV
$M_b$	4.685 GeV

(23)

The corresponding predicted spectrum is reported in the fifth column of Tables 1-4. The best fit parameters reported here differ slightly from those reported in Ref. [10] because we use here most recent value for  $m_{n,\ell,j,J}$ .

We remark that  $m_u$  and  $m_s$  are mass parameters which differ from the constituent quark masses for an overall undetermined constant shift.

As a consistency check of our results we observe that the mass splitting  $m_s - m_u \simeq 140\text{MeV}$  comes out in agreement with naive expectations based on Gell-Mann-Okubo type relations. This difference also agrees, within 1%, with the corresponding splitting determined in ref. [6] and used in ref. [5] as input for their calculations.

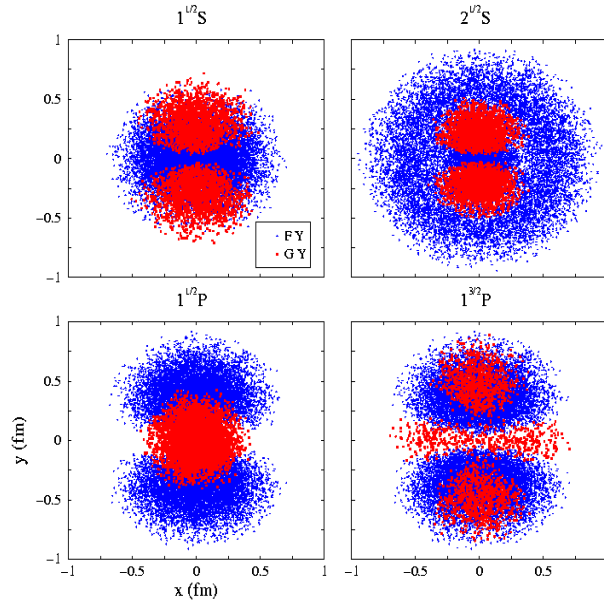


Figure 3: Orbitals for some excited B mesons.

Remarkably  $m_b \simeq M_b$  with much better agreement than expected. Moreover  $\lambda^{-1} \simeq 0.06\text{fm}$  is smaller than any other length scale involved in the problem, as was required.

Figure 2 shows some of the computed radial wavefunctions for non-strange mesons,  $f_{n,\ell,j}^0(r)$  and  $f_{n,\ell,j}^1(r)$ . These wavefunctions do not include  $1/m_h$  corrections, therefore they are the same for  $D$  and  $B$  mesons. The corresponding wavefunctions for strange mesons are very similar.

Figure 3 shows density plots for each couple of independent spin components of some of the computed light-quark wavefunctions,  $|f_{n,\ell,j}^0 Y_0^\ell|^2$  in black (blue) and  $|f_{n,\ell,j}^1 Y_0^{2j-\ell}|^2$  in gray (red). They represent the analogous, in the heavy meson systems, of the orbitals of the hydrogen atom.

## 2.6 Comparison with experiment

The comparison of our results to the present experimental information on the excitation spectrum of the  $(D, D_s, B, B_s)$  mesons is given in Table 5. States which were used in the determining our best fit parameters are so indicated.



charmed meson masses (MeV)				bottom meson masses (MeV)			
	model	exp	[Ref.]		model	exp	[Ref.]
$D^* - D$	137 [a]	141,142	[11]	$B^* - B$	45 [a]	46	[11]
$D_0^* - D$	512			$B_0^* - B$	427		
$D_1^* - D$	622	596(53)	[14]	$B_1^* - B$	463	391(16)	[12][b]
$D_1 - D$	549 [a]	558(2)	[11]	$B_1 - B$	421	459(9)	[13][b]
				$B_1 - B$	421	431(20)	[18][b]
$D_2^* - D$	592 [a]	594(2)	[11]	$B_2^* - B$	435	489(8)	[12][b]
						460(13)	[19][b]
				$(B^{**} - B)$		418(9)	[11][c]
$D' - D$	721			$B' - B$	607		
$D^{*'} - D$	824	772(6)	[15]	$B^{*'} - B$	641		
		not seen	[16, 17]				
$D_s - D$	97 [a]	99,104	[11]	$B_s - B$	94 [a]	90(2)	[11]
$D_s^* - D_s$	148 [a]	144	[11]	$B_s^* - B_s$	48 [a]	46	[11]
$D_{s0}^* - D_s$	512			$B_{s0}^* - B_s$	431		
$D_{s1}^* - D_s$	640			$B_{s1}^* - B_s$	469		
$D_{s1} - D_s$	570 [a]	566(1)	[11]	$B_{s1} - B_s$	432		
$D_{s2}^* - D_s$	616 [a]	605(2)	[11]	$B_{s2}^* - B_s$	447		
				$(B_{s2}^{**} - B_s)$		484(15)	[11][c]
$D_s' - D_s$	735			$B_s' - B_s$	612		
$D_s^{*'} - D_s$	841			$B_s^{*'} - B_s$	646		

Table 5: The heavy-light spectrum compared to experiment. We report the difference between the excited state masses and the ground state ( $D$  or  $B$ ) in each case.

[a] Experimental input to model parameters fit.

[b] Theoretical estimates for some of the mass splittings have been used as input.

[c] Experimental signal is a sum over resonances with  $J = 0, 1, 2$ .

Our model is in excellent agreement with the better established P waves in the  $D$  and  $D_s$  systems. In particular the  $D_1^*$  ( $1\frac{1}{2}P_1$ ) fits the recent measurement of CLEO [14]. For the P-waves of the B meson systems the agreement with preliminary measurements is somewhat less impressive.

However many of the existing experimental fits for individual masses of these states relied on patterns of masses for the  $j_l = 1/2$  states not found in our model. For example, our relativistic quark model predict  $m_{1,1,\frac{1}{2},1} > m_{1,1,\frac{3}{2},1}$  for a relatively broad range of parameters consistent with light spectroscopy<sup>1</sup>. Also, we obtain a splitting for the  $\frac{1}{2}P_J$  states more than twice as big as the splitting for the  $\frac{3}{2}P_J$  states.

Preliminary results from L3 [12] for the masses of P-wave  $B$  meson excitations are:

$$B_1^* : m_{1,1,\frac{1}{2},1} = (5.670 \pm 0.010_{\text{stat}} \pm 0.013_{\text{syst}})\text{GeV} \quad (\text{L3}) \quad (24)$$

$$B_2^* : m_{1,1,\frac{3}{2},2} = (5.768 \pm 0.005_{\text{stat}} \pm 0.006_{\text{syst}})\text{GeV} \quad (\text{L3}) \quad (25)$$

$$(26)$$

The L3 results were derived using the constraint that  $m_{1,1,\frac{1}{2},1} - m_{1,1,\frac{1}{2},0} = m_{1,1,\frac{3}{2},2} - m_{1,1,\frac{3}{2},1} = 12$  MeV. This assumption is not realized in our model. Similar assumptions are needed for the extractions the masses of P-wave  $B$  meson excitations from OPAL [13] and CDF [18]. It would be interesting to reanalyze results using the pattern expected in this relativistic quark model.

Finally, the observation of the  $D^{*'} by DELPHI [15] is not consistent with searches by CLEO [16] and OPAL [17].$

## 2.7 Regge trajectories

We find that  $E_{n,\ell,j,J} - M_h$  all lie on Regge trajectories parameterized by  $mJ + q_{n,\ell,j}$  with  $m \simeq 0.7$  (as shown in Figure 4). This is a well understood phenomenon for light spectroscopy but, for light mesons,  $m \simeq 2\pi b$  (where  $b$  is the string tension). This is about a factor two bigger than we find. Our result can be explained in the non relativistic limit or, alternatively, in a simple and naive string picture: Ignoring the short distance behavior of the potential, we model the meson as a classical light quark attached through a string to the center of mass of the system. The energy of the system,  $E$ ,

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<sup>1</sup>This result is known in the literature as spin-orbit inversion. It was first predicted by Schnitzer [20] and later by the models of Isgur [21] and Ebert [22].

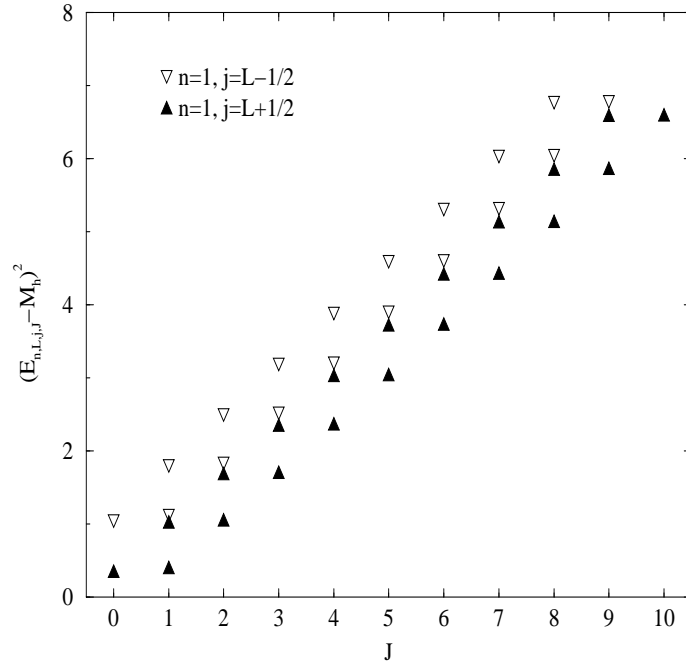


Figure 4: Regge trajectories for some of our orbitally excited heavy mesons.

(i.e. the energy of the string) is related to the classical angular momentum,  $J$ , by  $E^2 = \pi b J$ . The factor two in the light meson picture can be explained with the fact that the latter rotate around a center of mass that is located at the middle of the string while for heavy-light mesons the center of mass coincides with one of the two ends of the string.

This simple picture shows that the bulk of an heavy meson mass is dominated by the mass of the heavy quark plus the potential energy associated to the large distance interaction ( $\propto br$ ), and again gives support to our assumption that short distance behavior of the potential has a small contribution to the spectrum.

### 3 Hadronic Transitions

#### 3.1 Transition amplitudes

We start by considering the most general hadronic transition of the form

$$H' \rightarrow H + x \quad (27)$$

where  $H'$  and  $H$  are two heavy-light mesons containing the same heavy quark, with wavefunctions  $\Psi_{n',\ell',j',J',M'}$  and  $\Psi_{n,\ell,j,J,M}$  respectively and  $x$  can be any light meson with momentum  $\mathbf{p}$ . Although we keep our formalism general, in this paper we only compute numerically decays in which  $x$  is a pseudoscalar meson belonging to the flavor octet ( $\pi$ ,  $K$ ,  $\eta$ ).

In the context of the chiral quark model [4] this transition is mediated by an effective interaction of the form

$$\mathcal{L}_{\text{int}} = \frac{g_A^8}{\sqrt{2}f_x} \bar{q}'_i X \mathcal{M}^{ij} q_j + \mathcal{O}(\partial^2) \quad (28)$$

where  $f_x$  can be identified with  $f_\pi \simeq 130\text{MeV}$  and  $g_A^8$  is an effective coupling.  $X = \not{\partial}\gamma^5$  is the spin structure associated to the transition,  $i, j$  are  $SU(3)_{\text{flavor}}$  indices and

$$\mathcal{M} = \sqrt{2} \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix} \quad (29)$$

is the usual  $SU(3)_{L+R}$  invariant representation of the pseudoscalar mesons.

$H' \rightarrow H + x$	$\zeta$	$H' \rightarrow H + x$	$\zeta$
$B^0 \rightarrow B^0 + \pi^0$	1	$B_s \rightarrow B_s + \eta_8$	$-2/\sqrt{3}$
$B^\pm \rightarrow B^\pm + \pi^0$	1	$B_s \rightarrow B^0 + K$	$\sqrt{2}$
$B^\pm \rightarrow B^0 + \pi^\pm$	$\sqrt{2}$	$B_s \rightarrow B^\pm + K^\mp$	$\sqrt{2}$
$B^0 \rightarrow B^\pm + \pi^\mp$	$\sqrt{2}$	$B^0 \rightarrow B_s + \bar{K}$	$\sqrt{2}$
$B^0 \rightarrow B^0 + \eta_8$	$1/\sqrt{3}$	$B^\pm \rightarrow B_s + K^\pm$	$\sqrt{2}$
$B^\pm \rightarrow B^\pm + \eta_8$	$1/\sqrt{3}$	$B_q \rightarrow B_q + \eta_1$	$\sqrt{\frac{2}{3}} + \mathcal{O}(\frac{1}{N_c})$

Table 6: List of decay channels for  $B$  (or  $D$ ) mesons with the corresponding flavor factor  $\zeta$ .

The transition mediated by this Lagrangian is associated to the following matrix element

$$I^{H'Hx}(\mathbf{p}) = \frac{ig_A^8 \zeta}{\sqrt{2}f_x} \int \bar{\Psi}_{n,\ell,j,J,M}(z) X e^{i\mathbf{p}\cdot\mathbf{z}} \Psi_{n',\ell',j',J',M'}(z) d^3z \quad (30)$$

where  $\zeta$  is a coefficient that characterize the flavor structure of the decay. A list of all possible cases has been derived from Eq. (29) and is reported in Table 6. The physical  $\eta$  and  $\eta'$  are of course mixtures of the ideal  $\eta_8$  and  $\eta_1$ . In particular,  $\eta = \eta_8 \cos(\theta_p) - \eta_1 \sin(\theta_p)$  where  $\theta_p \approx -10.1$  deg with a large uncertainty. In this work we ignore this mixing and we assume  $\theta_p = 0$ . The corrective multiplicative factor for a different choice for  $\theta_p$  can be derived by the reader using Table 6.

The exponential in Eq. (30) can be expanded in products of spherical harmonics and spherical Bessel functions, thus giving

$$I^{H'Hx}(\mathbf{p}) = \sum_{\ell_x, m_x} Y_{m_x}^{\ell_x*}(\hat{p}) C_{J,M;\ell_x,m_x}^{J',M'} \mathcal{A}_{\ell_x}^{H'Hx}(X, p) \quad (31)$$

Eq. (31) implicitly defines the transition amplitude,  $\mathcal{A}_{\ell_x}^{H' \rightarrow Hx}(X, p)$ , for a  $x$  in a given eigenstate  $\ell_x$  of its angular momentum. By projecting the matrix  $X$  on the basis presented in the Appendix A, the transition amplitude can be rewritten as a linear combination of terms, each factorized into a radial part and a spin dependent part

$$\mathcal{A}_{\ell_x}^{H'Hx}(X, p) = \frac{ig_A^8 \zeta}{\sqrt{2}f_x} \sum_{ab=\{0,1\}} \sum_k c_{\ell_x}^{ab,k}(X) \int_0^\infty f_{n',\ell',j'}^a(r) j_k(rp) f_{n,\ell,j}^b(r) r^2 dr \quad (32)$$

The coefficients  $c_{\ell_x}^{ab,k}(X)$  depend on the quantum numbers of the mother and the daughter heavy mesons. Their explicit expression is given in the Appendix A. The integrals are computed numerically.

One can extend our analysis for octet pseudoscalar transitions to the approximately flavor singlet  $\eta'$ . In the large  $N_c$  limit the  $\eta_1$  combines with the octet to form a nonet. In that case the effective interaction in the Lagrangian takes the form

$$\mathcal{L}_{\text{int}} = \frac{g_A^1 \zeta}{\sqrt{2} f_{\eta_1}} \bar{q}'_i X \eta_1 q_i + \mathcal{O}(\partial^2) \quad (33)$$

with  $X = \not{p}$  and  $g_A^1 \simeq g_A^8$ . This symmetry is badly broken in QCD. However it is reasonable to assume that in these transitions that the form (Eq. (33)) still holds. If one further assumes that the spatial wavefunctions of  $\pi$  and  $\eta'$  are the approximately equal, one obtains  $f_{\eta'} \simeq f_\pi$ . Hence the coefficient  $\zeta$  can be set to  $\sqrt{2/3}$  both for heavy strange and non strange decaying heavy mesons.

The situation for decays in which  $x$  is a light vector mesons ( $\rho, \omega, K^*$ ) is different. When compared to the pseudoscalar mesons, they have a different spin coupling to the quarks ( $X = \not{\epsilon}_\mu$  where  $\epsilon_\mu$  is the polarization vector of the meson), a different effective coupling ( $g_V \neq g_A^8$ ), and a different wavefunction ( $f_\rho \neq f_\pi$ ). With these replacements Eq. (32) remains valid for decays with emission of light vector mesons.<sup>2</sup> The detailed study of these vector meson transitions is deferred to a future paper.

## 3.2 Partial widths

The partial width for the transition in Eq. (27) (for a light meson  $x$  emitted with total momentum  $p$  and angular momentum  $\ell_x$ ) is given by

$$\Gamma_x(H' \rightarrow H + x; \ell_x) = \frac{p}{8\pi^2} \frac{2J+1}{2J'+1} \frac{m_H}{m_{H'}} \left| \mathcal{A}_{\ell_x}^{H'Hx}(X, p) \right|^2 \quad (34)$$

where  $m_{H'}$  and  $m_H$  are the masses of the mother and daughter heavy mesons respectively.

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<sup>2</sup>It is possible to relate these the pseudoscalar and vector couplings and coefficients within the context of an approximate  $SU(6)_W$  symmetry for the low lying states.

channel	$l_\pi$	$p_\pi$ (MeV)	$\Gamma_\pi/(g_A^8)^2(\text{keV})$
$D^{*0}(1^{\frac{1}{2}}S_1) \rightarrow D^0(1^{\frac{1}{2}}S_0) + \pi^0$	1	$42.8 \pm .2$	$62 \pm 1$
$D^{*+}(1^{\frac{1}{2}}S_1) \rightarrow D^0(1^{\frac{1}{2}}S_0) + \pi^+$	1	$39.4 \pm .5$	$97 \pm 3$
$D^{*+}(1^{\frac{1}{2}}S_1) \rightarrow D^+(1^{\frac{1}{2}}S_0) + \pi^0$	1	$38.1 \pm .3$	$44 \pm 1$

Table 7: List of partial decay rates for  $1S$   $D$  mesons. The measured  $D^*$  and  $D$  masses [11] are used in these results.

The total hadronic decay width (via a pseudoscalar meson transition) is defined simply as the sum of the partial widths:

$$\Gamma_{\mathcal{M}}^{H'} = \sum_H \sum_{x=\{\pi, \eta_8, K\}} \sum_{\ell_x} \Gamma_x(H' \rightarrow H + x; \ell_x) \quad (35)$$

Transitions involving excited states very near their kinematic threshold for an allowed decay (e.g. where the light pseudoscalar momentum is less than 100 MeV) are extremely sensitive to our calculated mass values. This is particularly true for the allowed transitions within the  $1S$  multiplets. In these cases, even the small mass differences between the the charged and neutral states are important. Using the physical masses for the various  $D$  mesons [11], the individual pion transitions are shown in Table 7.

After removing these phase space uncertainties, reasonable variations in our model parameters gave variations of about 10% in the overall hadronic widths. The listed branching ratios with emission of a  $\pi$  are flavor blind and sum over the final state pion charge (i.e. they have been computed with  $\zeta = \sqrt{3}$ ). Each exclusive decay can be deduced by correcting for this factor using Table 6 to determine the relative strength of the charged and neutral decays. In addition, a small phase space correction should be included appropriate to the slight difference in the masses of the various charge states. These rates are shown in Table 8 for the  $D$  and  $D_s$  mesons and in Table 9 for the  $B$  and  $B_s$  mesons. For the  $1^{\frac{3}{2}}P_{(1,2)}$   $B_s$  states, our model predicts that they are below threshold for  $K$  transitions to the the  $1^{\frac{1}{2}}S_{(0,1)}$   $B$  states. However, this is very sensitive to the details of the model. So, for completeness, we note the partial rates divided by the appropriate phase space factor at  $p_K = 0$  in Table 10.

A list of the allowed transitions for other low-lying excited states is reported in Appendix B.

$H'(n'^{j'}\ell_{J'})$	$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}P_0)$	$D(1^{\frac{1}{2}}S_0)$	$\pi$	0	437	189
$D(1^{\frac{3}{2}}P_1)$	$D(1^{\frac{1}{2}}S_1)$	$\pi$	0	355	(*) 1.7
	$D(1^{\frac{1}{2}}S_1)$	$\pi$	2	355	14.5
$D(1^{\frac{3}{2}}P_2)$	$D(1^{\frac{1}{2}}S_0)$	$\pi$	2	506	24.6
	$D(1^{\frac{1}{2}}S_1)$	$\pi$	2	394	13.7
$D(1^{\frac{1}{2}}P_1)$	$D(1^{\frac{1}{2}}S_1)$	$\pi$	0	420	181
$D_s(1^{\frac{1}{2}}P_0)$	$D(1^{\frac{1}{2}}S_0)$	$K$	0	325	236
$D_s(1^{\frac{3}{2}}P_1)$	$D(1^{\frac{1}{2}}S_1)$	$K$	0	175	(*) 1.89
	$D(1^{\frac{1}{2}}S_1)$	$K$	2	175	0.3
$D_s(1^{\frac{3}{2}}P_2)$	$D(1^{\frac{1}{2}}S_0)$	$K$	2	442	8.9
	$D(1^{\frac{1}{2}}S_1)$	$K$	2	264	1.4
	$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	2	248	0.4
$D_s(1^{\frac{1}{2}}P_1)$	$D(1^{\frac{1}{2}}S_1)$	$K$	0	302	224

Table 8: The heavy-light 1P state hadronic transition rates for  $D$  and  $D_s$  mesons.  $H' \rightarrow H + x$ . Decays denoted with an (\*) are allowed only because of the order  $1/m_h$  mixing of states.  $p_x$  and  $\Gamma_x/(g_A^8)^2$  are in MeV.

$H'(n'^{j'}\ell_{J'})$	$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}P_0)$	$B(1^{\frac{1}{2}}S_0)$	$\pi$	0	388	186
$B(1^{\frac{3}{2}}P_1)$	$B(1^{\frac{1}{2}}S_1)$	$\pi$	0	338	(*) 0.5
	$B(1^{\frac{1}{2}}S_1)$	$\pi$	2	338	13.1
$B(1^{\frac{3}{2}}P_2)$	$B(1^{\frac{1}{2}}S_0)$	$\pi$	2	396	10.6
	$B(1^{\frac{1}{2}}S_1)$	$\pi$	2	352	9.5
$B(1^{\frac{1}{2}}P_1)$	$B(1^{\frac{1}{2}}S_1)$	$\pi$	0	381	180
$B_s(1^{\frac{1}{2}}P_0)$	$B(1^{\frac{1}{2}}S_0)$	$K$	0	170	159
$B_s(1^{\frac{1}{2}}P_1)$	$B(1^{\frac{1}{2}}S_1)$	$K$	0	153	143

Table 9: The 1P state hadronic transition rates for  $B$  and  $B_s$  systems.  $H' \rightarrow H + x$ . Decays denoted with an (\*) are allowed only because of the order  $1/m_h$  mixing of states. Values for  $p_x$  and  $\Gamma_x/(g_A^8)^2$  are in MeV.



$H'(n'^{j'}\ell_{j'})$	$H(n^j\ell_J)$	$x$	$\ell_x$	$\Gamma_x/(g_A^8)^2 \times (100/p_x)^{(2\ell_x+1)}$
$B_s(1^{\frac{3}{2}}P_1)$	$B(1^{\frac{1}{2}}S_1)$	$K$	0	(*) $4.92 \times 10^{-1}$
$B_s(1^{\frac{3}{2}}P_1)$	$B(1^{\frac{1}{2}}S_1)$	$K$	2	$2.38 \times 10^{-2}$
$B_s(1^{\frac{3}{2}}P_2)$	$B(1^{\frac{1}{2}}S_0)$	$K$	2	$9.48 \times 10^{-3}$
$B_s(1^{\frac{3}{2}}P_2)$	$B(1^{\frac{1}{2}}S_1)$	$K$	2	$1.43 \times 10^{-2}$

Table 10: Decay rates for  $1^{\frac{3}{2}}P_{(1,2)}$   $B_s$  mesons with phase space dependence divided out. These states are very near the kinematical threshold in our model. Values for  $p_x$  and  $\Gamma_x/(g_A^8)^2$  are in MeV.

### 3.3 Comparison to lattice results

As one more consistency check of our model we compare our prediction for the transition<sup>3</sup>  $B \rightarrow B^* + \pi$  with model independent results coming from lattice simulations. We define

$$\mathcal{A}^{BB^*\pi}(r) = \frac{1}{3} \sum_{\mu=1,2,3} \int \langle B^* | A_\mu(\mathbf{r}) | B \rangle d\Omega_r \quad (36)$$

with  $A_\mu(\mathbf{r}) = \bar{q}(t, \mathbf{r}) \gamma_\mu \gamma^5 q(t, \mathbf{r})$  at  $t = 0$ . The same matrix element can be expressed in terms of our radial wavefunction and, in the limit  $p_\pi \rightarrow 0$ ,

$$\mathcal{A}^{BB^*\pi}(r) = -g_A^8 \left[ (f_{1,0,\frac{1}{2}}^0(r))^2 - \frac{1}{3} (f_{1,0,\frac{1}{2}}^1(r))^2 \right] + \mathcal{O}(p_\pi) \quad (37)$$

$g_A^8$  is the effective coupling of the transition as defined in Eq. (28)<sup>4</sup> In the chiral quark model  $g_A^8$  is an effective parameter and it has to be given as input. On the other side, in the context of lattice computations, the matrix element in Eq. (36) follows directly from first principles (the QCD Lagrangian) and can be computed explicitly. By fitting the lattice results of Ref. [24] with our prediction for  $\mathcal{A}^{BB^*\pi}(r)$  as function of  $g_A^8$  we are able to

<sup>3</sup>Even if this transition is kinematically forbidden it is physically relevant to the  $B \rightarrow \pi + \ell + \bar{\nu}$  exclusive decay under the assumption of vector meson dominance.

<sup>4</sup>Note from Eq. (37) that in the non relativistic limit the coupling  $g_A^8$  coincides with the coupling constant  $g$  that appears in the Heavy Meson Chiral Lagrangian [23]. The lattice result for this quantity is  $g = 0.42 \pm 0.09$ .

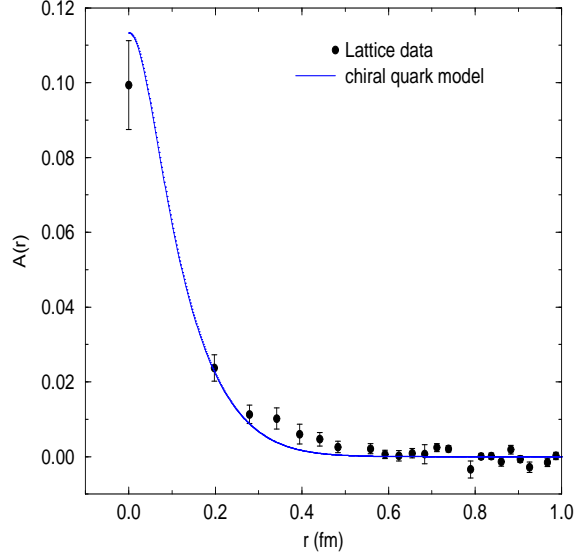


Figure 5: Comparison between a prediction of our model and the lattice QCD result [24].

determine<sup>5</sup>

$$g_A^8 = Z_A g_A^{8(\text{lattice})} = 0.53 \pm 0.11 \quad (38)$$

where  $g_A^{8(\text{lattice})}$  is the naive lattice result extracted from the fit and  $Z_A = 0.78$  is lattice matching factor discussed in Ref. [24]. The error includes the statistical error due to the simulation and the fits ( $\simeq 10\%$ ), and an estimate of the systematic error in the matching coefficient and in the the chiral extrapolation. This is a preliminary result, as those of Ref. [24] are, because of the small lattice size and the poor chiral extrapolation. In any case our result is in agreement with lattice determination of Ref. [25],  $g_A^8 = 0.61 \pm 0.13$ , and with experimental results from nucleon and hyperon  $\beta$  decays,  $g_A^8 = 0.58 \pm 0.02$ , [26]. A more precise lattice determination is possible and may be carried out in the near future.

Apart for the overall normalization given by  $g_A^8$ , the radial dependence of the function  $\mathcal{A}_{B^*B\pi}(r)$  is predicted independently by our model and by the lattice computation. In Figure 5 we present a comparison between our

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<sup>5</sup>We set to zero terms of the order  $\mathcal{O}(p_\pi)$  for consistency with the lattice computation.

analytical result, with adjusted normalization, and the lattice data. We believe this comparison provides a satisfactory consistency check of the two methods<sup>6</sup>.

### 3.4 Comparison to experiment

The total width of the  $D^{*+}$  meson has recently been measured by the CLEO Collaboration [27]. They obtain  $\Gamma = 96 \pm 4_{\text{stat}} \pm 22_{\text{syst}}(\text{keV})$ . Combining this measurement with the well-known branching ratios for the various pionic transitions, gives a measurement of chiral coupling constant. We obtain

$$g_A^8 = 0.82 \pm 0.09 \quad (39)$$

within our model.

Within the chiral quark model, the coupling determined from any transition should agree. (i.e the coupling is independent of particular initial or final heavy-light states.) Table 11 lists the various determinations of  $g_A^8$  from existing data. Within the existing large uncertainties the various determinations are consistent.

## 4 Conclusions

We have computed the spectrum and hadronic decay width of the excited  $D$ ,  $D_s$ ,  $B$  and  $B_s$  mesons using a relativistic quark model for the masses and wavefunction of the heavy-light mesons. This work is based on that of refs. [8, 6, 5] but departs from these previous works because we choose a simpler form for the potential and determined its parameters exclusively from fitting the experimental heavy-light spectrum. Moreover we computed all corrections within the model to order  $1/m_h$ , including mixing between nearby states with the same  $J^P$ .

Our spectrum results agree very well with the existing data in the  $D$  and  $D_s$  systems. The agreement in the  $B$  and  $B_s$  systems is also fairly good but the experimental situation for the P states is not yet completely resolved.

For example, our model predicts a spin-orbit inversion for the excited P-wave states in these systems. This agrees with the recent CLEO [14] results

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<sup>6</sup> It also suggests a possible use of chiral quark model wavefunctions to isolate excited states contributions in lattice correlation functions.

state	width (exp)	[Ref.]	$\Gamma/(g_A^8)^2$ (model)	$g_A^8$
$D^+(1\frac{1}{2}S_1)$	$96 \pm 4 \pm 22$ (keV)	[27]	143 (keV) [a]	$0.82 \pm 0.09$
$D^0(1\frac{3}{2}P_1)$	$18.9^{+4.6}_{-3.5}$		16	$1.09^{+0.12}_{-0.11}$
$D^+(1\frac{3}{2}P_1)$	$28 \pm 8$		16	$1.32^{+0.18}_{-0.27}$
$D^+(1\frac{1}{2}P_1)$	$290^{+101}_{-79} \pm 26 \pm 36$	[14]	181	$1.27 \pm 0.22$
$D^0(1\frac{3}{2}P_2)$	$23 \pm 5$		38	$0.77 \pm 0.08$
$D^+(1\frac{3}{2}P_2)$	$25 \pm 8$		38	$0.81^{+0.12}_{-0.14}$
$D_s(1\frac{3}{2}P_1)$	$\leq 2.3$		2.0	$\leq 1.07$
$D_s(1\frac{3}{2}P_2)$	$15 \pm 5$		10.9	$1.17^{+0.18}_{-0.11}$
$B(1\frac{1}{2}P_1)$	$73 \pm 44$	[12][b]	180	$0.64^{+0.17}_{-0.21}$
$B(1\frac{3}{2}P_1)$	$18^{+15}_{-13} \text{ } ^{+29}_{-23}$	[13][b]	14.0	$1.13^{+0.77}_{-1.13}$
$B(1\frac{3}{2}P_2)$	$41 \pm 43$	[12][b]	20.0	$1.43^{+0.61}_{-1.43}$

Table 11: The  $1S$  and  $1P$  heavy-light hadronic transition rates compared to experiment. All widths are in MeV unless otherwise indicated. Experimental values from PDG [11] unless otherwise indicated.

[a] Theoretical value corrected for phase space observed mass(see Table 7) and the 1.6% branching ratio to  $D^+ + \gamma$  [11].

[b] Experimental results depend strongly on model dependent assumptions.

for the  $D$  mesons; but is in disagreement with preliminary L3 results [12] for the  $B$  mesons. However, in our model we find that the splitting between the  $j_l = 1/2$  P-wave states ( $J = 0, 1$ ) more than twice as large as the splitting of the  $j_l = 3/2$  P-wave states ( $J = 1, 2$ ). which is inconsistent with the assumption of equal splitting used by L3 [12] in their analysis.

The information on the spectrum and the wavefunction was used to compute a complete list of allowed hadronic decays for these excited mesons into lower energy states with emission of a light pseudoscalar meson ( $\eta$ ,  $\pi$  or  $K$ ) and their relative branching ratios.

We also compared our model prediction for  $\langle B^* | A_\mu^*(r) | B \rangle$  with lattice results. We find good agreement between the shapes of the decay amplitudes. We used this comparison to extract a preliminary lattice determination of  $g_A^8$ , the effective coupling of the chiral quark model. We find the value  $g_A^8 = 0.53 \pm 0.11$ . Using this value for  $g_A^8$  to translate the total hadronic decay widths in physical units, we would conclude that the widths of the  $D$  meson  $P$  waves are consistently below experimental findings. Of course, the lattice results have not yet been extrapolated to the continuum.

Comparison of our results with a recent experiment measurement of the  $D^{*+}$  width [27] yields  $g_A^8 = 0.82 \pm 0.09$ . Using this value, we find much better overall agreement with experimental findings.

Finally, there is also a whole set of hadronic decays with emission of light vector mesons which we did not include in our study. For the higher excited states these transitions give an important contribution to the total physical widths. We intend to study these transitions in a future paper.

## Acknowledgment

We wish to acknowledge the authors of Ref. [24] from which we extracted the lattice data of Fig. 5. One of us, D.P., thanks G. Chiodini for stimulating discussions on experimental issues.

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## Appendix A

In order to be able to factorize the expression for the transition amplitude, Eq. (31) into radial and angular parts, it is convenient to adopt the following basis for the  $\Gamma$  matrices

$$\Gamma_\mu^{00} = \begin{pmatrix} \sigma_\mu & 0 \\ 0 & 0 \end{pmatrix}, \quad \Gamma_\mu^{01} = \begin{pmatrix} 0 & \sigma_\mu \\ 0 & 0 \end{pmatrix}, \quad (40)$$

$$\Gamma_\mu^{10} = \begin{pmatrix} 0 & 0 \\ \sigma_\mu & 0 \end{pmatrix}, \quad \Gamma_\mu^{11} = \begin{pmatrix} 0 & 0 \\ 0 & \sigma_\mu \end{pmatrix} \quad (41)$$

where  $\sigma_0$  is the  $2 \times 2$  identity and  $\sigma_i$  are the usual Pauli matrices.

In this basis we obtain simple expressions for the  $c_{\ell_x}^{ab,k}(X)$  coefficients<sup>7</sup>

$$c_{\ell_x}^{00,k}(X) = c_0 \text{tr}(\gamma^0 X \Gamma_\mu^{00}) \langle j', m', \ell' | \sigma^\mu Y_{k,m_k} | j, m, \ell \rangle \quad (43)$$

$$c_{\ell_x}^{01,k}(X) = c_0 \text{tr}(\gamma^0 X \Gamma_\mu^{01}) \langle j', m', \ell' | \sigma^\mu Y_{k,m_k} | j, m, 2j - \ell \rangle \quad (44)$$

$$c_{\ell_x}^{10,k}(X) = c_0 \text{tr}(\gamma^0 X \Gamma_\mu^{10}) \langle j', m', 2j' - \ell' | \sigma^\mu Y_{k,m_k} | j, m, \ell \rangle \quad (45)$$

$$c_{\ell_x}^{11,k}(X) = c_0 \text{tr}(\gamma^0 X \Gamma_\mu^{11}) \langle j', m', 2j' - \ell' | \sigma^\mu Y_{k,m_k} | j, m, 2j - \ell \rangle \quad (46)$$

where

$$c_0 = 4\pi(-i)^{\ell_x} \frac{\sum_s C_{j',M'-s;\frac{1}{2},s}^{J',M'} C_{j,M-s;\frac{1}{2},s}^{J,M}}{C_{\ell_x,m_x;j,M}^{J',M'}} \frac{1}{2} \quad (47)$$

For the particular case  $X = \not{p}\gamma^5$  the angular dependence from the  $\mathbf{p}$  vector disappears and we obtain the following explicit expression

$$c_{\ell_x}^{00,k}(\not{p}\gamma^5) = +c_2 |p| \langle j', \ell' | T_{\ell_x}^{(k)} | j, \ell \rangle \quad (48)$$

$$c_{\ell_x}^{01,k}(\not{p}\gamma^5) = +c_1 p_0 \langle j', \ell' | Y_k | j, 2j - \ell \rangle \quad (49)$$

$$c_{\ell_x}^{10,k}(\not{p}\gamma^5) = -c_1 p_0 \langle j', 2j' - \ell' | Y_k | j, \ell \rangle \quad (50)$$

$$c_{\ell_x}^{11,k}(\not{p}\gamma^5) = -c_2 |p| \langle j', 2j' - \ell' | T_{\ell_x}^{(k)} | j, 2j - \ell \rangle \quad (51)$$

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<sup>7</sup>In this Appendix we follow the notation of Elbaz [28] where

$$[a_1 \dots a_n] = \sqrt{(2a_1 + 1) \dots (2a_n + 1)} \quad (42)$$

with

$$c_1 = 4\pi i(-i)^{\ell_x}(-)^{j'-\frac{1}{2}+J'+\ell'-\ell+\ell_x}[J] \left\{ \begin{matrix} \ell_x & j & j' \\ \frac{1}{2} & J' & J \end{matrix} \right\} \delta_{k,\ell_x} \quad (52)$$

$$c_2 = 4\pi(-i)^k(-)^{j'-\frac{1}{2}+J'-k}[Jk] \left\{ \begin{matrix} \ell_x & j & j' \\ \frac{1}{2} & J' & J \end{matrix} \right\} \begin{pmatrix} 1 & k & \ell_\pi \\ 0 & 0 & 0 \end{pmatrix} \quad (53)$$

Explicit expressions for the Wigner-Eckart reduced tensors are

$$\langle \ell' j' \| Y_k \| \ell j \rangle = \frac{[j j' \ell \ell' k]}{\sqrt{4\pi}} (-)^{j+\ell'-\ell+1/2} \begin{pmatrix} \ell' & k & \ell \\ 0 & 0 & 0 \end{pmatrix} \left\{ \begin{matrix} k & \ell' & \ell \\ \frac{1}{2} & j & j' \end{matrix} \right\} \quad (54)$$

and

$$\langle \ell' j' \| T_{\ell_x}^{(k)} \| \ell j \rangle = \sqrt{\frac{3}{2\pi}} [j j' \ell \ell' k \ell_x] (-)^{\ell'} \begin{pmatrix} \ell' & k & \ell \\ 0 & 0 & 0 \end{pmatrix} \left\{ \begin{matrix} \frac{1}{2} & \ell' & j' \\ \frac{1}{2} & \ell & j \\ 1 & k & \ell_x \end{matrix} \right\} \quad (55)$$

Our expression for the spin structure of the decay amplitudes, reported in this Appendix, disagree with Ref. [5] in the overall phase factor. This factor does not affect their results but is relevant in case of mixing.

## Appendix B

In this appendix we list the hadronic transitions  $H' \rightarrow H + x$  for the low-lying excited states not discussed in Section 3.2. The following Tables list the transitions in decending order according to:

- The flavor of the decaying heavy meson  $H'$ ;
- Its mass;
- The decay channel.

Transitions with a branching ratio less than 1% are not reported. Some decays are marked with an asterisk. These are decays that apparently do not conserve the heavy quark spin ( $|j' - j| \leq \ell_x \leq |j' + j|$ ) but, we remind the reader, our initial and final states are physical states and therefore such decays become allowed because of mixing effects.

$$H' = D(2^{\frac{1}{2}}S_0) \quad m = 2.589 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$\pi$	1	504	14.5
$D(1^{\frac{1}{2}}P_0)$	$\pi$	0	154	7.0

$$H' = D(2^{\frac{1}{2}}S_1) \quad m = 2.692 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$\eta$	1	518	1.4
$D(1^{\frac{1}{2}}S_0)$	$\pi$	1	688	39.9
$D(1^{\frac{1}{2}}S_1)$	$\pi$	1	587	30.4
$D(1^{\frac{3}{2}}P_1)$	$\pi$	2	225	1.9
$D(1^{\frac{1}{2}}P_1)$	$\pi$	0	141	6.2
$D_s(1^{\frac{1}{2}}S_0)$	$K$	1	460	5.6

$$H' = D(1^{\frac{5}{2}}D_2) \quad m = 2.775 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$\pi$	3	652	20.1
$D(1^{\frac{1}{2}}P_0)$	$\pi$	2	347	7.3
$D(1^{\frac{3}{2}}P_1)$	$\pi$	2	308	4.3
$D(1^{\frac{3}{2}}P_2)$	$\pi$	2	266	1.4
$D(1^{\frac{1}{2}}P_1)$	$\pi$	2	236	1.3
$D_s(1^{\frac{1}{2}}S_1)$	$K$	3	387	0.5

$$H' = D(1^{\frac{3}{2}}D_1) \quad m = 2.795 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$\eta$	1	620	4.0
$D(1^{\frac{1}{2}}S_0)$	$\pi$	1	764	18.6
$D(1^{\frac{1}{2}}S_1)$	$\pi$	1	668	6.8
$D(1^{\frac{3}{2}}P_1)$	$\pi$	0	328	87.2
$D(1^{\frac{3}{2}}P_1)$	$\pi$	2	328	2.4
$D(1^{\frac{3}{2}}P_2)$	$\pi$	2	286	1.4
$D_s(1^{\frac{1}{2}}S_0)$	$K$	1	566	15.0
$D_s(1^{\frac{1}{2}}S_1)$	$K$	1	412	3.3

$$H' = D(1^{\frac{5}{2}}D_3) \quad m = 2.799 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$\eta$	3	624	0.7
$D(1^{\frac{1}{2}}S_0)$	$\pi$	3	767	18.0
$D(1^{\frac{1}{2}}S_1)$	$\pi$	3	671	13.2
$D(1^{\frac{3}{2}}P_1)$	$\pi$	2	331	2.5
$D(1^{\frac{3}{2}}P_2)$	$\pi$	2	290	5.2
$D(1^{\frac{1}{2}}P_1)$	$\pi$	2	261	3.5
$D_s(1^{\frac{1}{2}}S_0)$	$K$	3	570	2.1

$$H' = D(1^{\frac{3}{2}}D_2) \quad m = 2.833 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$\eta$	1	528	4.4
$D(1^{\frac{1}{2}}S_1)$	$\pi$	1	697	22.9
$D(1^{\frac{1}{2}}P_0)$	$\pi$	2	400	1.5
$D(1^{\frac{3}{2}}P_1)$	$\pi$	2	363	3.6
$D(1^{\frac{3}{2}}P_2)$	$\pi$	0	323	87.0
$D(1^{\frac{3}{2}}P_2)$	$\pi$	2	323	3.2
$D_s(1^{\frac{1}{2}}S_1)$	$K$	1	456	13.0

$$H' = D(2^{\frac{1}{2}}P_0) \quad m = 2.949 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$\eta$	0	756	11.7
$D(1^{\frac{1}{2}}S_0)$	$\pi$	0	875	88.0
$D(1^{\frac{3}{2}}P_1)$	$\pi$	1	467	15.2
$D(1^{\frac{1}{2}}P_1)$	$\pi$	1	403	60.6
$D(2^{\frac{1}{2}}S_0)$	$\pi$	0	311	51.9
$D_s(1^{\frac{1}{2}}S_0)$	$K$	0	706	66.6

$$H' = D(2^{\frac{3}{2}}P_1) \quad m = 2.995 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$\eta$	2	685	2.7
$D(1^{\frac{1}{2}}S_1)$	$\pi$	2	818	62.5
$D(1^{\frac{1}{2}}P_0)$	$\pi$	1	540	1.5
$D(1^{\frac{3}{2}}P_1)$	$\pi$	1	506	5.9
$D(1^{\frac{3}{2}}P_2)$	$\pi$	3	470	4.0
$D(1^{\frac{1}{2}}P_1)$	$\pi$	1	444	3.9
$D(2^{\frac{1}{2}}S_1)$	$\pi$	2	255	5.1
$D(1^{\frac{3}{2}}D_1)$	$\pi$	0	138	3.8
$D_s(1^{\frac{1}{2}}S_1)$	$K$	2	620	9.9



$$H' = D(2^{\frac{3}{2}}P_2) \quad m = 3.035 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$\eta$	2	828	3.3
$D(1^{\frac{1}{2}}S_0)$	$\pi$	2	936	53.4
$D(1^{\frac{1}{2}}S_1)$	$\eta$	2	721	2.3
$D(1^{\frac{1}{2}}S_1)$	$\pi$	2	848	47.1
$D(1^{\frac{3}{2}}P_1)$	$\pi$	3	541	4.3
$D(1^{\frac{3}{2}}P_2)$	$\pi$	1	505	4.2
$D(1^{\frac{3}{2}}P_2)$	$\pi$	3	505	2.2
$D(1^{\frac{1}{2}}P_1)$	$\pi$	1	480	6.1
$D(2^{\frac{1}{2}}S_0)$	$\pi$	2	393	10.8
$D(2^{\frac{1}{2}}S_1)$	$\pi$	2	296	5.8
$D(1^{\frac{3}{2}}D_2)$	$\pi$	0	142	3.9
$D_s(1^{\frac{1}{2}}S_0)$	$K$	2	779	15.3
$D_s(1^{\frac{1}{2}}S_1)$	$K$	2	658	8.7

$$H' = D(2^{\frac{1}{2}}P_1) \quad m = 3.045 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$\eta$	0	730	10.9
$D(1^{\frac{1}{2}}S_1)$	$\pi$	0	855	85.4
$D(1^{\frac{1}{2}}P_0)$	$\pi$	1	582	61.0
$D(1^{\frac{3}{2}}P_1)$	$\pi$	1	549	6.6
$D(1^{\frac{3}{2}}P_2)$	$\pi$	1	513	19.9
$D(1^{\frac{1}{2}}P_1)$	$\pi$	1	488	61.5
$D(2^{\frac{1}{2}}S_1)$	$\pi$	0	306	50.6
$D_s(1^{\frac{1}{2}}S_1)$	$K$	0	667	59.3

$$H' = D(1^{\frac{7}{2}}F_3) \quad m = 3.074 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$\eta$	4	754	0.5
$D(1^{\frac{1}{2}}S_1)$	$\pi$	4	875	13.1
$D(1^{\frac{1}{2}}P_0)$	$\pi$	3	606	11.4
$D(1^{\frac{3}{2}}P_1)$	$\pi$	3	573	7.3
$D(1^{\frac{3}{2}}P_2)$	$\pi$	3	538	3.8
$D(1^{\frac{1}{2}}P_1)$	$\pi$	3	513	5.0
$D(1^{\frac{5}{2}}D_2)$	$\pi$	2	251	2.9
$D(1^{\frac{3}{2}}D_1)$	$\pi$	2	230	3.3
$D_s(1^{\frac{1}{2}}S_1)$	$K$	4	693	1.5

$$H' = D(1^{\frac{7}{2}}F_4) \quad m = 3.091 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$\eta$	4	872	0.6
$D(1^{\frac{1}{2}}S_0)$	$\pi$	4	974	9.8
$D(1^{\frac{1}{2}}S_1)$	$\pi$	4	887	7.8
$D(1^{\frac{3}{2}}P_1)$	$\pi$	3	587	4.4
$D(1^{\frac{3}{2}}P_2)$	$\pi$	3	552	9.9
$D(1^{\frac{1}{2}}P_1)$	$\pi$	3	527	9.6
$D(1^{\frac{5}{2}}D_2)$	$\pi$	2	268	0.6
$D(1^{\frac{5}{2}}D_3)$	$\pi$	2	244	2.9
$D(1^{\frac{3}{2}}D_2)$	$\pi$	2	208	2.4
$D_s(1^{\frac{1}{2}}S_0)$	$K$	4	824	2.0
$D_s(1^{\frac{1}{2}}S_1)$	$K$	4	707	0.9

$$H' = D(1^{\frac{5}{2}}F_2) \quad m = 3.101 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$\pi$	2	981	3.7
$D(1^{\frac{1}{2}}S_1)$	$\pi$	2	895	1.8
$D(1^{\frac{3}{2}}P_1)$	$\eta$	1	362	3.7
$D(1^{\frac{3}{2}}P_1)$	$\pi$	1	595	22.2
$D(1^{\frac{3}{2}}P_1)$	$\pi$	3	595	1.4
$D(1^{\frac{3}{2}}P_2)$	$\pi$	1	560	2.2
$D(1^{\frac{3}{2}}P_2)$	$\pi$	3	560	2.1
$D(1^{\frac{1}{2}}P_1)$	$\pi$	3	536	2.6
$D(1^{\frac{5}{2}}D_2)$	$\pi$	0	279	56.8
$D(1^{\frac{5}{2}}D_2)$	$\pi$	2	279	3.4
$D_s(1^{\frac{1}{2}}S_0)$	$K$	2	832	3.1
$D_s(1^{\frac{1}{2}}S_1)$	$K$	2	716	1.2
$D_s(1^{\frac{3}{2}}P_1)$	$K$	1	250	6.0

$$H' = D(1^{\frac{5}{2}}F_3) \quad m = 3.123 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$\pi$	2	910	4.9
$D(1^{\frac{1}{2}}P_0)$	$\pi$	3	645	4.3
$D(1^{\frac{3}{2}}P_1)$	$\pi$	3	613	3.2
$D(1^{\frac{3}{2}}P_2)$	$\eta$	1	332	3.4
$D(1^{\frac{3}{2}}P_2)$	$\pi$	1	579	23.7
$D(1^{\frac{3}{2}}P_2)$	$\pi$	3	579	2.6
$D(1^{\frac{1}{2}}P_1)$	$\pi$	3	554	1.2
$D(1^{\frac{5}{2}}D_2)$	$\pi$	2	300	1.2
$D(1^{\frac{5}{2}}D_3)$	$\pi$	0	277	56.7
$D(1^{\frac{5}{2}}D_3)$	$\pi$	2	277	3.6
$D_s(1^{\frac{1}{2}}S_1)$	$K$	2	735	3.3
$D_s(1^{\frac{3}{2}}P_2)$	$K$	1	203	3.7

$$H' = D(3^{\frac{1}{2}}S_0) \quad m = 3.141 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$\eta$	1	811	1.7
$D(1^{\frac{1}{2}}S_1)$	$\pi$	1	923	44.5
$D(1^{\frac{1}{2}}P_0)$	$\pi$	0	660	2.9
$D(1^{\frac{3}{2}}P_2)$	$\pi$	2	594	15.1
$D(2^{\frac{1}{2}}S_1)$	$\pi$	1	396	16.3
$D(2^{\frac{1}{2}}P_0)$	$\pi$	0	128	6.5
$D_s(1^{\frac{1}{2}}S_1)$	$K$	1	751	8.7
$D_s(1^{\frac{1}{2}}P_0)$	$K$	0	384	1.4

$$H' = D(3^{\frac{1}{2}}S_1) \quad m = 3.226 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$\eta$	1	976	3.2
$D(1^{\frac{1}{2}}S_0)$	$\pi$	1	1066	50.2
$D(1^{\frac{1}{2}}S_1)$	$\pi$	1	984	53.5
$D(1^{\frac{3}{2}}P_1)$	$\pi$	2	697	23.1
$D(1^{\frac{3}{2}}P_2)$	$\pi$	2	663	17.0
$D(2^{\frac{1}{2}}S_0)$	$\pi$	1	560	41.3
$D(2^{\frac{1}{2}}S_1)$	$\pi$	1	473	33.5
$D(2^{\frac{1}{2}}P_1)$	$\pi$	0	113	5.6
$D_s(1^{\frac{1}{2}}S_0)$	$K$	1	930	17.6
$D_s(1^{\frac{1}{2}}S_1)$	$K$	1	822	13.4

$$H' = D_s(2^{\frac{1}{2}}S_0) \quad m = 2.700 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$K$	1	424	3.12
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	187	0.04

$$H' = D_s(2^{\frac{1}{2}}S_1) \quad m = 2.806 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$K$	1	661	21.1
$D(1^{\frac{1}{2}}S_1)$	$K$	1	539	12.2
$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	1	540	6.2
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	371	1.5

$$H' = D_s(1^{\frac{5}{2}}D_2) \quad m = 2.900 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$K$	3	629	10.6
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	3	486	1.4

$$H' = D_s(1^{\frac{3}{2}}D_1) \quad m = 2.913 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$K$	1	752	26.1
$D(1^{\frac{1}{2}}S_1)$	$K$	1	641	10.7
$D(1^{\frac{3}{2}}P_1)$	$K$	0	47	39.7
$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	1	644	15.2
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	501	4.5

$$H' = D_s(1^{\frac{5}{2}}D_3) \quad m = 2.925 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$K$	3	762	11.4
$D(1^{\frac{1}{2}}S_1)$	$K$	3	652	7.3
$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	3	656	3.1
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	3	514	1.1

$$H' = D_s(1^{\frac{3}{2}}D_2) \quad m = 2.953 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$K$	1	677	35.0
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	543	16.4

$$H' = D_s(2^{\frac{1}{2}}P_0) \quad m = 3.067 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$K$	0	875	74.1
$D(1^{\frac{3}{2}}P_1)$	$K$	1	377	32.3
$D(1^{\frac{1}{2}}P_1)$	$K$	1	270	17.8
$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	0	780	49.1

$$H' = D_s(2^{\frac{3}{2}}P_1) \quad m = 3.114 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$K$	0	813	(*) 0.7
$D(1^{\frac{1}{2}}S_1)$	$K$	2	813	36.6
$D(1^{\frac{1}{2}}P_0)$	$K$	1	482	5.5
$D(1^{\frac{3}{2}}P_1)$	$K$	1	436	1.6
$D(1^{\frac{3}{2}}P_2)$	$K$	3	383	0.9
$D(1^{\frac{1}{2}}P_1)$	$K$	1	343	4.5
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	2	700	11.1
$D_s(1^{\frac{1}{2}}P_0)$	$\eta$	1	275	1.6

$$H' = D_s(2^{\frac{3}{2}}P_2) \quad m = 3.157 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$K$	2	943	34.9
$D(1^{\frac{1}{2}}S_1)$	$K$	2	848	28.9
$D(1^{\frac{3}{2}}P_1)$	$K$	3	485	1.8
$D(1^{\frac{1}{2}}P_1)$	$K$	1	400	11.0
$D(2^{\frac{1}{2}}S_0)$	$K$	2	255	1.3
$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	2	854	14.8
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	2	738	9.5

$$H' = D_s(2^{\frac{1}{2}}P_1) \quad m = 3.165 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$K$	0	854	72.1
$D(1^{\frac{1}{2}}P_0)$	$K$	1	537	42.6
$D(1^{\frac{3}{2}}P_1)$	$K$	1	494	12.6
$D(1^{\frac{3}{2}}P_2)$	$K$	1	446	41.3
$D(1^{\frac{1}{2}}P_1)$	$K$	1	410	28.7
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	0	745	45.1
$D_s(1^{\frac{1}{2}}P_0)$	$\eta$	1	357	8.1
$D_s(1^{\frac{3}{2}}P_1)$	$\eta$	1	280	2.7
$D_s(1^{\frac{3}{2}}P_2)$	$\eta$	1	184	3.4

$$H' = D_s(1^{\frac{7}{2}}F_3) \quad m = 3.203 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$K$	4	884	9.2
$D(1^{\frac{1}{2}}P_0)$	$K$	3	575	5.5
$D(1^{\frac{3}{2}}P_1)$	$K$	3	534	3.2
$D(1^{\frac{3}{2}}P_2)$	$K$	3	489	1.5
$D(1^{\frac{1}{2}}P_1)$	$K$	3	456	1.6
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	4	778	2.2
$D_s(1^{\frac{1}{2}}P_0)$	$\eta$	3	409	0.5

$$H' = D_s(1^{\frac{7}{2}}F_4) \quad m = 3.220 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$K$	4	990	7.2
$D(1^{\frac{1}{2}}S_1)$	$K$	4	897	5.6
$D(1^{\frac{3}{2}}P_1)$	$K$	3	552	2.0
$D(1^{\frac{3}{2}}P_2)$	$K$	3	508	4.0
$D(1^{\frac{1}{2}}P_1)$	$K$	3	475	3.3
$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	4	904	2.4
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	4	793	1.4

$$H' = D_s(1^{\frac{5}{2}}F_2) \quad m = 3.224 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$K$	2	993	5.4
$D(1^{\frac{1}{2}}S_1)$	$K$	2	900	3.1
$D(1^{\frac{3}{2}}P_1)$	$K$	1	556	39.1
$D(1^{\frac{3}{2}}P_2)$	$K$	3	556	0.9
$D(1^{\frac{1}{2}}P_2)$	$K$	1	512	4.0
$D(1^{\frac{3}{2}}P_2)$	$K$	3	512	1.1
$D(1^{\frac{1}{2}}P_1)$	$K$	3	480	0.9
$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	2	907	3.1
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	2	796	1.5
$D_s(1^{\frac{3}{2}}P_1)$	$\eta$	1	372	14.0
$D_s(1^{\frac{3}{2}}P_2)$	$\eta$	1	302	0.9

$$H' = D_s(1^{\frac{5}{2}}F_3) \quad m = 3.247 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$K$	2	918	8.2
$D(1^{\frac{1}{2}}P_0)$	$K$	3	619	2.2
$D(1^{\frac{3}{2}}P_1)$	$K$	3	580	2.0
$D(1^{\frac{3}{2}}P_2)$	$K$	1	536	42.2
$D(1^{\frac{3}{2}}P_2)$	$K$	3	536	1.5
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	2	815	3.9
$D_s(1^{\frac{3}{2}}P_2)$	$\eta$	1	339	12.6

$$H' = D_s(3^{\frac{1}{2}}S_0) \quad m = 3.259 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_1)$	$K$	1	927	19.0
$D(1^{\frac{1}{2}}P_0)$	$K$	0	630	2.1
$D(1^{\frac{3}{2}}P_2)$	$K$	2	549	5.1
$D(2^{\frac{1}{2}}S_1)$	$K$	1	254	1.0
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	825	6.8
$D_s(1^{\frac{1}{2}}P_0)$	$\eta$	0	478	0.9

$$H' = D_s(3^{\frac{1}{2}}S_1) \quad m = 3.345 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$D(1^{\frac{1}{2}}S_0)$	$K$	1	1080	28.0
$D(1^{\frac{1}{2}}S_1)$	$K$	1	993	26.6
$D(1^{\frac{3}{2}}P_1)$	$K$	2	675	12.2
$D(1^{\frac{3}{2}}P_2)$	$K$	2	635	8.1
$D(1^{\frac{1}{2}}P_1)$	$K$	0	607	1.8
$D(2^{\frac{1}{2}}S_0)$	$K$	1	507	18.8
$D(2^{\frac{1}{2}}S_1)$	$K$	1	385	8.4
$D_s(1^{\frac{1}{2}}S_0)$	$\eta$	1	1001	13.6
$D_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	896	10.6
$D_s(1^{\frac{3}{2}}P_1)$	$\eta$	2	523	1.7
$D_s(2^{\frac{1}{2}}S_0)$	$\eta$	1	309	1.7

$$H' = B(2^{\frac{1}{2}}S_0) \quad m = 5.886 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$\pi$	1	519	21.9
$B(1^{\frac{1}{2}}P_0)$	$\pi$	0	114	4.9

$$H' = B(2^{\frac{1}{2}}S_1) \quad m = 5.920 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$\pi$	1	591	19.2
$B(1^{\frac{1}{2}}S_1)$	$\pi$	1	550	22.9
$B(1^{\frac{3}{2}}P_1)$	$\pi$	2	167	0.5
$B(1^{\frac{1}{2}}P_1)$	$\pi$	0	109	4.6

$$H' = B(1^{\frac{5}{2}}D_2) \quad m = 5.985 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$\pi$	3	611	17.4
$B(1^{\frac{3}{2}}P_1)$	$\pi$	2	244	1.8
$B(1^{\frac{1}{2}}P_0)$	$\pi$	2	237	1.6
$B(1^{\frac{3}{2}}P_2)$	$\pi$	2	228	0.7
$B(1^{\frac{1}{2}}P_1)$	$\pi$	2	195	0.5

$$H' = B(1^{\frac{5}{2}}D_3) \quad m = 5.993 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$\pi$	3	658	11.1
$B(1^{\frac{1}{2}}S_1)$	$\pi$	3	618	10.6
$B(1^{\frac{3}{2}}P_1)$	$\pi$	2	252	0.6
$B(1^{\frac{3}{2}}P_2)$	$\pi$	2	237	2.2
$B(1^{\frac{1}{2}}P_1)$	$\pi$	2	204	1.3

$$H' = B(1^{\frac{3}{2}}D_1) \quad m = 6.025 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$\eta$	1	475	2.8
$B(1^{\frac{1}{2}}S_1)$	$\pi$	1	687	18.2
$B(1^{\frac{1}{2}}S_1)$	$\pi$	1	647	7.5
$B(1^{\frac{3}{2}}P_1)$	$\pi$	0	286	81.4
$B(1^{\frac{3}{2}}P_1)$	$\pi$	2	286	1.4
$B_s(1^{\frac{1}{2}}S_0)$	$K$	1	403	7.2
$B_s(1^{\frac{1}{2}}S_1)$	$K$	1	330	2.0

$$H' = B(1^{\frac{3}{2}}D_2) \quad m = 6.037 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$\eta$	1	431	3.3
$B(1^{\frac{1}{2}}S_1)$	$\pi$	1	658	23.9
$B(1^{\frac{3}{2}}P_1)$	$\pi$	2	299	1.3
$B(1^{\frac{3}{2}}P_2)$	$\pi$	0	284	81.1
$B(1^{\frac{3}{2}}P_2)$	$\pi$	2	284	2.0
$B_s(1^{\frac{1}{2}}S_1)$	$K$	1	350	7.1

$$H' = B(2^{\frac{1}{2}}P_0) \quad m = 6.163 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$\eta$	0	643	9.9
$B(1^{\frac{1}{2}}S_0)$	$\pi$	0	810	97.4
$B(1^{\frac{3}{2}}P_1)$	$\pi$	1	425	21.1
$B(1^{\frac{1}{2}}P_1)$	$\pi$	1	383	52.9
$B(2^{\frac{1}{2}}S_0)$	$\pi$	0	233	39.6
$B_s(1^{\frac{1}{2}}S_0)$	$K$	0	576	51.0

$$H' = B(2^{\frac{3}{2}}P_1) \quad m = 6.175 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$\eta$	2	606	1.5
$B(1^{\frac{1}{2}}S_1)$	$\pi$	2	782	59.6
$B(1^{\frac{3}{2}}P_1)$	$\pi$	1	437	1.6
$B(1^{\frac{1}{2}}P_0)$	$\pi$	1	431	2.4
$B(1^{\frac{3}{2}}P_2)$	$\pi$	3	423	2.6
$B(1^{\frac{1}{2}}P_1)$	$\pi$	1	395	3.4
$B(2^{\frac{1}{2}}S_1)$	$\pi$	2	209	2.3
$B(1^{\frac{3}{2}}D_1)$	$\pi$	0	55	1.4
$B_s(1^{\frac{1}{2}}S_1)$	$K$	2	534	4.6

$$H' = B(2^{\frac{3}{2}}P_2) \quad m = 6.188 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$\eta$	2	671	1.2
$B(1^{\frac{1}{2}}S_0)$	$\pi$	2	832	36.0
$B(1^{\frac{1}{2}}S_1)$	$\eta$	2	621	1.1
$B(1^{\frac{1}{2}}S_1)$	$\pi$	2	793	39.7
$B(1^{\frac{3}{2}}P_1)$	$\pi$	3	449	2.2
$B(1^{\frac{3}{2}}P_2)$	$\pi$	3	436	1.2
$B(1^{\frac{1}{2}}P_1)$	$\pi$	1	408	5.7
$B(2^{\frac{1}{2}}S_0)$	$\pi$	2	261	2.4
$B(2^{\frac{1}{2}}S_1)$	$\pi$	2	224	1.9
$B(1^{\frac{3}{2}}D_2)$	$\pi$	0	57	1.5
$B_s(1^{\frac{1}{2}}S_0)$	$K$	2	605	4.2
$B_s(1^{\frac{1}{2}}S_1)$	$K$	2	550	3.4

$$H' = B(2^{\frac{1}{2}}P_1) \quad m = 6.194 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$\eta$	0	629	9.2
$B(1^{\frac{1}{2}}S_1)$	$\pi$	0	799	93.2
$B(1^{\frac{3}{2}}P_1)$	$\pi$	1	455	6.1
$B(1^{\frac{1}{2}}P_0)$	$\pi$	1	449	30.6
$B(1^{\frac{3}{2}}P_2)$	$\pi$	1	442	22.6
$B(1^{\frac{1}{2}}P_1)$	$\pi$	1	414	39.5
$B(2^{\frac{1}{2}}S_1)$	$\pi$	0	231	38.7
$B_s(1^{\frac{1}{2}}S_1)$	$K$	0	557	46.3

$$H' = B(1^{\frac{7}{2}}F_3) \quad m = 6.220 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$\eta$	4	659	0.3
$B(1^{\frac{1}{2}}S_1)$	$\pi$	4	822	11.7
$B(1^{\frac{3}{2}}P_1)$	$\pi$	3	481	3.5
$B(1^{\frac{1}{2}}P_0)$	$\pi$	3	475	3.8
$B(1^{\frac{3}{2}}P_2)$	$\pi$	3	468	1.9
$B(1^{\frac{1}{2}}P_1)$	$\pi$	3	440	2.1
$B(1^{\frac{5}{2}}D_2)$	$\pi$	2	186	0.8
$B(1^{\frac{3}{2}}D_1)$	$\pi$	2	135	0.3
$B_s(1^{\frac{1}{2}}S_1)$	$K$	4	588	0.5

$$H' = B(1^{\frac{7}{2}}F_4) \quad m = 6.226 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$\pi$	4	865	7.0
$B(1^{\frac{1}{2}}S_1)$	$\pi$	4	827	6.7
$B(1^{\frac{3}{2}}P_1)$	$\pi$	3	486	1.5
$B(1^{\frac{3}{2}}P_2)$	$\pi$	3	473	4.7
$B(1^{\frac{1}{2}}P_1)$	$\pi$	3	445	4.4
$B(1^{\frac{5}{2}}D_3)$	$\pi$	2	183	0.8
$B_s(1^{\frac{1}{2}}S_0)$	$K$	4	647	0.5
$B_s(1^{\frac{1}{2}}S_1)$	$K$	4	594	0.3

$$H' = B(1^{\frac{5}{2}}F_2) \quad m = 6.264 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$\pi$	2	898	3.7
$B(1^{\frac{1}{2}}S_1)$	$\pi$	2	860	2.0
$B(1^{\frac{3}{2}}P_1)$	$\pi$	1	522	18.9
$B(1^{\frac{3}{2}}P_2)$	$\pi$	1	509	2.0
$B(1^{\frac{3}{2}}P_2)$	$\pi$	3	509	1.3
$B(1^{\frac{1}{2}}P_1)$	$\pi$	3	482	1.3
$B(1^{\frac{5}{2}}D_2)$	$\pi$	0	236	51.2
$B(1^{\frac{5}{2}}D_2)$	$\pi$	2	236	1.6
$B_s(1^{\frac{1}{2}}S_0)$	$K$	2	688	1.9
$B_s(1^{\frac{1}{2}}S_1)$	$K$	2	637	0.9

$$H' = B(1^{\frac{5}{2}}F_3) \quad m = 6.271 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$\eta$	2	714	1.0
$B(1^{\frac{1}{2}}S_1)$	$\pi$	2	866	5.2
$B(1^{\frac{3}{2}}P_1)$	$\pi$	3	529	1.2
$B(1^{\frac{1}{2}}P_0)$	$\pi$	3	523	1.0
$B(1^{\frac{3}{2}}P_2)$	$\pi$	1	516	20.4
$B(1^{\frac{3}{2}}P_2)$	$\pi$	3	516	1.5
$B(1^{\frac{5}{2}}D_3)$	$\pi$	0	235	51.0
$B(1^{\frac{5}{2}}D_3)$	$\pi$	2	235	1.7
$B_s(1^{\frac{1}{2}}S_1)$	$K$	2	644	2.3

$$H' = B(3^{\frac{1}{2}}S_0) \quad m = 6.320 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$\eta$	1	766	1.1
$B(1^{\frac{1}{2}}S_1)$	$\pi$	1	908	49.5
$B(1^{\frac{1}{2}}P_0)$	$\pi$	0	569	1.8
$B(1^{\frac{3}{2}}P_2)$	$\pi$	2	562	11.0
$B(2^{\frac{1}{2}}S_1)$	$\pi$	1	363	9.5
$B(2^{\frac{1}{2}}P_0)$	$\pi$	0	72	3.5
$B_s(1^{\frac{1}{2}}S_1)$	$K$	1	697	5.1

$$H' = B(3^{\frac{1}{2}}S_1) \quad m = 6.347 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$\pi$	1	970	31.3
$B(1^{\frac{1}{2}}S_1)$	$\pi$	1	932	43.0
$B(1^{\frac{3}{2}}P_1)$	$\pi$	2	600	9.4
$B(1^{\frac{3}{2}}P_2)$	$\pi$	2	587	7.9
$B(1^{\frac{1}{2}}P_1)$	$\pi$	0	560	1.7
$B(2^{\frac{1}{2}}S_0)$	$\pi$	1	423	9.3
$B(2^{\frac{1}{2}}S_1)$	$\pi$	1	390	10.8
$B(2^{\frac{1}{2}}P_1)$	$\pi$	0	64	3.0
$B_s(1^{\frac{1}{2}}S_0)$	$K$	1	775	5.0
$B_s(1^{\frac{1}{2}}S_1)$	$K$	1	726	5.2

$$H' = B_s(2^{\frac{1}{2}}S_0) \quad m = 5.985 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$K$	1	416	3.15

$$H' = B_s(2^{\frac{1}{2}}S_1) \quad m = 6.019 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$K$	1	517	5.6
$B(1^{\frac{1}{2}}S_1)$	$K$	1	462	4.9
$B_s(1^{\frac{1}{2}}S_0)$	$\eta$	1	325	0.4

$$H' = B_s(1^{\frac{5}{2}}D_2) \quad m = 6.095 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$K$	3	555	6.62
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	3	370	0.30

$$H' = B_s(1^{\frac{5}{2}}D_3) \quad m = 6.103 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$K$	3	614	5.03
$B(1^{\frac{1}{2}}S_1)$	$K$	3	564	4.17
$B_s(1^{\frac{1}{2}}S_0)$	$\eta$	3	453	0.46
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	3	383	0.21

$$H' = B_s(1^{\frac{3}{2}}D_1) \quad m = 6.127 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$K$	1	641	26.9
$B(1^{\frac{1}{2}}S_1)$	$K$	1	592	11.5
$B_s(1^{\frac{1}{2}}S_0)$	$\eta$	1	486	10.1
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	420	3.4

$$H' = B_s(1^{\frac{3}{2}}D_2) \quad m = 6.140 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$K$	1	607	36.2
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	438	11.5

$$H' = B_s(2^{\frac{1}{2}}P_0) \quad m = 6.264 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$K$	0	785	77.7
$B(1^{\frac{3}{2}}P_1)$	$K$	1	262	20.6
$B(1^{\frac{1}{2}}P_1)$	$K$	1	164	3.8
$B_s(1^{\frac{1}{2}}S_0)$	$\eta$	0	652	40.5

$$H' = B_s(2^{\frac{3}{2}}P_1) \quad m = 6.278 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$K$	0	755	(*) 0.7
$B(1^{\frac{1}{2}}S_1)$	$K$	2	755	28.7
$B(1^{\frac{1}{2}}P_0)$	$K$	1	278	3.3
$B(1^{\frac{1}{2}}P_1)$	$K$	1	201	1.4
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	2	614	5.8

$$H' = B_s(2^{\frac{3}{2}}P_2) \quad m = 6.292 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$K$	2	813	19.2
$B(1^{\frac{1}{2}}S_1)$	$K$	2	769	19.8
$B(1^{\frac{1}{2}}P_1)$	$K$	1	232	4.2
$B_s(1^{\frac{1}{2}}S_0)$	$\eta$	2	683	4.8
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	2	630	4.2

$$H' = B_s(2^{\frac{1}{2}}P_1) \quad m = 6.296 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$K$	0	773	73.8
$B(1^{\frac{3}{2}}P_1)$	$K$	1	319	7.0
$B(1^{\frac{1}{2}}P_0)$	$K$	1	309	9.3
$B(1^{\frac{3}{2}}P_2)$	$K$	1	296	24.5
$B(1^{\frac{1}{2}}P_1)$	$K$	1	241	6.0
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	0	634	37.1

$$H' = B_s(1^{\frac{7}{2}}F_3) \quad m = 6.332 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$K$	4	808	7.07
$B(1^{\frac{3}{2}}P_1)$	$K$	3	375	0.51
$B(1^{\frac{1}{2}}P_0)$	$K$	3	366	0.50
$B(1^{\frac{3}{2}}P_2)$	$K$	3	354	0.22
$B(1^{\frac{1}{2}}P_1)$	$K$	3	307	0.14
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	4	674	1.04

$$H' = B_s(1^{\frac{7}{2}}F_4) \quad m = 6.337 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$K$	4	857	4.5
$B(1^{\frac{1}{2}}S_1)$	$K$	4	814	4.1
$B(1^{\frac{3}{2}}P_1)$	$K$	3	383	0.2
$B(1^{\frac{3}{2}}P_2)$	$K$	3	363	0.6
$B(1^{\frac{1}{2}}P_1)$	$K$	3	317	0.3
$B_s(1^{\frac{1}{2}}S_0)$	$\eta$	4	732	0.8
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	4	681	0.6

$$H' = B_s(1^{\frac{5}{2}}F_2) \quad m = 6.369 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$K$	2	888	6.0
$B(1^{\frac{1}{2}}S_1)$	$K$	2	845	3.5
$B(1^{\frac{3}{2}}P_1)$	$K$	1	428	29.6
$B(1^{\frac{3}{2}}P_2)$	$K$	1	409	3.0
$B_s(1^{\frac{1}{2}}S_0)$	$\eta$	2	766	2.4
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	2	715	1.3
$B_s(1^{\frac{3}{2}}P_1)$	$\eta$	1	129	0.9

$$H' = B_s(1^{\frac{5}{2}}F_3) \quad m = 6.376 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$K$	2	853	9.0
$B(1^{\frac{3}{2}}P_2)$	$K$	1	420	31.6
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	2	723	3.3

$$H' = B_s(3^{\frac{1}{2}}S_0) \quad m = 6.421 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_1)$	$K$	1	896	16.5
$B(1^{\frac{1}{2}}P_0)$	$K$	0	489	0.3
$B(1^{\frac{3}{2}}P_2)$	$K$	2	479	1.7
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	770	3.9

$$H' = B_s(3^{\frac{1}{2}}S_1) \quad m = 6.449 \text{ GeV}$$

$H(n^j\ell_J)$	$x$	$\ell_x$	$p_x$	$\Gamma_x/(g_A^8)^2$
$B(1^{\frac{1}{2}}S_0)$	$K$	1	963	13.2
$B(1^{\frac{1}{2}}S_1)$	$K$	1	922	16.0
$B(1^{\frac{3}{2}}P_1)$	$K$	2	531	2.2
$B(1^{\frac{3}{2}}P_2)$	$K$	2	514	1.7
$B_s(1^{\frac{1}{2}}S_0)$	$\eta$	1	848	3.9
$B_s(1^{\frac{1}{2}}S_1)$	$\eta$	1	800	4.1

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