Threshold effects in P-wave charmed-strange and bottom-strange mesons

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P.G. Ortega (Valencia), D.R. Entem (Salamanca) and F. Fernández (Salamanca).

The heavy-light meson sectors were reasonably well understood in the $m_Q \to \infty$ limit

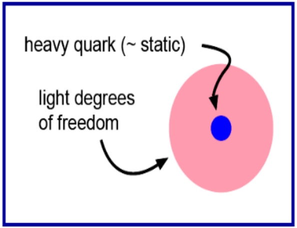
☞ *Heavy Quark Symmetry (HQS) holds*

N. Isgur and M.B. Wise, Phys. Rev. Lett. 66 (1991) 1130.

☞ The heavy quark acts as a static color source, its s_Q is decoupled from j_q and they are separately conserved.

☞ The heavy-light mesons can be organized in doublets, each one corresponding to a particular value of j_q and parity.

☞ The members of each doublet differ on the orientation of s_Q with respect to j_q. Mass degeneracy is broken at $1/m_Q$.



☞ For **the lowest P-wave heavy-light mesons** HQS predicts two doublets which are labeled by:

- $j_q^P = 1/2^+$ with $J^P = 0^+, 1^+$,
- $j_q^P = 3/2^+$ with $J^P = 1^+, 2^+$.

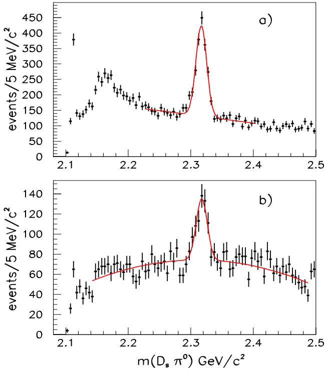
☞ The **strong decays** of the:

- $Q\bar{q}\,(j_q = 1/2)$ proceed only through S-waves $\Rightarrow$ Broad states.
- $Q\bar{q}\,(j_q = 3/2)$ proceed only through D-waves $\Rightarrow$ Narrow states.

The discovery of the $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$ mesons

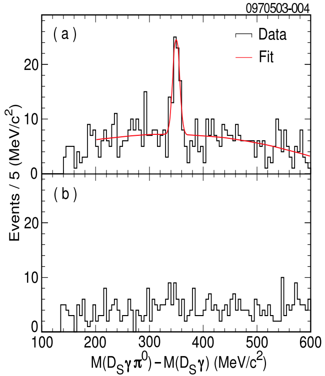
The $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$ mesons are considered to be members of the $j_q^P = 1/2^+$ doublet and thus being almost degenerated and broad.

B. Aubert *et al.*, PRL 90 (2003) 242001



- Quantum numbers: $J^P = 0^+$.
- Mass: $(2318.0 \pm 1.0)\,\mathrm{MeV}$.
- Width: $< 3.8\,\mathrm{MeV}$.
- $m_{D_{s0}^{*}(2317)} - m_{DK} \approx -45\,\mathrm{MeV}$.

D. Besson *et al.*, PRD 68 (2003) 032002



- Quantum numbers: $J^P = 1^+$.
- Mass: $(2459.6 \pm 0.9)\,\mathrm{MeV}$.
- Width: $< 3.5\,\mathrm{MeV}$.
- $m_{D_{s1}(2460)} - m_{D^* K} \approx -45\,\mathrm{MeV}$.

Theoretical interpretations

Results leading to many theoretical speculations about the nature of these resonances

- Conventional charmed-strange states

  Fayyazuddin:2003aa, Sadzikowski:2003jy, Lakhina:2006fy, Green:2016occ...

- Molecular or compact tetraquark interpretations

  Barnes:2003dj, Lipkin:2003zk, Szczepaniak:2003vy, Browder:2003fk, Nussinov:2003uj, Bicudo:2004dx, Dmitrasinovic:2005gc...

- Dynamical resonances in coupled-channels calculations

  Gamermann:2006nm, Gamermann:2007fi, MartinezTorres:2011pr, Doring:2011ip, Liu:2012zya, Guo:2015dha...

- **Particularly relevant suggestion:** The coupling of the $J^P = 0^+$ (1^+) $c\bar{s}$ state to the DK (D^*K) threshold plays an important dynamical role in lowering the bare mass to the observed value.

  vanBeveren:2003kd, vanBeveren:2003jv

- **In the same line...** Lattice studies find good agreement with experiment when operators for DK and D^*K scattering states are included.

  Mohler:2013rwa, Lang:2014yfa

Study the low-lying P-wave charmed-strange mesons using a nonrelativistic constituent quark model in which quark-antiquark and meson-meson d.o.f. are incorporated

Tightly constrained:

- The quark model has been applied to a wide range of hadronic observables and thus the model parameters are completely constrained.

Vijande:2004he, Valcarce:2005em, Fernandez:1992xs, Garcilazo:2001ck, Segovia:2008zz, Segovia:2013wma...

- The coupling between quark-antiquark and meson-meson Fock components is done using a modified version of the $^3P_0$ decay model.

Ortega:2010qq, Segovia:2012cd, Ortega:2012rs...

Advantages:

- Introduce the coupling with the D-wave D^*K channel $\rightarrow$ It could play an important role in the 1^+ $c\bar{s}$ sector, in particular for the $j_q^P = 3/2^+$ D_{s1} meson.
- Compute the probabilities associated with the different Fock components of the physical state.

These features cannot be addressed nowadays by any other theoretical approach

☞ The interaction between quarks. **Constituent Quark Model (CQM)**: Confining interaction + Goldstone-boson exchanges + perturbative one-gluon exchange potential.

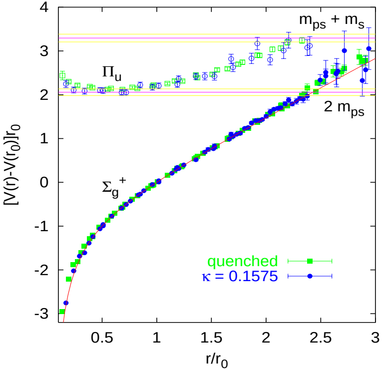
☞ The interaction between mesons. **Resonating Group Method (RGM)**: the Hamiltonian for the meson-meson states is obtained from the quark-antiquark interaction.

☞ Coupling between 1- and 2-meson states. Requires the creation of a light $q\bar{q}$-pair and thus the associated operator should be similar to the one which describes the open-flavour meson strong decays: $^3\mathbf{P}_0$ **decay model**.

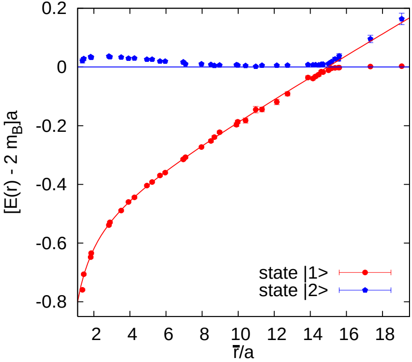
☞ Solve the coupled system.

- Perturbative way: Mass shifts, widths and mixing.
- Study the two-meson dynamics including coupling with the one-meson sector.
- Solving the coupled equations allows to obtain states above threshold.

G.S. Bali *et al.* Phys. Rep. 343 (2001) 1.



G.S. Bali *et al.* Phys. Rev. D71 (2005) 114513.



LINEAR SCREENED POTENTIAL

$$V_{\rm CON}(r) = \left[-a_c(1-e^{-\mu_c r}) + \Delta\right](\vec{\lambda}_i \cdot \vec{\lambda}_j)$$

- *Flavor independent*
- $r \to 0 \quad \Rightarrow \quad V_{\rm CON}(r) \to (-a_c\mu_c r + \Delta)(\vec{\lambda}_i \cdot \vec{\lambda}_j) \quad \Rightarrow$ *Linear.*
- $r \to \infty \quad \Rightarrow \quad V_{\rm CON}(r) \to (-a_c + \Delta)(\vec{\lambda}_i \cdot \vec{\lambda}_j) \quad \Rightarrow$ *Threshold.*

☞ QCD Lagrangian invariant under the chiral transformation

Chiral symmetry is spontanously broken

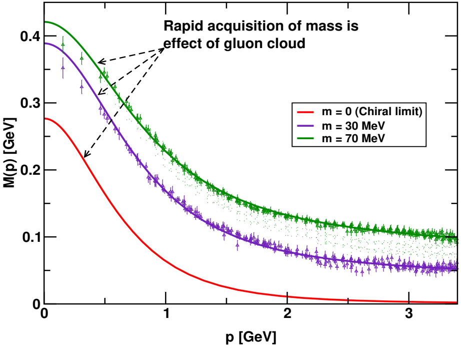
$$\mathcal{L} = \bar{\psi}\left(i\gamma^{\mu}\partial_{\mu} - M(q^2)U^{\gamma_5}\right)\psi$$

☞ Pseudo-Goldstone Bosons ($\vec{\pi}$, K_i and η_8)

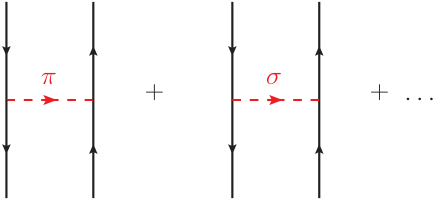
$$U^{\gamma_5} = \exp\left(i\pi^a\lambda^a\gamma_5/f_{\pi}\right)$$
$$\sim 1 + \frac{i}{f_{\pi}}\gamma^5\lambda^a\pi^a - \frac{1}{2f_{\pi}^2}\pi^a\pi^a + \ldots$$

☞ Constituent quark mass

$$M(q^2) = m_q F\left(q^2\right) = m_q \left[\frac{\Lambda^2}{\Lambda^2 + q^2}\right]^{1/2}$$



C.D. Roberts, arXiv:1109.6325v1 [nucl-th]



Beyond the chiral symmetry breaking scale

$\Downarrow$

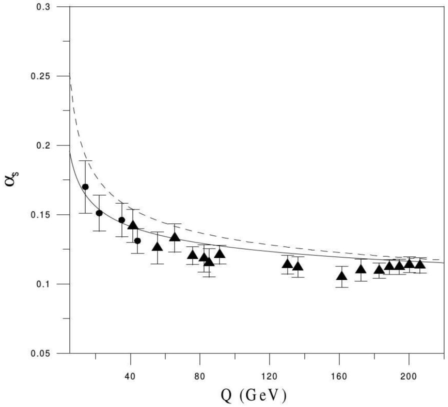
Dynamics to be governed by QCD perturbative effects

- We take them into account through the one-gluon exchange (OGE) potential.
- The OGE is a standard color Fermi-Breit interaction obtained from the vertex:

$$\mathcal{L}_{\mathrm{qqg}} = i\sqrt{4\pi\alpha_s}\,\bar{\psi}\gamma_\mu G_c^\mu \lambda^c \psi$$

- Effective scale dependent strong coupling constant:

$$\alpha_s(\mu) = \frac{\alpha_0}{\ln\left(\frac{\mu^2+\mu_0^2}{\Lambda_0^2}\right)}$$



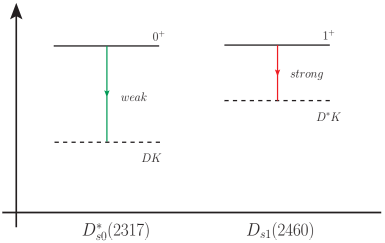
J. Vijande *et al.* J. Phys. G31 (2005) 481.

Addition of the one-loop QCD corrections to the spin-dependent terms of the potential
S.N. Gupta and S.F. Radford, Phys. Rev. D24 (1981) 2309.
O. Lakhina and E.S. Swanson, Phys. Lett. B650 (2007) 159.

- A spin-dependent term which affects only to mesons with different flavor quarks.
- The 0^+ state is more sensitive to the inclusion of the one-loop corrections.

	$j_q^P = 1/2^+$		$j_q^P = 3/2^+$	
	0^+	1^+	1^+	2^+
This work (α_s)	2510	2593	2554	2591
This work (α_s^2)	2383	2570	2560	2609
Exp.	2318.0 ± 1.0	2459.6 ± 0.9	2535.12 ± 0.25	2572.6 ± 0.9

- The potentially generated mass-shifts depend only on the energy difference between the bare $c\bar{s}$ state and the open-flavored threshold.



- The states should be degenerated.
- They should couple equally to DK and D^*K.
- **NEED OF AN EXTRA MECHANISM.**

- The 1-hadron wave function:

$$\psi_H = \phi_H(\vec{p}_{\xi_H})\,\chi_{SF}\,\xi_c$$

- The 2-hadron wave function:

$$\begin{aligned}\psi_{H_1H_2} &= \mathcal{A}\left[\chi(\vec{P})\,\psi^{SF}_{H_1H_2}\right] \\ &= \mathcal{A}\left[\phi_{H_1}(\vec{p}_{\xi_{H_1}})\,\phi_{H_2}(\vec{p}_{\xi_{H_2}})\,\chi(\vec{P})\,\chi^{SF}_{H_1H_2}\,\xi_c\right] \\ &= \int \mathcal{A}\left[\phi_{H_1}(\vec{p}_{\xi_{H_1}})\,\phi_{H_2}(\vec{p}_{\xi_{H_2}})\,\delta^{(3)}(\vec{P}-\vec{P}_i)\,Z(\vec{P}_{\rm CM})\right]\chi(\vec{P}_i)d\vec{P}_i\end{aligned}$$

- Dynamics of the bound state governed by the Schrödinger equation:

$$(\mathcal{H}-E_T)\,|\,\psi\,\rangle = 0 \quad \Leftrightarrow \quad \mathcal{H} = \sum_{i=1}^{N}\frac{\vec{p}_i^{\,2}}{2m_i} + \sum_{i<j} V_{ij} - T_{\rm CM}$$

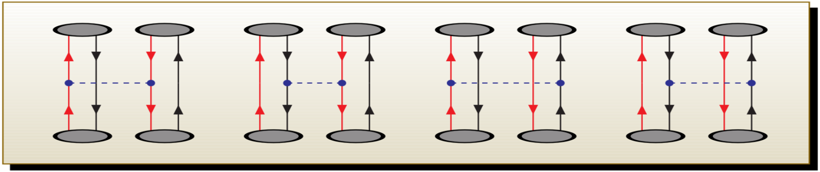
$$\left(\frac{\vec{P}'^{\,2}}{2\mu} - E\right)\chi(\vec{P}') + \int\left({}^{\rm RGM}V_D(\vec{P}',\vec{P}_i) + {}^{\rm RGM}V_E(\vec{P}',\vec{P}_i)\right)\chi(\vec{P}_i)d\vec{P}_i = 0$$

- Dynamics of the scattering state governed by the Lippmann-Schwinger equation:

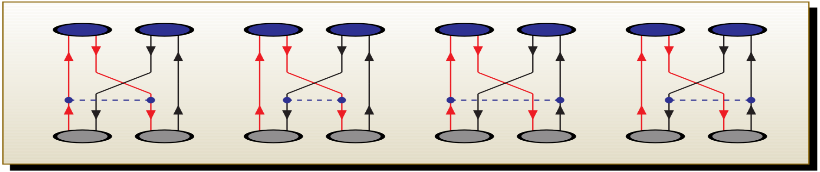
$$T_\alpha^{\alpha'}(z;p',p) = V_\alpha^{\alpha'}(p',p) + \sum_{\alpha''}\int dp''\,p''^2\,V_{\alpha''}^{\alpha'}(p',p'')\frac{1}{z-E_{\alpha''}(p'')}T_\alpha^{\alpha''}(z;p'',p)$$

$$^{RGM}V_{D(E)}(\vec{P}', \vec{P}_i) = \sum_{i\in H_1, j\in H_2} \int d\vec{p}_{\xi'_{H_1}} d\vec{p}_{\xi'_{H_2}} d\vec{p}_{\xi_{H_1}} d\vec{p}_{\xi_{H_2}} \phi^*_{H_1}(\vec{p}_{\xi'_{H_1}}) \phi^*_{H_2}(\vec{p}_{\xi'_{H_2}}) V_{ij}^{D(E)}(\vec{P}', \vec{P}_i) \phi_{H_1}(\vec{p}_{\xi_{H_1}}) \phi_{H_2}(\vec{p}_{\xi_{H_2}})$$

Direct terms



Exchange terms



Strong decay $A \to B + C$ is mediated by the creation of a $q\bar{q}$ pair from the vacuum.
– $q\bar{q}$ quantum numbers $J^{PC} = 0^{++}$ –

L. Micu, Nucl. Phys. B10 (1969) 521.
A. Le Yaouanc et al., Phys. Rev. D8 (1973) 2223.

- Pair creation Hamiltonian:

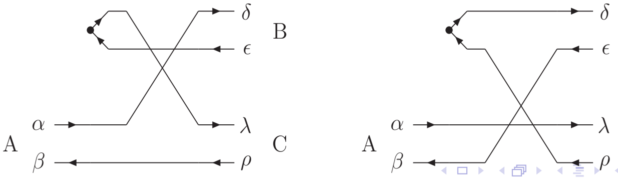
$$\mathcal{H} = \sqrt{3}\, g \int d^3x \, \bar{\psi}(\vec{x})\, \psi(\vec{x})$$

- Non-relativistic reduction:

$$\mathcal{T} = -\sqrt{3}\,\gamma' \sum_{\mu,\nu} \int d^3p\, d^3p'\, \delta^{(3)}(\vec{p}+\vec{p}\,') \left[\mathcal{Y}_1\left(\frac{\vec{p}-\vec{p}\,'}{2}\right) \otimes \left(\frac{1}{2}\,\frac{1}{2}\right) 1\right]_0 a^\dagger_\mu(\vec{p})\, b^\dagger_\nu(\vec{p}\,')$$

with $\gamma' = 2^{5/2}\pi^{1/2}\gamma$, $\gamma = \frac{g}{2m}$ (in the light quark sector).

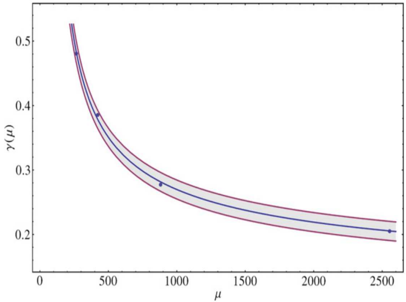
- Diagrams that contribute:



$$\gamma(\mu) = \frac{\gamma_0}{\log(\mu/\mu_\gamma)}$$

with $\gamma_0 = 0.81 \pm 0.02$
$\mu_\gamma = 49.84 \pm 2.58\,\mathrm{MeV}.$

- **Data points:** value of γ needed to reproduce the meson decay widths shown in Table.
- **Solid line:** fit; **Shaded area:** 90% confidence interval.



Meson	I	J	P	C	Mass (MeV)	$\Gamma_{\mathrm{Exp.}}$ (MeV)
$D_1(2420)^\pm$	1/2	1	+1	-	2423.4 ± 3.1	25 ± 6
$D_2^*(2460)^\pm$	1/2	2	+1	-	2460.1 ± 4.4	37 ± 6
$D_{s1}(2536)^\pm$	0	1	+1	-	2535.12 ± 0.25	1.03 ± 0.13
$D_{s2}^*(2575)^\pm$	0	2	+1	-	2572.6 ± 0.9	20 ± 5
$\psi(3770)$	0	1	−1	−1	3775.2 ± 1.7	27.6 ± 1.0
$\Upsilon(4S)$	0	1	−1	−1	10579.4 ± 1.2	20.5 ± 2.5

J. Segovia *et al.*, Phys. Lett B715 (2012) 322-327.

Global description of the total decay widths

Meson	I	J	P	C	n	Mass (MeV)	$\Gamma_{\rm Exp.}$ (MeV)	$\Gamma_{\rm The.}$ (MeV)
$D^*(2010)^\pm$	1/2	1	-1	-	1	2010.25 ± 0.14	0.096 ± 0.022	0.036
$D_0^*(2400)^\pm$	1/2	0	$+1$	-	1	2403 ± 38	283 ± 42	212.01
$D_1(2420)^\pm$	1/2	1	$+1$	-	1	2423.4 ± 3.1	25 ± 6	25.27
$D_1(2430)^0$	1/2	1	$+1$	-	2	2427 ± 36	384 ± 150	229.12
$D_2^*(2460)^\pm$	1/2	2	$+1$	-	1	2460.1 ± 4.4	37 ± 6	64.07
$D(2550)^0$	1/2	0	-1	-	2	2539.4 ± 8.2	130 ± 18	132.07
$D^*(2600)^0$	1/2	1	-1	-	2	2608.7 ± 3.5	93 ± 14	96.91
$D_J(2750)^0$	1/2	2	-1	-	1	2752.4 ± 3.2	71 ± 13	229.86
$D_J^*(2760)^0$	1/2	3	-1	-	1	2763.3 ± 3.3	60.9 ± 6.2	116.41
$D_{s1}(2536)^\pm$	0	1	$+1$	-	1	2535.12 ± 0.25	1.03 ± 0.13	0.99
$D_{s2}^*(2575)^\pm$	0	2	$+1$	-	1	2572.6 ± 0.9	20 ± 5	18.67
$D_{s1}^*(2710)^\pm$	0	1	-1	-	2	2710 ± 14	149 ± 65	170.76
$D_{sJ}^*(2860)^\pm$	0	$\begin{bmatrix}1\\3\end{bmatrix}$	-1	-	$\begin{bmatrix}3\\1\end{bmatrix}$	2862 ± 6	48 ± 7	$\begin{bmatrix}153.19\\85.12\end{bmatrix}$
$D_{sJ}(3040)^\pm$	0	1	$+1$	-	$\begin{bmatrix}3\\4\end{bmatrix}$	3044 ± 31	239 ± 71	$\begin{bmatrix}301.52\\432.54\end{bmatrix}$
$\psi(3770)$	0	1	-1	-1	3	3775.2 ± 1.7	27.6 ± 1.0	26.47
$\psi(4040)$	0	1	-1	-1	4	4039 ± 1	80 ± 10	111.27
$\psi(4160)$	0	1	-1	-1	5	4153 ± 3	103 ± 8	115.95
$X(4360)$	0	1	-1	-1	6	4361 ± 9	74 ± 18	113.92
$\psi(4415)$	0	1	-1	-1	7	4421 ± 4	119 ± 16	159.02
$X(4640)$	0	1	-1	-1	8	4634 ± 8	92 ± 52	206.37
$X(4660)$	0	1	-1	-1	9	4664 ± 11	48 ± 15	135.06
$\Upsilon(4S)$	0	1	-1	-1	6	10579.4 ± 1.2	20.5 ± 2.5	20.59
$\Upsilon(10860)$	0	1	-1	-1	8	10865 ± 8	55 ± 28	27.89
$\Upsilon(11020)$	0	1	-1	-1	10	11019 ± 8	79 ± 16	79.16

J. Segovia *et al.*, Phys. Lett B715 (2012) 322-327.

- The hadronic state:

$$|\Psi\rangle = \sum_\alpha c_\alpha |\psi_\alpha\rangle + \sum_\beta \chi_\beta(P)|\phi_A\phi_B\beta\rangle$$

- A Schrödinger-type equation for coupled-channels:

$$\begin{pmatrix} \mathcal{H}_{q\bar{q}} & \mathcal{T} \\ \mathcal{T} & \mathcal{H}_{AB} \end{pmatrix} \begin{pmatrix} \psi_\alpha \\ \psi_{AB} \end{pmatrix} = E \begin{pmatrix} \psi_\alpha \\ \psi_{AB} \end{pmatrix}$$

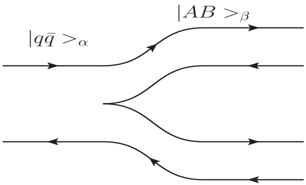
- We end-up with the coupled-channels equations:

$$c_\alpha M_\alpha + \sum_\beta \int h_{\alpha\beta}(P)\chi_\beta(P)P^2 dP = E c_\alpha$$

$$\sum_\beta \int H_{\beta'\beta}(P',P)\chi_\beta(P)P^2 dP + \sum_\alpha h_{\beta'\alpha}(P')c_\alpha = E\chi_{\beta'}(P')$$

- Transition potential:

$$\langle \phi_A\phi_B\beta|\mathcal{T}|\psi_\alpha\rangle = P\, h_{\beta\alpha}(P)\, \delta^{(3)}(\vec{P}_{\rm cm})$$



☞ Lippmann-Schwinger equation:

$$T^{\beta'\beta}(E;P',P) = V_{\rm T}^{\beta'\beta}(P',P) + \sum_{\beta''}\int dP''P''^2 V_{\rm T}^{\beta'\beta''}(P',P'')\frac{1}{E-E_{\beta''}(P'')}T^{\beta''\beta}(E;P'',P)$$

with $V_{\rm T}^{\beta'\beta}(P',P) = V_{\rm RGM}^{\beta'\beta}(P',P) + V_{\rm eff}^{\beta'\beta}(P',P)$, $V_{\beta'\beta}^{\rm eff}(P',P) = \sum_\alpha \frac{h_{\beta'\alpha}(P')h_{\alpha\beta}(P)}{E-M_\alpha}$

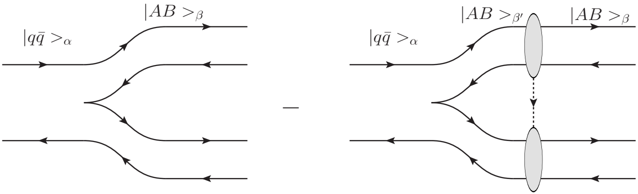
☞ Solution: (V. Baru *et al.*, Eur. Phys. J A44 (2010) 93)

$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'}\phi^{\beta'\alpha'}(E;P')\,\Delta_{\alpha'\alpha}^{-1}(E)\,\bar{\phi}^{\alpha\beta}(E;P)$$

- Non resonant contribution
- Resonant contribution

with

$$T_V^{\beta'\beta}(E;P',P) = V^{\beta'\beta}(P',P) + \sum_{\beta''}\int dP''P''^2 V^{\beta'\beta''}(P',P'')\frac{1}{E-E_{\beta''}(P'')}T_V^{\beta''\beta}(E;P'',P)$$



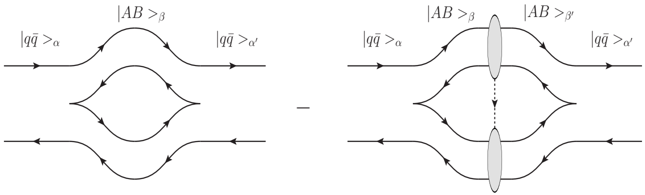
☞ Solution: (V. Baru *et al.*, Eur. Phys. J A44 (2010) 93)

$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'} \phi^{\beta'\alpha'}(E;P')\,\Delta^{-1}_{\alpha'\alpha}(E)\,\bar{\phi}^{\alpha\beta}(E;P)$$

- Non-resonant contribution
- Resonant contribution

$$\phi^{\alpha\beta'}(E;P) = h_{\alpha\beta'}(P) - \sum_{\beta}\int \frac{T_V^{\beta'\beta}(E;P,q)h_{\alpha\beta}(q)}{q^2/2\mu - E}\,q^2\,dq,$$

$$\bar{\phi}^{\alpha\beta}(E;P) = h_{\alpha\beta}(P) - \sum_{\beta'}\int \frac{h_{\alpha\beta'}(q)T_V^{\beta'\beta}(E;q,P)}{q^2/2\mu - E}\,q^2\,dq$$



☞ Solution: (V. Baru *et al.*, Eur. Phys. J A44 (2010) 93)

$$T^{\beta'\beta}(E;P',P) = T_V^{\beta'\beta}(E;P',P) + \sum_{\alpha,\alpha'} \phi^{\beta'\alpha'}(E;P')\,\Delta^{-1}_{\alpha'\alpha}(E)\,\bar{\phi}^{\alpha\beta}(E;P)$$

- Non resonant contribution
- Resonant contribution

$$\Delta^{\alpha'\alpha}(E) = \left\{(E - M_\alpha)\delta^{\alpha'\alpha} + \mathcal{G}^{\alpha'\alpha}(E)\right\}$$

$$\mathcal{G}^{\alpha'\alpha}(E) = \sum_\beta \int dq q^2 \frac{\phi^{\alpha\beta}(q,E) h_{\beta\alpha'}(q)}{q^2/2\mu - E}$$

- Resonance mass (pole position):

$$\left|\Delta^{\alpha'\alpha}(\bar{E})\right| = \left|(\bar{E} - M_\alpha)\delta^{\alpha'\alpha} + \mathcal{G}^{\alpha'\alpha}(\bar{E})\right| = 0$$

- Bare $q\bar{q}$ probabilities:

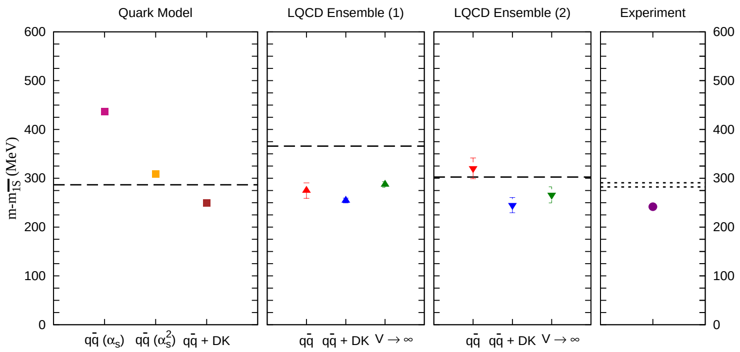
$$\left[M_\alpha \delta^{\alpha\alpha'} - \mathcal{G}^{\alpha'\alpha}(\bar{E})\right] c_{\alpha'}(\bar{E}) = \bar{E} c_\alpha(\bar{E})$$

- Molecular wave function:

$$\chi_{\beta'}(P') = -2\mu_{\beta'} \sum_\alpha \frac{\phi_{\beta'\alpha}(E;P')c_\alpha}{P'^2 - k^2_{\beta'}}$$

- Normalization:

$$\sum_\alpha |c_\alpha|^2 + \sum_\beta \langle\chi_\beta|\chi_\beta\rangle = 1$$



P.G. Ortega *et al.*, arXiv: 1603.07000 [hep-ph].

☞ Observations:

- The mass is much higher using the naive quark model and without the 1-loop corrections to the OGE potential.
- The mass-shift due to the α_s^2-corrections allows that the 0^+ state be close to the DK threshold. This makes the DK coupling a relevant dynamical mechanism.
- When we couple the 0^+ $c\bar{s}$ ground state with the DK threshold, the splitting $m_{D_{s0}^*(2317)} - m_{\overline{1S}} = 249.6\,\mathrm{MeV}$ is in good agreement with experiment.

☞ Probabilities of the different Fock components:

State	Mass	$\mathcal{P}[q\bar{q}\,(^3P_0)]$	$\mathcal{P}[DK(S-wave)]$
$D_{s0}^*(2317)$	2323.7	66.3%	33.7%

Scattering lengths are sensitive to the amount of DK in $D_{s0}^*(2317)$ wave function

However, at the moment, the theoretical errors do not allow to disentangle precisely the molecular component.

☞ Scattering length computed within our framework:

$$a(0^+) = -1.03\,\mathrm{fm}$$

☞ The numbers above can be compared with:

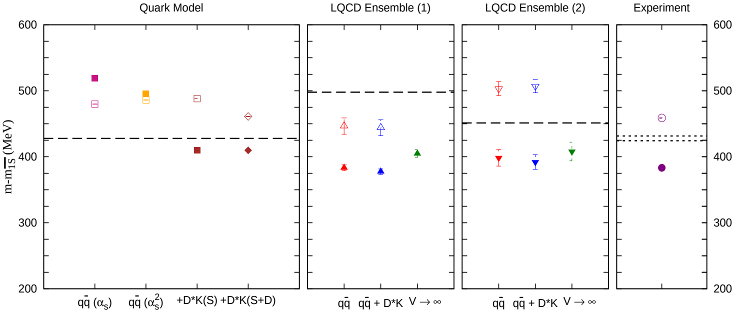
- EFT estimation: A. Martinez-Torres *et al.*, JHEP 05 (2015) 153.

$$a(0^+) = -1.3 \pm 0.5\,\mathrm{fm}$$

- LQCD estimation: C.B. Lang *et al.* Phys. Rev. D 90 (2014) 034510.

Ensemble 1: $a(0^+) = -0.756 \pm 0.025\,\mathrm{fm}$

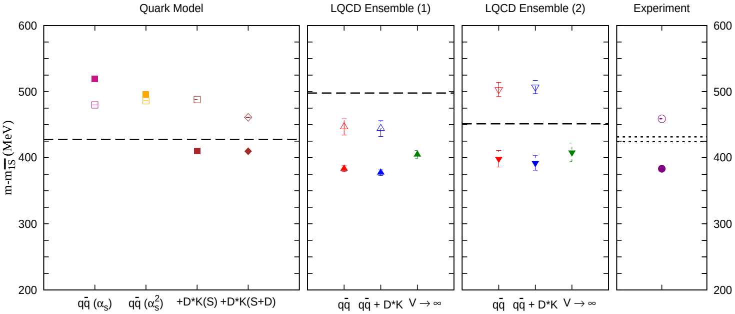
Ensemble 2: $a(0^+) = -1.33 \pm 0.20\,\mathrm{fm}$



P.G. Ortega *et al.*, arXiv: 1603.07000 [hep-ph]

☞ Observations:

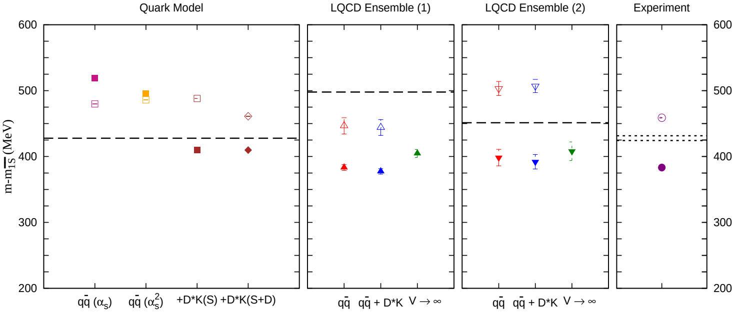
- The naive quark model predicts states almost degenerated, with masses close to the experimentally observed mass of the $D_{s1}(2536)$.
- The inclusion of the 1-loop corrections to the OGE potential does not improve the situation, making the splitting between the two states even smaller.



P.G. Ortega *et al.*, arXiv: 1603.07000 [hep-ph]

☞ Coupling the D^*K threshold in a S-wave:

- The $D_{s1}(2460)$ state goes down in the spectrum and it is located below D^*K threshold with a mass compatible with the experimental value.
- The $D_{s1}(2536)$ state is almost insensitive to this coupling $\Rightarrow |3/2, 1^+\rangle$ state $\Rightarrow$ couples mostly in a D-wave to the D^*K threshold.



P.G. Ortega *et al.*, arXiv: 1603.07000 [hep-ph]

☞ Coupling the D^*K threshold in a D-wave:

- The $D_{s1}(2460)$ meson experience a very small modification $\Rightarrow |1/2, 1^+\rangle$ state $\Rightarrow$ couples mostly in a S-wave to the D^*K.
- The state associated with $D_{s1}(2536)$ meson suffers a moderate mass-shift approaching to the experimental value.

☞ Probabilities of the different Fock components:

State	Mass	Width	$\mathcal{P}[q\bar{q}\,(^1P_1)]$	$\mathcal{P}[q\bar{q}\,(^3P_1)]$	$\mathcal{P}[D^*K(S)]$	$\mathcal{P}[D^*K(D)]$
$D_{s1}(2460)$	2484.0	0.00	12.9%	32.8%	54.3%	-
$D_{s1}(2536)$	2562.1	0.22	34.4%	15.8%	49.8%	-
$D_{s1}(2460)$	2484.0	0.00	12.1%	33.6%	54.1%	0.2%
$D_{s1}(2536)$	2535.2	0.56	31.9%	14.5%	16.8%	36.8%

Scattering lengths are sensitive to the amount of D^*K in $D_{s1}(2460)$ wave function

However, at the moment, the theoretical errors do not allow to disentangle precisely the molecular component.

☞ Scattering length computed within our framework:

$$a(1^+) = -1.11\,\text{fm}$$

☞ The numbers above can be compared with:

- EFT estimation: A. Martinez-Torres *et al.*, JHEP 05 (2015) 153.

$$a(1^+) = -1.1 \pm 0.5\,\text{fm}$$

- LQCD estimation: C.B. Lang *et al.* Phys. Rev. D 90 (2014) 034510.

Ensemble 1: $a(1^+) = -0.665 \pm 0.025\,\text{fm}$

Ensemble 2: $a(1^+) = -1.15 \pm 0.19\,\text{fm}$ (set 1) or $-1.11 \pm 0.11\,\text{fm}$ (set 2)

☞ Probabilities of the different Fock components:

State	Mass	Width	$\mathcal{P}[q\bar{q}\,(^1P_1)]$	$\mathcal{P}[q\bar{q}\,(^3P_1)]$	$\mathcal{P}[D^*K(S)]$	$\mathcal{P}[D^*K(D)]$
$D_{s1}(2460)$	2484.0	0.00	12.9%	32.8%	54.3%	-
$D_{s1}(2536)$	2562.1	0.22	34.4%	15.8%	49.8%	-
$D_{s1}(2460)$	2484.0	0.00	12.1%	33.6%	54.1%	0.2%
$D_{s1}(2536)$	2535.2	0.56	31.9%	14.5%	16.8%	36.8%

The quark-antiquark component in the wave function of the $D_{s1}(2536)$ meson holds quite well the $^1P_1$ and $^3P_1$ composition predicted by HQS.

☞ Crucial in order to have a very narrow state and describe well its decay properties

$$\Gamma(D_{s1}(2536)^+) = \Gamma(D^{*0}K^+) + \Gamma(D^{*+}K^0)$$

$$R_1 = \frac{\Gamma(D_{s1}(2536)^+ \to D^{*0}K^+)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)}$$

$$R_2 = \frac{\Gamma_S(D_{s1}(2536)^+ \to D^{*+}K^0)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)}$$

$$R_3 = \frac{\Gamma(D_{s1}(2536)^+ \to D^+\pi^-K^+)}{\Gamma(D_{s1}(2536)^+ \to D^{*+}K^0)}$$

	This work	Experiment
Γ (MeV)	0.56	$0.92 \pm 0.03 \pm 0.04$
R_1	1.15	1.18 ± 0.16
R_2	0.52	$0.72 \pm 0.05 \pm 0.01$
$R_3(\%)$	14.5	$3.27 \pm 0.18 \pm 0.37$

- The mass and total decay width of the $D_{s2}^*(2573)$ meson are predicted well in potential models and thus this state is commonly expected to be conventional.

- Mass slightly higher than the experimental one but compatible.

State	J^P	The. (α_s)	The. (α_s^2)	Exp.
$D_{s2}^*(2573)$	2^+	2592	2609	2571.9 ± 0.8

- The same reasoning was followed in Lattice QCD computations and thus only quark-antiquark basis operators were used

- They obtain also a qualitative agreement with experiment confirming that this state can be described well within the $c\bar{s}$ picture.

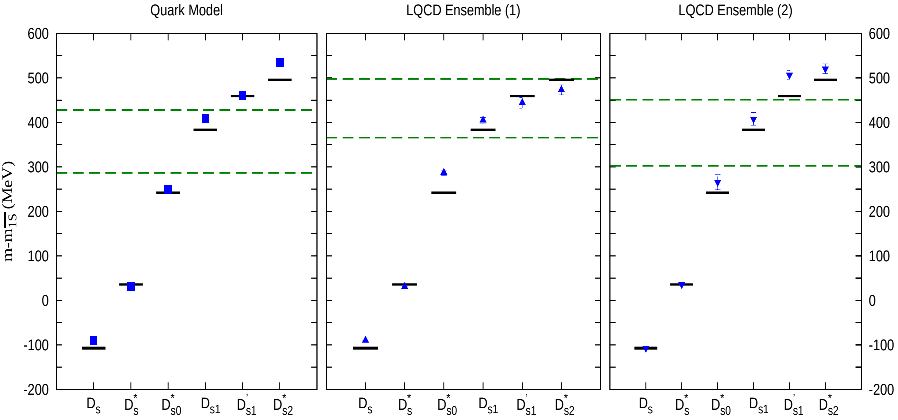
Partial and total strong decay widths

- The DK channel is clearly dominant with respect the other two possible decay channels: D^*K and $D_s\eta$.

- Mass-shift mainly given by the DK threshold. They should be in a relative D-wave and thus small shift.

Channel	$\Gamma_{^3P_0}$ (MeV)	$\mathcal{B}_{^3P_0}$ (%)	$\Gamma_{\rm exp.}$ (MeV)
D^+K^0	8.02	42.95	-
D^0K^+	8.69	46.54	-
$D^{*+}K^0$	0.82	4.40	-
$D^{*0}K^+$	1.06	5.67	-
$D_s^+\eta$	0.08	0.44	-
total	18.67	100	17 ± 4

Overall agreement between quark model, lattice QCD and experimental data



☞ Theoretical results on $D^*_{s1}(2700)$, the $D^*_{sJ}(2860)$ and the $D_{sJ}(3040)$

J. Segovia *et al.*, Phys. Rev. D 91, 094020 (2015).

It is commonly believed that the $D_{s1}^*(2700)$ is the first excitation of the D_s^* meson.

However, there is some tension between quark model predictions and experimental measurements that need to be solved.

Meson	$n\,J^P$	Channel	$\Gamma_{^3P_0}$ (MeV)	$\mathcal{B}_{^3P_0}$ (%)	$\Gamma_{\rm exp.}$ (MeV)
$D_{s1}^*(2700)$	$2\,1^-$	DK	36.99	21.67	
		D^*K	97.78	57.26	
		$D_s\eta$	3.67	2.15	
		$D_s^*\eta$	9.51	5.57	
		$D^*K_0^*$	22.80	13.35	
		total	170.75	100	125 ± 30

J. Segovia *et al.*, Phys. Lett B715 (2012) 322-327.
J. Segovia *et al.*, Phys. Rev. D91 (2015) 094020.

☞ Observations:

- The total decay width is slightly larger but close to the experimental value.
- The D^*K decay channel is dominant but the DK and $D^*K_0^*$ are also important.
- The $D_{s1}^*(2700)$ has traces in $D_s\eta$ and $D_s^*\eta$ with partial widths of several MeV.

A careful re-examination of the $\bar{D}^0 K^-$ invariant mass around $2.86\,\mathrm{GeV}$ in the decay $B_s^0 \to \bar{D}^0 K^- \pi^+$ finds that a spin-1 state and a spin-3 state overlap under the peak

Roel Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. (2014) 162001.
Roel Aaij et al. (LHCb Collaboration), Phys. Rev. D90 (2014) 072003.

Meson	$n\,J^P$	Channel	$\Gamma_{^3P_0}$ (MeV)	$\mathcal{B}_{^3P_0}$ (%)	$\Gamma_{\rm exp.}$ (MeV)
$D^*_{sJ}(2860)$	$3\,1^-$	DK	53.34	34.81	
		D^*K	38.43	25.08	
		$D_s\eta$	12.12	7.92	
		$D_s^*\eta$	5.06	3.30	
		$D^*K_0^*$	7.15	4.67	
		DK^*	37.10	24.22	
		total	153.20	100	$159 \pm 23 \pm 27 \pm 72$
$D^*_{sJ}(2860)$	$1\,3^-$	DK	38.57	45.32	
		D^*K	26.17	30.74	
		$D_s\eta$	1.06	1.24	
		$D_s^*\eta$	0.35	0.41	
		$D^*K_0^*$	16.16	18.99	
		DK^*	2.81	3.30	
		total	85.12	100	$53 \pm 7 \pm 4 \pm 6$

J. Segovia *et al.*, Phys. Lett B715 (2012) 322-327.
J. Segovia *et al.*, Phys. Rev. D91 (2015) 094020.

Meson	$n\,J^P$	Channel	$\Gamma_{^3P_0}$	$\mathcal{B}_{^3P_0}$	$\Gamma_{\rm exp.}$
$D_{sJ}(3040)$	$nJ^P = 3\,1^+$	D^*K	25.22	8.36	
		DK_0^*	0.76	0.25	
		$D_s^*\eta$	3.26	1.08	
		$D^*K_0^*$	0.02	0.01	
		DK^*	44.28	14.69	
		$D_{s0}^*\eta$	0.97	0.32	
		D_0^*K	2.81	0.93	
		D^*K^*	156.78	52.00	
		D_1K	39.81	13.20	
		$D_1'K$	0.69	0.23	
		D_2^*K	11.19	3.71	
		$D_s\phi$	15.54	5.15	
		$D_{s1}(2460)\eta$	0.19	0.07	
		total	301.52	100	$239\pm 35^{+46}_{-42}$
$D_{sJ}(3040)$	$nJ^P = 4\,1^+$	D^*K	53.48	12.37	
		DK_0^*	0.30	0.07	
		$D_s^*\eta$	4.97	1.15	
		$D^*K_0^*$	1.10	0.25	
		DK^*	100.38	23.21	
		$D_{s0}^*\eta$	1.66	0.38	
		D_0^*K	2.31	0.53	
		D^*K^*	130.91	30.27	
		D_1K	11.58	2.68	
		$D_1'K$	0.04	0.01	
		D_2^*K	123.74	28.61	
		$D_s\phi$	1.97	0.45	
		$D_{s1}(2460)\eta$	0.09	0.02	
		total	432.53	100	$239\pm 35^{+46}_{-42}$

The Bottom-strange mesons

Much of the $b\bar{s}$ excitation spectrum remains to be observed

Bottom, Strange Mesons (B = +−1, S = −+1)
B(s)0
B(s)*
B(s1)(5830)0
B(s2)*(5840)0
B(sJ)*(5850)

K.A. Olive et al. (Particle Data Group), Chin. Phys. C38 (2014) 090001.

It is expected that the situation will change in the near future thanks to the LHCb experiment and to the future high-luminosity flavour and $p-\bar{p}$ facilities.

- Address the mass-shifts, due to the $B^{(*)}K$ thresholds, of the lowest lying P-wave $b\bar{s}$ states with total spin and parity quantum numbers $J^P=0^+$, 1^+, 2^+.
- This computation is important because flavour symmetry holds in the heavy quark limit and relates same doublets that belong to different heavy quark sectors.
- As shown in the $c\bar{s}$ sector, the naive theoretical result can be wrong by more than $100\,\text{MeV}$ for the $j_q^P=1/2^+$ doublet.

Naive quark model prediction

Masses (in MeV) of the lowest-lying bottom-strange mesons

- *The original constituent quark model* (α_s).
- *Including one-loop corrections to the one-gluon exchange potential* (α_s^2).

State	J^P	The. (α_s)	The. (α_s^2)	Exp.
B_s	0^-	5348	5348	5366.7 ± 0.4
B_s^*	1^-	5393	5393	5415.8 ± 1.5
B_{s0}^*	0^+	5851	5801	-
B'_{s1}	1^+	5883	5858	-
$B_{s1}(5830)$	1^+	5841	5850	5828.40 ± 0.41
$B_{s2}^*(5840)$	2^+	5856	5867	5839.98 ± 0.20

☞ Observations:

- Our values for the B_s and B_s^* masses as well as for their hyperfine mass-splitting are in reasonable agreement with experiment.
- The masses of the $B_{s1}(5830)$ and $B_{s2}^*(5840)$ mesons which belong to the doublet $j_q^P = 3/2^+$ are slightly higher than the experimental figures but compatible.

☞ **Mass** in MeV predicted by this work and the results from various approaches:

This work: $q\bar{q}\ \mathcal{O}(\alpha_s)$		5851
This work: $q\bar{q}\ \mathcal{O}(\alpha_s^2)$		5801
This work: $q\bar{q}\ \mathcal{O}(\alpha_s^2) + BK$		5739
LQCD: $q\bar{q} + BK$	Lang:2015hza	5713(11)(19)
LQCD: $q\bar{q}$	Gregory:2010gm	5752(16)(5)(25)
Covariant (U)ChPT	Altenbuchinger:2013vwa	5726(28)
NLO UHMChPT	Cleven:2010aw	5696(20)(30)
LO UChPT	Guo:2006fu,Guo:2006rp	5725(39)
LO χ-SU(3)	Kolomeitsev:2003ac	5643
HQET + ChPT	Colangelo:2012xi	5706.6(1.2)
Bardeen, Eichten, Hill	Bardeen:2003kt	5718(35)
Relativistic quark model	DiPierro:2001dwf	5804
Relativistic quark model	Ebert:2009ua	5833
Relativistic quark model	Sun:2014wea	5830

☞ **Probabilities** in % of the different Fock components of the B_{s0}^* state:

State	Mass	$\mathcal{P}[q\bar{q}\,(^3P_0)]$	$\mathcal{P}[BK(S-wave)]$
B_{s0}^*	5739.1	60.9%	39.1%

☞ **Mass** in MeV predicted by this work and the results from various approaches:

This work: $q\bar{q}$ $\mathcal{O}(\alpha_s)$		5883	5841
This work: $q\bar{q}$ $\mathcal{O}(\alpha_s^2)$		5858	5850
This work: $q\bar{q}$ $\mathcal{O}(\alpha_s^2)$ + $B^*K(S)$		5793	5850
This work: $q\bar{q}$ $\mathcal{O}(\alpha_s^2)$ + $B^*K(S+D)$		5793	5833
LQCD: $q\bar{q}$ + $B^*K(S)$	Lang:2015hza	5750(17)(19)	
LQCD: $q\bar{q}$	Gregory:2010gm	5806(15)(5)(25)	
Covariant (U)ChPT	Altenbuchinger:2013vwa	5778(26)	
NLO UHMChPT	Cleven:2010aw	5742(20)(30)	
LO UChPT	Guo:2006fu,Guo:2006rp	5778(7)	
LO χ-SU(3)	Kolomeitsev:2003ac	5690	
HQET + ChPT	Colangelo:2012xi	5765.6(1.2)	
Bardeen, Eichten, Hill	Bardeen:2003kt	5765(35)	
Relativistic quark model	DiPierro:2001dwf	5842	
Relativistic quark model	Ebert:2009ua	5865	
Relativistic quark model	Sun:2014wea	5858	

☞ **Probabilities** in % of the different Fock components of the B'_{s1} state:

State	Mass	Width	$\mathcal{P}[q\bar{q}\,(^1P_1)]$	$\mathcal{P}[q\bar{q}\,(^3P_1)]$	$\mathcal{P}[B^*K(S)]$	$\mathcal{P}[B^*K(D)]$
B'_{s1}	5792.5	0.000	13.5%	42.3%	44.2%	-
$B_{s1}(5830)$	5850.0	0.024	37.2%	12.8%	50.0%	-
B'_{s1}	5792.5	0.000	13.2%	42.6%	44.2%	0.002%
$B_{s1}(5830)$	5832.9	0.058	35.4%	12.1%	15.9%	36.6%

We have performed a coupled-channel computation taking into account the $J^P = 0^+, 1^+, 2^+$ charmed-strange mesons and the DK and D^*K thresholds

☞ The $D_{s0}^*(2317)$ meson

- The naive quark model predicts a state much higher than the experimental value.
- The 1-loop corrections to the OGE potential brings down this level and locates it slightly above the DK threshold.
- When coupling, the level is down-shifted again towards the experimental mass which is below the DK threshold.
- We predict a probability of 34% for the DK component of the $D_{s0}^*(2317)$ wave function.

☞ The $D_{s1}(2460)$ and $D_{s1}(2536)$ mesons

- The naive quark model predicts states almost degenerated, with masses close to the experimentally observed mass of the $D_{s1}(2536)$.
- The inclusion of the 1-loop corrections to the OGE potential does not improve the situation, making the splitting between the two states even smaller.
- Coupling the D^*K threshold in a S-wave: The $D_{s1}(2460)$ state goes down in the spectrum and it is located below D^*K threshold.
- Coupling the D^*K threshold in a D-wave: The state associated with $D_{s1}(2536)$ meson suffers a moderate mass-shift approaching to the experimental value.

We have performed a coupled-channel computation taking into account the $J^P = 0^+, 1^+, 2^+$ bottom-strange mesons and the BK and B^*K thresholds

The B_{s0}^* meson

- The naive quark model predicts a state compatible with other phenomenological models but much higher than the ones computed by lattice and EFT approaches.
- The 1-loop corrections to the OGE potential brings down this level and locates it slightly above the BK threshold.
- When coupling, the level is down-shifted again towards the value predicted by lattice and EFT approaches, which is below the BK threshold.
- We predict a probability of 39% for the BK component of the B_{s0}^* wave function.

The B'_{s1} and $B_{s1}(5830)$ mesons

- The B'_{s1} and $B_{s1}(5830)$ mesons appear almost degenerated using the naive quark model that includes the one-loop corrections to the OGE potential.
- Coupling the B^*K threshold in a S-wave: The B'_{s1} state goes down in the spectrum and it is located below B^*K threshold.
- Coupling the B^*K threshold in a D-wave: The state associated with $B_{s1}(5830)$ meson suffers a moderate mass-shift.