Molecular components in $D^*_{s0}(2317)$ and $D_{s1}(2460)$ mesons

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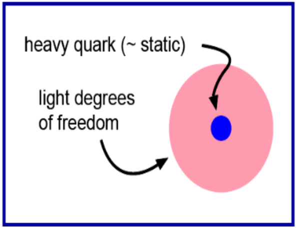
The heavy-light meson sectors were reasonably well understood in the $m_Q \to \infty$ limit
☞ *Heavy Quark Symmetry (HQS) holds*

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

☞ The heavy quark acts as a static color source, its spin s_Q is decoupled from the total angular momentum of the light quark 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 and, in the heavy quark limit, are degenerated. Mass degeneracy is broken at order $1/m_Q$.



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

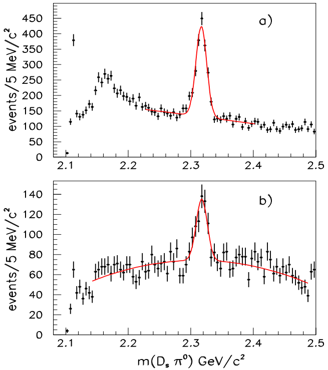
- $j_q^P = 1/2^+$ with $J^P = 0^+, 1^+$,
- $j_q^P = 3/2^+$ with $J^P = 1^+, 2^+$.

☞ The strong decays of the:

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

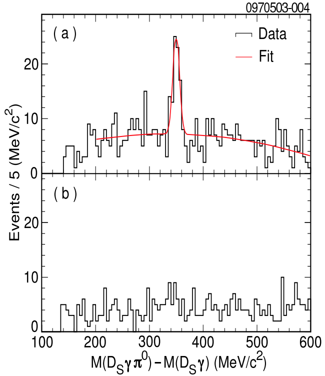
The $D_{s0}^{*}(2317)$ and $D_{s1}(2460)$ mesons are considered to be the members of the $j_q^P = 1/2^+$ doublet and thus being almost degenerated and broad.

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



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

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



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

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 finds 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:

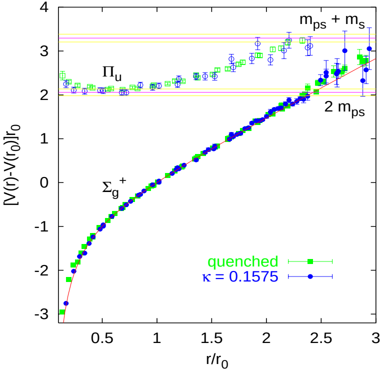
- Our calculation allows to introduce the coupling with the D-wave D^*K channel.

  $\rightarrow$ 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.

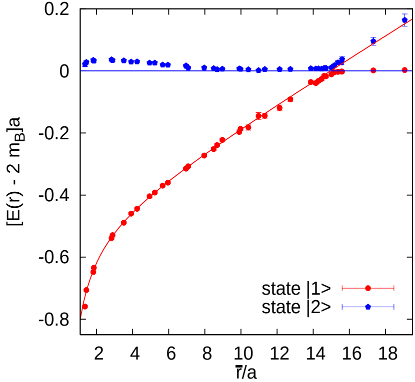
- The computation of the probabilities associated with the different Fock components of the physical state.

These features cannot be addressed nowadays by any other theoretical approach

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



G.S. Bali *et al.* Phys. Rev. D 71, 114513 (2005)



LINEAR SCREENED POTENTIAL

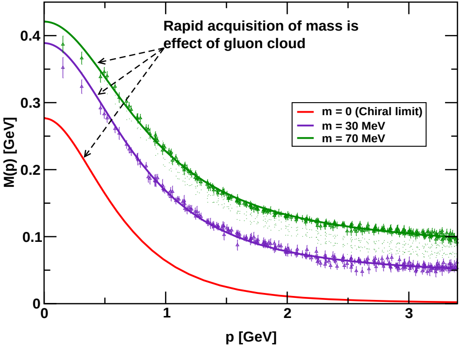
$$V_{\rm CON}(r) = \left[-a_c(1-e^{-\mu_c r}) + \Delta\right](\vec{\lambda}_i\cdot\vec{\lambda}_j)$$

- *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

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



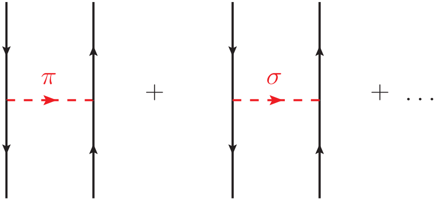
C.D. Roberts, arXiv:1109.6325v1 [nucl-th]

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

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

- Constituent quark mass

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



One-gluon exchange potential

Beyond the chiral symmetry breaking scale

$\Downarrow$

Dynamics to be governed by QCD perturbative effects

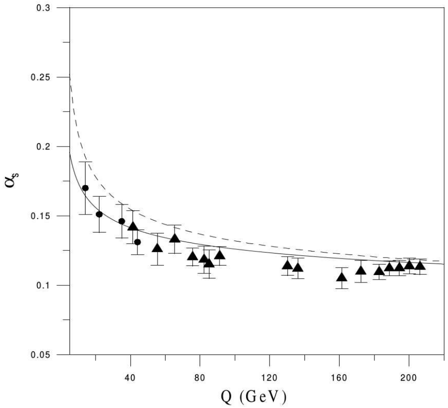
- We take them into account through the one-gluon exchange (OGE) potential.

- The OGE is a standard color Fermi-Breit interaction obtained from the vertex:

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

- 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. G 31, 481 (2005)

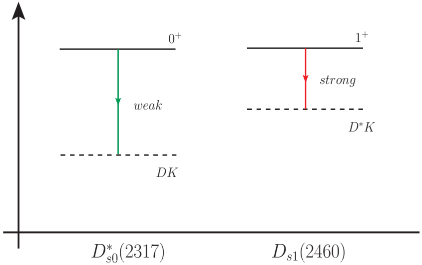
Addition of the one-loop QCD corrections to the spin-dependent terms of the potential
S.N. Gupta and S.F. Radford, Phys. Rev. D 24, 2309 (1981)

- There is a spin-dependent term which affects only to mesons with different flavor quarks.
  O. Lakhina and E.S. Swanson, Phys. Lett. B 650, 159 (2007)

- The 0^+ state is more sensitive to the inclusion of the one-loop corrections.

	$j_q^P = 1/2^-$		$j_q^P = 1/2^+$		$j_q^P = 3/2^+$	
	0^-	1^-	0^+	1^+	1^+	2^+
This work (α_s)	1984	2110	2510	2593	2554	2591
This work (α_s^2)	1984	2104	2383	2570	2560	2609
Exp.	1969.0 ± 1.4	2112.3 ± 0.5	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.



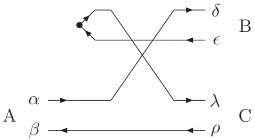
- The states should be degenerated.
- They should couple equally to DK and D^*K.

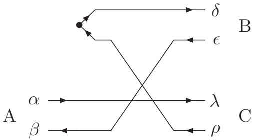
- The $^3P_0$ interaction Hamiltonian:

$$\mathcal{H}_I = \sqrt{3}\, g_s \int d^3x\, \bar{\psi}(\vec{x})\, \psi(\vec{x}), \text{ with } \gamma = g_s/2m$$

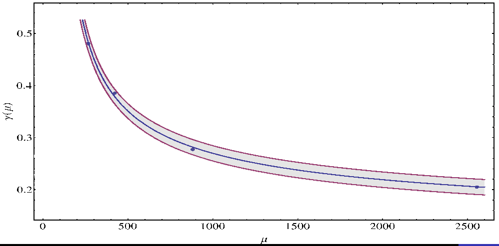
$$T = -\sqrt{3} \sum_{\mu,\nu} \int d^3p_\mu d^3p_\nu \delta^{(3)}(\vec{p}_\mu + \vec{p}_\nu) \frac{\sqrt{2^5\pi}\, g_s}{2m_\mu} \left[\mathcal{Y}_1\left(\frac{\vec{p}_\mu - \vec{p}_\nu}{2}\right) \otimes \left(\frac{1}{2}\frac{1}{2}\right) 1 \right]_0 a^\dagger_\mu(\vec{p}_\mu) b^\dagger_\nu(\vec{p}_\nu)$$

- Diagrams that contribute:





- Running of the $^3P_0$ strength



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

- $\gamma_0 = 0.81 \pm 0.02$.
- $\mu_\gamma = 49.84 \pm 2.58\,\mathrm{MeV}$.
- Solid line is the fit.
- Shaded area $\Rightarrow$ 90% C.L.

$$\gamma(\mu_{c\bar{s}}) = 0.379$$

Running of the $^3P_0$ strength

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

We get a quite reasonable global description of the total decay widths

The quark-antiquark bound state can be strongly influenced by nearby multiquark channels

- The hadronic state:

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

- The transition potential (within the $^3P_0$ model):

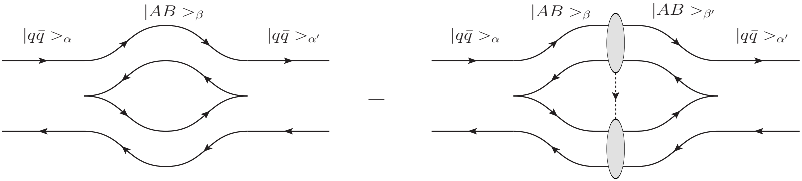
$$\langle\phi_A\phi_B\beta|T|\psi_\alpha\rangle = P\, h_{\beta\alpha}(P)\,\delta^{(3)}(\vec{P}_{\rm cm})\,,$$

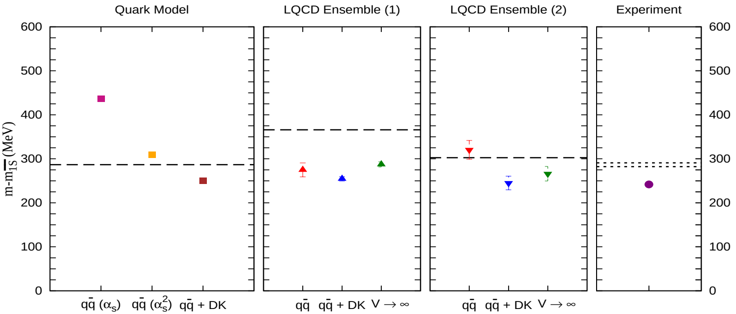
$\rightarrow$ Vertices that are too hard specially when work at high momenta:

$$h_{\beta\alpha}(P) \rightarrow h_{\beta\alpha}(P) \times e^{-\frac{P^2}{2\Lambda^2}}\,, \quad \text{with} \quad \Lambda = 0.84\,\text{GeV}$$

- A Schrödinger-type equation:

$$\sum_\beta \int dP\, P^2 \left[V^{\rm eff}_{\beta'\beta}(E;P',P) - H^{M_1M_2}_{\beta'\beta}(P',P)\right] \chi_\beta(P) = E\,\chi_{\beta'}(P')$$





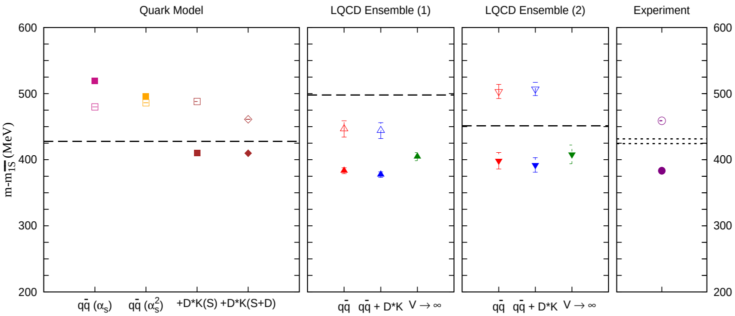
P.G. Ortega *et al.*, arXiv: 1603.07000 [hep-ph]

☞ Observations:

- The mass is much higher using the naive quark model and without the 1-loop spin 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%

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

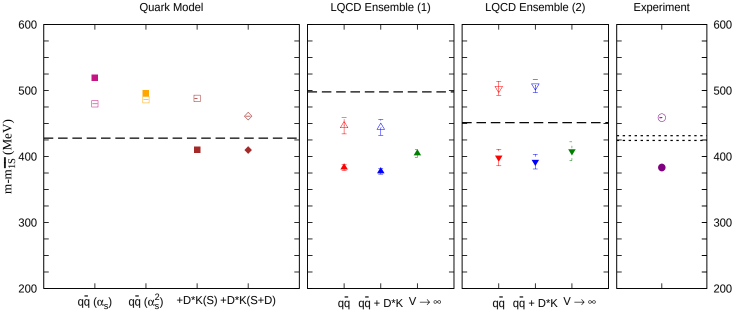


P.G. Ortega *et al.*, arXiv: 1603.07000 [hep-ph]

☞ 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.

The $D_{s1}(2460)$ and $D_{s1}(2536)$ mesons (I). Continuation



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.

☞ 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%

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 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.

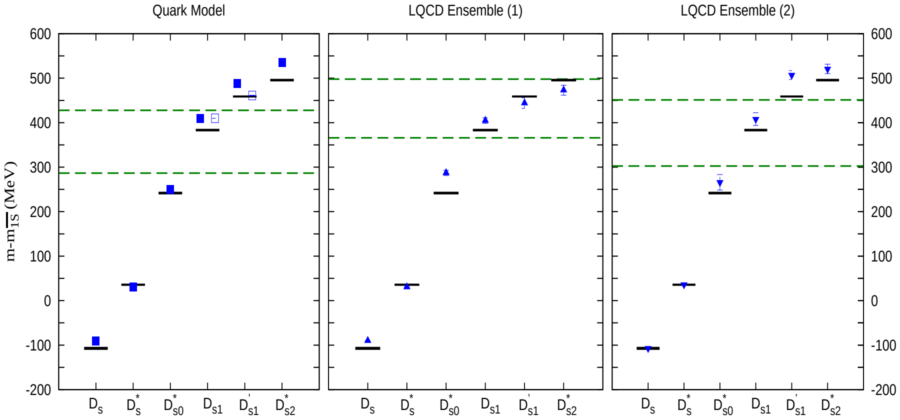
Partial and total strong decay widths

- 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).

We have performed a coupled-channel computation taking into account the $D_{s0}^*(2317)$, $D_{s1}(2460)$ and $D_{s1}(2536)$ 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.