The $T_{cs/c\bar{s}}(2900)$ in the hidden gauge approach and its spin partners

R. Molina, T. Branz, L. R. Dai and E. Oset

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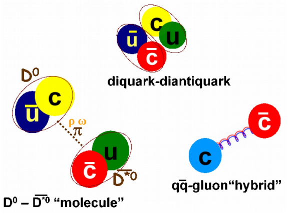
Intro

Since the X(3872) many exotics discovered ...

- $Z_c(3900)$, BESIII, 2013
  close to $D\bar{D}^*$, $c\bar{q}q\bar{c}$ $(q = u, d)$
- $Z_{cs}(3985)$, BESIII, 2021
  close to $\bar{D}_s^* D/\bar{D}_s D^*$, $c\bar{q}s\bar{c}$
  See M. Albaladejo's talk, Thursday 7pm
- $X_0(2866), X_1(2900)$ now $T_{cs}(2900)$,
  LHCb, 2020
  close to $D^*\bar{K}^*$, $c\bar{q}s\bar{q}$
- $T_{cc}(3875)$, LHCb, 2021
  close to DD^*, $c\bar{q}c\bar{q}$
- $T_{c\bar{s}}(2900)$, LHCb, 2022
  close to D^*K^*, $c\bar{s}q\bar{q}$
  Talk review LHCb, Rosa Anna, Tuesday 12pm



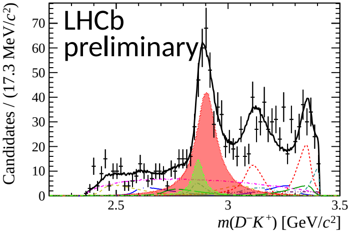
$\Longrightarrow$ Do not fit into $q\bar{q}$ basic mesons of the quark model predictions
Are the meson-meson molecules? tetraquarks? interaction?

New flavor exotic tetraquark ($C = -1, S = 1, I_3 = 0$)

LHCb (2020)

Two states $J^P = 0^+, 1^-$ decaying to $\bar{D}K$. First clear example of an heavy-flavor exotic tetraquark, $\sim \bar{c}\bar{s}ud$. Now $T_{cs}(2900)$

$$X_0(2866): M = 2866 \pm 7 \quad \text{and} \quad \Gamma = 57.2 \pm 12.9\,\text{MeV},$$
$$X_1(2900): M = 2904 \pm 5 \quad \text{and} \quad \Gamma = 110.3 \pm 11.5\,\text{MeV}.$$

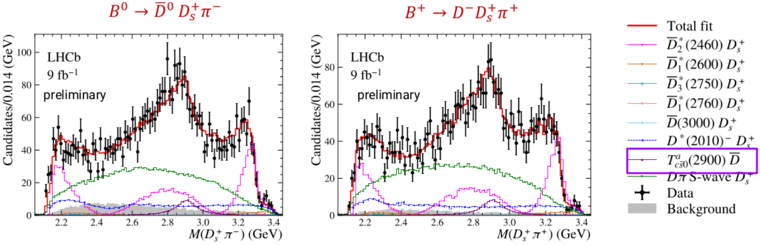


R. Aaij et al. (LHCb Collaboration), PRL125(2020), PRD102(2020)

New exotic tetraquark seen in $D_s^+\pi^+$ $(C=1, S=1, I=1)$

LHCb (2022)

One state decaying $T_{c\bar{s}}(2900)$ decaying to $D_s^+\pi^-$ and $D_s^+\pi^+$ has been observed.



- The analysis favors $J^P = 0^+$
- Mass, $m = 2908 \pm 11 \pm 20$ MeV
- Width, $\Gamma = 136 \pm 23 \pm 11$ MeV

LHCb-PAPER-2022-026

Note that,

D^*K^* th.: 2903 MeV

$D_s^*\rho$ th.: 2890 MeV

Flavour exotic states

- 2010. Prediction of several flavour exotic states

PHYSICAL REVIEW D **82,** 014010 (2010)

New interpretation for the $D_{s2}^*(2573)$ and the prediction of novel exotic charmed mesons

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(Received 4 May 2010; published 21 July 2010)

In this manuscript we study the vector-vector interaction within the hidden-gauge formalism in a coupled channel unitary approach. In the sector $C = 1, S = 1, J = 2$ we get a pole in the T matrix around 2572 MeV that we identify with the $D_{s2}^*(2573)$, coupling strongly to the $D^*K^*(D_s^*\phi(\omega))$ channels. In addition we obtain resonances in other exotic sectors which have not been studied before such as $C = 1, S = -1, C = 2, S = 0$ and $C = 2, S = 1$. These "flavor-exotic" states are interpreted as $D^*\bar{K}^*$, D^*D^*, and $D_s^*D^*$ molecular states but have not been observed yet. In total we obtain nine states with different spin, isospin, charm, and strangeness of non-$C = 0, S = 0$ and $C = 1, S = 0$ character, which have been reported before.

DOI: 10.1103/PhysRevD.82.014010 PACS numbers: 14.40.Rt, 12.40.Vv, 13.75.Lb, 14.40.Lb

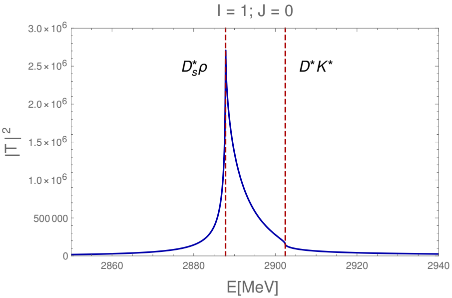
- Free parameter fixed with $D_{s2}(2573)$; couples to D^*K^*, $c\bar{q}q\bar{s}$
- Flavour exotic states with $I = 0$, $J^P = \{0, 1, 2\}^+$ coupling to $D^*\bar{K}^*$ are predicted, $c\bar{q}s\bar{q}$
- Doubly charm states, $I = 0$; $J^P = 1^+$, close to D^*D^* are predicted, $c\bar{q}c\bar{q}$, and $I = 1/2$; $J^P = 1^+$, close to $D^*D_s^*$ $c\bar{q}c\bar{s}$

Exotic states

Phys. Rev. D 82 (2010), Molina, Branz, Oset

3.5 $C = 1; S = 1; I = 1$

In this sector the potential is attractive for the $D^*K^* \to D_s^*\rho$ reaction. For $J = 0$ and 1 this potential is around $-7\,g^2$ whereas it is by a factor of two bigger $-13\,g^2$ for $J = 2$ (see Table 14). In fact, we only obtain a pole for $J = 2$. For $J = 0$ and 1 we only observe a cusp in the $D_s^*\rho$ threshold. In Table 5 we show the pole position and couplings to the different channels. Both channels, D^*K^* and $D_s^*\rho$, are equally important as one can deduce from the corresponding couplings. The broad width of the ρ meson has to be taken into account



$\alpha = -1.6$

ρ width not included

$D^*K^* \to DK$ considered

Cusp around $D_s^*\rho$, D^*K^* th.

separated only by 14 MeV

Flavour exotic states

Molina,Branz,Oset, PRD82(2010)

C, S	Channels	$I[J^P]$	$\sqrt{s}$	$\Gamma_A(\Lambda = 1400)$	$\Gamma_B(\Lambda = 1200)$	State	$\sqrt{s}_{exp}$	Γ_{exp}
$1, -1$	$D^* \bar{K}^*$	$0[0^+]$	2848	23	59	$X_0(2866)$ or $T_{cs}(2900)$	2866	57
		$0[1^+]$	2839	3	3			
		$0[2^+]$	2733	11	36			
$1, 1$	$D^* K^*$, $D_s^* \omega$	$0[0^+]$	2683	20	71			
	$D_s^* \phi$	$0[1^+]$	2707	4×10^{-3}	4×10^{-3}			
		$0[2^+]$	2572	7	23	$D_{s2}(2573)$	2572	20
$1, 1$	$D^* K^*$, $D_s^* \rho$	$1[0^+]$	Cusp structure around $D_s^* \rho$, $D^* K^*$			new $T_{c\bar{s}}(2900)$	2908	136
$1, 1$		$1[1^+]$	Cusp structure around $D_s^* \rho$, $D^* K^*$					
$1, 1$		$1[2^+]$	2786	8	11			
$2, 0$	$D^* D^*$	$0[1^+]$	3969	0	0			
$2, 1$	$D^* D_s^*$	$1/2[1^+]$	4101	0	0			

Table 1: Summary of the nine states obtained. The width is given for the model A, Γ_A, and B, Γ_B. All the quantities here are in MeV. Repulsion in $C = 0, S = 1, I = 1/2$; $C = 1, S = -1, I = 1$; $C = 1, S = 2, I = 1/2$; $C = 2, S = 0, I = 1$ and $C = 2, S = 2, I = 0$ is found.

Form factors in the $D^* D\pi$ vertex; Model A: $F_1(q^2) = \frac{\Lambda_b^2 - m_\pi^2}{\Lambda_b^2 - q^2}$, Titov, Kampfer EPJA7, PRC65 with $\Lambda_b = 1.4, 1.5$ GeV and $g = M_\rho / 2 f_\pi$. Model B: $F_2(q^2) = e^{q^2/\Lambda^2}$ Navarra, Nielsen, Bracco PRD65 (2002), $\Lambda = 1, 1.2$ GeV and $g_D = g^{\rm exp}_{D^* D\pi} = 8.95$ (experimental value). Subtraction constant $\alpha = -1.6$.

Many studies appeared after these discoveries ...

- He, Wang, Zhu, EPJC80, 1026 (2020), Karliner, Rosner, PRD102(2020), $X_0(2866)$, compact tetraquark
- X. H. Liu, Yan et al., EPJC80(2020), $X_0(2866)$, Triangle Singularity
- M. Z. Liu, Xie, Geng, PRD102(2020), $X_0(2866)$, $D^*\bar{K}^*$ molecule (one-boson ex.), $X_1(2900)$ cannot be, Qi, Wang et al. EPJC81(2021), X_1 is a $\bar{D}_1 K$ molecule (ρ, ω ex.)
- Ying-Hui Ge, X.H. Liu and H. W. Kei, 2207.09900, the $T_{c\bar{s}}$ could be a TS from the $\chi_{c1}D^*K^*$ loop. However, the TS peak around the $D_s^*\rho$ threshold from the $D^{**}D_s^*\rho$ loop cannot explain the $T_{c\bar{s}}(2900)$
- Du, Baru, Dong, Filin, Nieves, F. K. Guo, T_{cc}, PRD105, (2022), 3-body dynamics, $D^0D^0\pi^+$, contact+OPE, DD^* molecule
- Albaladejo, T_{cc} from DD^*, can have $I = 0$ or 1
- Feijoo, Liang, Oset, PRD104(2021), T_{cc} as DD^*, has $I = 0$, decay width to $D^0D^0\pi^+ \sim 43\ \mathrm{MeV}$
- Padmanath, Prelovsek, virtual s-wave bound state for $m_\pi = 280$ MeV of DD^* in LatticeQCD ...

The Local Hidden Gauge Approach

The hidden gauge formalism Bando,Kugo,Yamawaki

Lagrangian

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}_{III} \tag{1}$$

$$\begin{aligned} \mathcal{L}^{(2)} &= \frac{1}{4} f^2 \langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + \chi^\dagger U \rangle \\ \mathcal{L}_{III} &= -\frac{1}{4} \langle V_{\mu\nu} V^{\mu\nu} \rangle + \frac{1}{2} M_V^2 \langle [V_\mu - \frac{i}{g} \Gamma_\mu]^2 \rangle \end{aligned} \tag{2}$$

$$D_\mu U = \partial_\mu U - ieQA_\mu U + ieUQA_\mu, \qquad U = e^{i\sqrt{2}P/f} \tag{3}$$

$$\begin{aligned} \mathcal{L}_{V\gamma} &= -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q \rangle \\ \mathcal{L}_{VPP} &= -ig \langle V^\mu [P, \partial_\mu P] \rangle; \quad g = M_V/2f \\ \widetilde{\mathcal{L}}^{(2)} &= \frac{1}{12 f^2} \langle [P, \partial_\mu P]^2 + M P^4 \rangle. \end{aligned} \tag{4}$$

Local Hidden Gauge Approach

Vector-vector scattering

$$\mathcal{L}_{III} = -\frac{1}{4}\langle V_{\mu\nu}V^{\mu\nu}\rangle$$

$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle$$

$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle$$

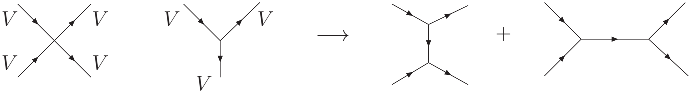
$V_{\mu\nu} =$

$$\partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

$$g = \frac{M_V}{2f}$$

$V_\mu =$

$$\begin{pmatrix} \frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\omega}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$



a) b) c) d)

Local Hidden Gauge Approach

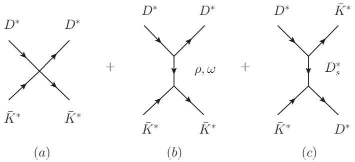


Figure 1: The $D^* \bar{K}^* \to D^* \bar{K}^*$ interaction at the tree level; (a) contact term; (b) exchange of light vectors; (c) exchange of a heavy vector.

Approximation

$$\epsilon_1^\mu = (0,1,0,0)$$
$$\epsilon_2^\mu = (0,0,1,0)$$
$$\epsilon_3^\mu = (|\vec{k}|,0,0,k^0)/m$$

$$k^\mu = (k^0, 0, 0, |\vec{k}|)$$

$$\vec{k}/m \simeq 0,\ k_j^\mu \epsilon_\mu^{(l)} \simeq 0$$

$$\epsilon_1^\mu = (0,1,0,0)$$
$$\epsilon_2^\mu = (0,0,1,0)$$
$$\epsilon_3^\mu = (0,0,0,1)$$

$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle = ig\langle[V_\mu, \partial_\nu V_\mu]V^\nu\rangle$$

Spin projectors

$$\mathcal{P}^{(0)} = \frac{1}{3}\epsilon_\mu \epsilon^\mu \epsilon_\nu \epsilon^\nu; \quad \mathcal{P}^{(1)} = \frac{1}{2}(\epsilon_\mu \epsilon_\nu \epsilon^\mu \epsilon^\nu - \epsilon_\mu \epsilon_\nu \epsilon^\nu \epsilon^\mu)$$

$$\mathcal{P}^{(2)} = \{\frac{1}{2}(\epsilon_\mu \epsilon_\nu \epsilon^\mu \epsilon^\nu + \epsilon_\mu \epsilon_\nu \epsilon^\nu \epsilon^\mu) - \frac{1}{3}\epsilon_\mu \epsilon^\mu \epsilon_\nu \epsilon^\nu\} \ .$$

The $X_0(2866)$ or $T_{cs}(2900)$

Local Hidden Gauge Approach

Potential V: contact + vector-meson exchange (ρ, ω)

J	Amplitude	Contact	V-exchange	$\sim$ Total
0	$D^*\bar{K}^* \to D^*\bar{K}^*$	$4g^2$	$-\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D^*_s}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} - \frac{3}{m^2_\rho})(p_1+p_3).(p_2+p_4)$	$-9.9g^2$
1	$D^*\bar{K}^* \to D^*\bar{K}^*$	0	$\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D^*_s}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} - \frac{3}{m^2_\rho})(p_1+p_3).(p_2+p_4)$	$-10.2g^2$
2	$D^*\bar{K}^* \to D^*\bar{K}^*$	$-2g^2$	$-\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D^*_s}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} - \frac{3}{m^2_\rho})(p_1+p_3).(p_2+p_4)$	$-15.9g^2$

Table 2: Tree level amplitudes for $D^*\bar{K}^*$ in $I=0$. Last column: $(V_{\rm th.})$.

J	Amplitude	Contact	V-exchange	$\sim$ Total
0	$D^*\bar{K}^* \to D^*\bar{K}^*$	$-4g^2$	$\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D^*_s}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} + \frac{1}{m^2_\rho})(p_1+p_3).(p_2+p_4)$	$9.7g^2$
1	$D^*\bar{K}^* \to D^*\bar{K}^*$	0	$-\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D^*_s}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} + \frac{1}{m^2_\rho})(p_1+p_3).(p_2+p_4)$	$9.9g^2$
2	$D^*\bar{K}^* \to D^*\bar{K}^*$	$2g^2$	$\frac{g^2(p_1+p_4).(p_2+p_3)}{m^2_{D^*_s}} + \frac{1}{2}g^2(\frac{1}{m^2_\omega} + \frac{1}{m^2_\rho})(p_1+p_3).(p_2+p_4)$	$15.7g^2$

Table 3: Tree level amplitudes for $D^*\bar{K}^*$ in $I=1$. Last column: $(V_{\rm th.})$.

The interaction is attractive for $I=0$ and repulsive for $I=1$.

Local Hidden Gauge Approach

J	Amplitude	Contact	V-exchange	$\sim$ Total
0	$D^*K^* \to D^*K^*$	0	$\frac{g^2}{2}(\frac{1}{m_\rho^2} - \frac{1}{m_\omega^2})(p_1 + p_3).(p_2 + p_4)$	$0.11g^2$
0	$D^*K^* \to D_s^*\rho$	$4g^2$	$-\frac{g^2(p_1+p_4)(p_2+p_3)}{m_{D^*}^2} - \frac{g^2(p_1+p_3).(p_2+p_4)}{m_{K^*}^2}$	$-6.8g^2$
0	$D_s^*\rho \to D_s^*\rho$	0	0	0
1	$D^*K^* \to D^*K^*$	0	$\frac{g^2}{2}(\frac{1}{m_\rho^2} - \frac{1}{m_\omega^2})(p_1 + p_3).(p_2 + p_4)$	$0.11g^2$
1	$D^*K^* \to D_s^*\rho$	0	$\frac{g^2(p_1+p_4)(p_2+p_3)}{m_{D^*}^2} - \frac{g^2(p_1+p_3).(p_2+p_4)}{m_{K^*}^2}$	$-6.6g^2$
1	$D_s^*\rho \to D_s^*\rho$	0	0	0
2	$D^*K^* \to D^*K^*$	0	$\frac{g^2}{2}(\frac{1}{m_\rho^2} - \frac{1}{m_\omega^2})(p_1 + p_3).(p_2 + p_4)$	$0.11g^2$
2	$D^*K^* \to D_s^*\rho$	$-2g^2$	$-\frac{g^2(p_1+p_4)(p_2+p_3)}{m_{D^*}^2} - \frac{g^2(p_1+p_3).(p_2+p_4)}{m_{K^*}^2}$	$-12.8g^2$
2	$D_s^*\rho \to D_s^*\rho$	0	0	0

Table 4: Tree level amplitudes for $D^*K^*, D_s^*\rho$ in $I = 1$. Last column: $(V_{\text{th.}})$ for $C = 1$, $S = 1$ and $I = 1$.

The interaction is attractive for both $I = 0$ and $I = 1$, favoring a $J^+ = 2^+$ state. (see PRD82 (2010) Molina, Branz, Oset, for $I = 0$)

New flavor exotic tetraquark ($C = 1, S = -1$)

Two-meson loop function

$$G_i(s) = \frac{1}{16\pi^2}\Big(\alpha + \mathrm{Log}\frac{M_1^2}{\mu^2} + \frac{M_2^2 - M_1^2 + s}{2s}\mathrm{Log}\frac{M_2^2}{M_1^2}$$
$$+ \frac{p}{\sqrt{s}}\Big(\mathrm{Log}\frac{s - M_2^2 + M_1^2 + 2p\sqrt{s}}{-s + M_2^2 - M_1^2 + 2p\sqrt{s}} + \mathrm{Log}\frac{s + M_2^2 - M_1^2 + 2p\sqrt{s}}{-s - M_2^2 + M_1^2 + 2p\sqrt{s}}\Big)\Big) ,$$

Bethe-Salpeter

$$\boxed{T = [\hat{1} - VG]^{-1} V}$$

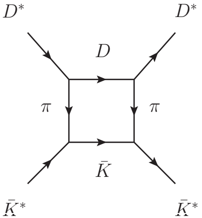
The states with $J^P = \{0, 2\}^+$ decay into $D\bar{K}$

$$\mathcal{L}_{VPP} = -ig\langle [P, \partial_\mu P] V^\mu \rangle$$

$$F(q) = e^{((p_1^0 - q^0)^2 - \vec{q}^{\,2})/\Lambda^2}$$

Navarra, PRD65(2002)

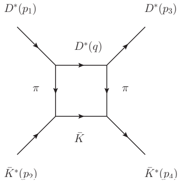
with $q_0 = (s + m_D^2 - m_K^2)/2\sqrt{s}$.



New flavor exotic tetraquark ($C = 1, S = -1$)

Recent work: Molina, Oset PLB811 2020, $\alpha = -1.474$, $\Lambda = 1300$.
Evaluation of the decay width of the $J^P = 1^+$ state

$$\mathcal{L} = \frac{iG'}{\sqrt{2}} \epsilon^{\mu\nu\alpha\beta} \langle \delta_\mu V_\nu \delta_\alpha V_\beta P \rangle$$
$$\mathcal{L}_{VPP} = -ig \langle [P, \partial_\mu P] V^\mu \rangle$$



Amplitude:

$$-it = \frac{9}{2}(G' g m_{D^*})^2 \int \frac{d^4q}{(2\pi)^4} \epsilon^{ijk} \epsilon^{i'j'k'} \left(\frac{1}{(p_1 - q)^2 - m_\pi^2 + i\epsilon} \right)^2 \frac{1}{q^2 - m_{D^*}^2 + i\epsilon} \frac{1}{(p_1 + p_2 - q)^2 - m_K^2 + i\epsilon}$$
$$\times \epsilon^{j(1)} \epsilon^{m(2)} \epsilon^{k(3')} q^i q^m \epsilon^{j'(1)} \epsilon^{m'(4)} \epsilon^{k'(3')} q^{i'} q^{m'} F^4(q) \quad (5)$$

$$t = \frac{9}{2}(G' g m_{D^*})^2 \int \frac{d^3q}{(2\pi)^3} (\delta_{ii'} \delta_{jj'} - \delta_{ij'} \delta_{i'j}) \left(\frac{1}{(p_1 - q)^2 - m_\pi^2} \right)^2 \frac{1}{2\omega^*(q)} \frac{1}{2\omega(q)} \frac{1}{\sqrt{s} - \omega^*(q) - \omega(q) + i\epsilon}$$
$$\times \epsilon^{j(1)} \epsilon^{m(2)} \epsilon^{j'(3)} \epsilon^{m'(4)} q^i q^m q^{i'} q^{m'} F^4(q) \quad (6)$$

with $\omega^*(q) = \sqrt{m_{D^*}^2 + \vec{q}^{\,2}}$, $\omega(q) = \sqrt{m_K^2 + \vec{q}^{\,2}}$, $p_1^0 = m_{D^*}$, $q^0 = \omega^*(q)$. We use $\mathrm{Im}\frac{1}{x + i\epsilon} = -i\pi\delta(x)$.

Decay of the $T_{cs}(2900)$ to $D^*\bar{K}$

Taking now into account that,

$$\int \frac{d^3q}{(2\pi)^3} f(\vec{q}^{\,2}) q^i q^m q^{i'} q^{m'} = \frac{1}{15} \int \frac{d^3q}{(2\pi)^3} f(\vec{q}^{\,2}) \vec{q}^{\,4} (\delta_{im}\delta_{i'm'} + \delta_{ii'}\delta_{mm'} + \delta_{im'}\delta_{m'i}) \ ,$$

one obtains,

$$4\epsilon^{j(1)}\epsilon^{m(2)}\epsilon^{j(3)}\epsilon^{m(4)} - \epsilon^{j(1)}\epsilon^{j(2)}\epsilon^{m(3)}\epsilon^{m(4)} - \epsilon^{j(1)}\epsilon^{m(2)}\epsilon^{m(3)}\epsilon^{j(4)} \ ,$$

which is a combination of the spin projectors, $5\mathcal{P}^{(1)} + 3\mathcal{P}^{(2)}$, zero component for $J = 0$ (violates parity). The imaginary part for $J = 1$ is,

$$\boxed{\mathrm{Im}\,t = -\frac{3}{2}\frac{1}{8\pi}(G' g m_{D^*})^2 q^5 \left(\frac{1}{(m_D^* - \omega^*(q))^2 - \omega^2(q)}\right)^2 \frac{1}{\sqrt{s}} F^4(q)}$$

$\omega(q) = \sqrt{m_K^2 + \vec{q}^{\,2}}; \omega^*(q) = \sqrt{m_{D^*}^2 + \vec{q}^{\,2}}; q = \frac{\lambda^{1/2}(s, m_{D^*}^2, m_K^2)}{2\sqrt{2}}$

Decay of the $T_{cs}(2900)$ to $D^*\bar{K}$

$I(J^P)$	M[MeV]	Γ[MeV]	Coupled channels	state
$0(2^+)$	2775	38	$D^*\bar{K}^*$	?
$0(1^+)$	2861	20	$D^*\bar{K}^*$	?
$0(0^+)$	2866	57	$D^*\bar{K}^*$	$T_{cs}(2900)$

Table 5: New results including the width of the D^*K channel.

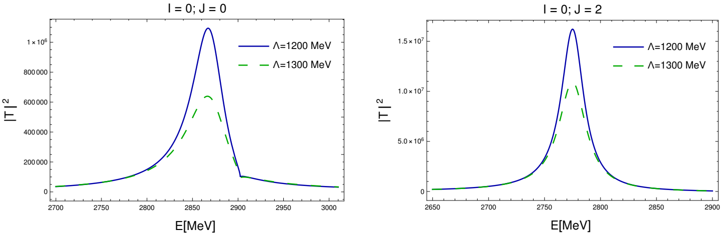


Figure 2: $|T|^2$ for $C = 1, S = -1, I = 0, J = 0$ and $J = 2$.

Decay of the $T_{cs}(2900)$ to $D^*\bar{K}$

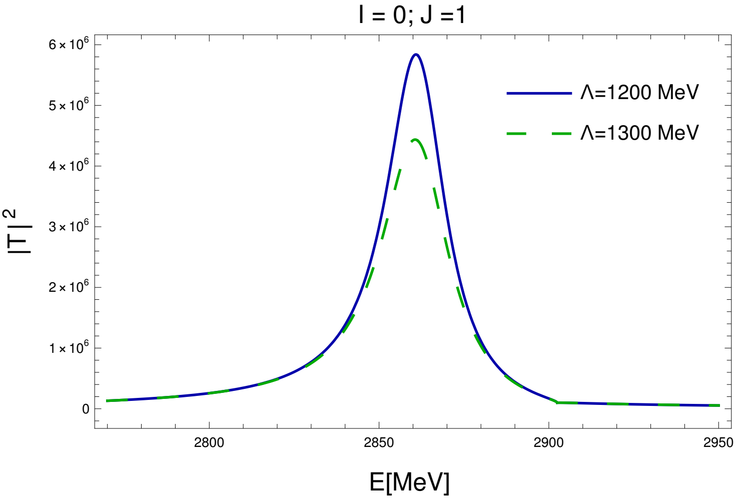


Figure 3: $|T|^2$ for $C = 1, S = -1, I = 0, J = 0$ and $J = 1$.

The $T_{c\bar{s}}(2900)$

$C = 1, S = 1, I = 1$ **The** $T_{c\bar{s}}(2900)$

Two channels: $D^* K^*$, $D_s^* \rho$. New results, $\alpha = -1.474$ to obtain the $T_{cs}(2900)$ state in $D^* \bar{K}^*$. We also consider both the ρ and K^* width.

Convolution due to the vector meson mass distribution

$$\tilde{G}(s) = \frac{1}{N} \int_{(M_1 - 4\Gamma_1)^2}^{(M_1 + 4\Gamma_1)^2} d\tilde{m}_1^2 (-\frac{1}{\pi}) \mathcal{I}m \frac{1}{\tilde{m}_1^2 - M_1^2 + i\Gamma(\tilde{m})\tilde{m}_1} G(s, \tilde{m}_1^2, M_2^2) \ ,$$

with

$$N = \int_{(M_1 - 4\Gamma_1)^2}^{(M_1 + 4\Gamma_1)^2} d\tilde{m}_1^2 (-\frac{1}{\pi}) \mathcal{I}m \frac{1}{\tilde{m}_1^2 - M_1^2 + i\Gamma(\tilde{m})\tilde{m}_1} \ , \tag{7}$$

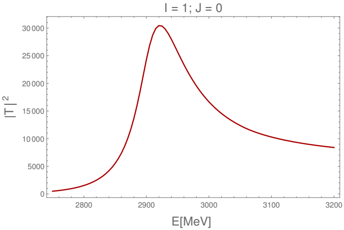
where M_1 and Γ_1 are the nominal mass and width of the vector meson.

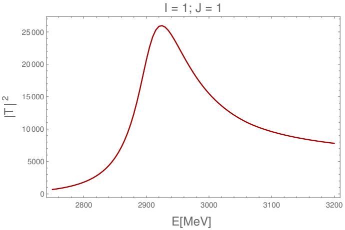
$$\tilde{\Gamma}(\tilde{m}) = \Gamma_0 \frac{q_{\rm off}^3}{q_{\rm on}^3} \Theta(\tilde{m} - m_1 - m_2) \tag{8}$$

with

$$q_{\rm off} = \frac{\lambda^{1/2}(\tilde{m}^2, m_1^2, m_2^2)}{2\tilde{m}}, \quad q_{\rm on} = \frac{\lambda^{1/2}(M_1^2, m_1^2, m_2^2)}{2M_1} \ . \tag{9}$$

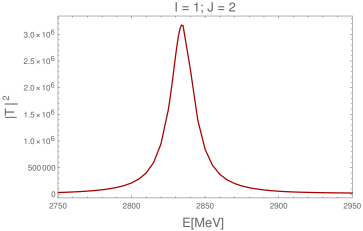
$C = 1, S = 1, I = 1$ **The** $T_{c\bar{s}}(2900)$





$(1,0): \ m = 2920$ MeV, $\Gamma = 130$ MeV $\quad (1,1): \ m = 2922$ MeV, $\Gamma = 145$ MeV

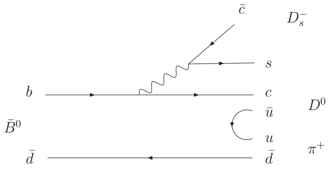
Exp. $m = 2908 \pm 11 \pm 20$ MeV, $\Gamma = 136 \pm 23 \pm 11$ MeV

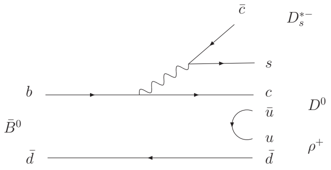


$(I, J) = (1,2): \ m = 2835$ MeV, $\Gamma = 20$ MeV

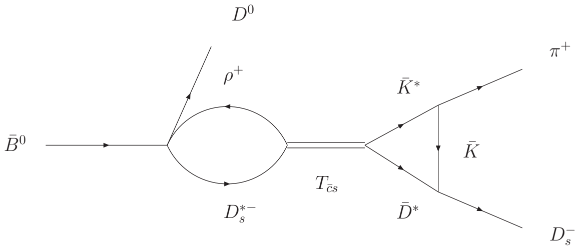
Production of the $T_{\bar{c}s}(2900)$

$\bar{B}^0 \to D_s^- D^0 \pi^+$ in B decays





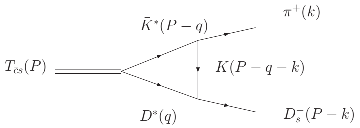
The $T_{\bar{c}s}(2900)$ can be produced by means of external emission



Production of the $T_{\bar{c}s}(2900)$ in B decays

$$\boxed{T(E) = aG(E)_{D_s^*\rho}\, t_{D_s^*\rho\to\bar{D}^*\bar{K}^*}(E)\, t_L(E) + b} \qquad (10)$$

where $E = M_{inv}(\pi^+ D_s^-)$, and a, b are constants adjusted to reproduce the experimental data. b stands for the background. t_L is the amplitude for the triangle loop.



$$t_L = -g^2 \int \frac{d^3q}{(2\pi)^3} (2\vec{k}+\vec{q})^2 F(\vec{k}+\vec{q}) \frac{1}{2\omega_{K^*}(q)} \frac{1}{2\omega_{D^*}(q)} \frac{1}{2\omega_K(\vec{q}+\vec{k})}$$

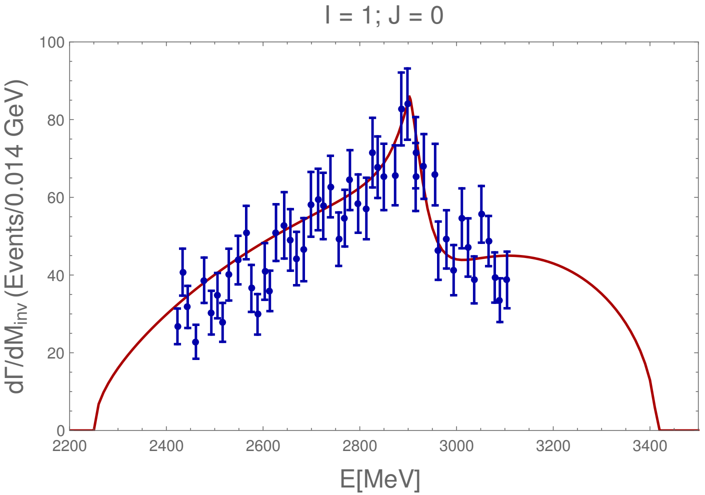
$$\times \left\{ \frac{1}{P^0 - \omega_{D^*}(q) - \omega_{K^*}(q) + i\epsilon} \frac{1}{P^0 - \omega_{D^*} - k^0 - \omega_K(\vec{q}+\vec{k}) + i\epsilon} \right.$$

$$\left. - \frac{1}{P^0 - \omega_{K^*}(q) - \omega_{D^*}(q) + i\epsilon} \frac{1}{\omega_{K^*}(q) + \omega(\vec{k}+\vec{q}) - k^0 - i\epsilon} \right\} \qquad (11)$$

Production of the $T_{\bar{c}s}(2900)$ in B decays

$\bar{B}^0 \to D_s^- D^0 \pi^+$

$$\frac{d\Gamma}{dM_{Inv}} = \frac{1}{(2\pi)^3} \frac{1}{4M_B^2} p_D \tilde{p}_\pi |T|^2$$



How can we observe the $J^P = 1^+$ $T_{cs}(2900)$ state?

Amo Sanchez et al. (BABAR), PRD83(2011).

The $\bar{B}^0 \to D^{*+}\bar{D}^{*0}K^-$ reaction:

- It proceeds via external emission (favoring the decay)
- It has the largest branching fraction (1.06%)
- It can produce the $D^{*+}K^-$ in $I = 0$ (decay mode of the 1^+ state).

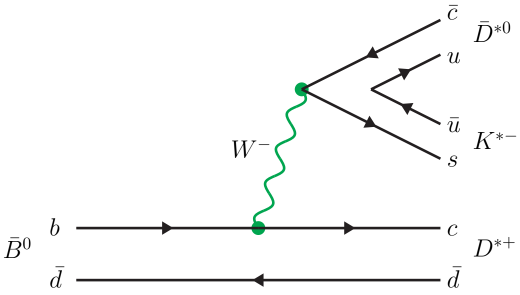


Figure 4: Diagrammatic decay of the $\bar{B}^0 \to \bar{D}^{*0}D^{*+}K^{*-}$ at the quark level.

How can we observe the $J^P = 1^+$ $T_{cs}(2900)$ state?

Hadronization + decay

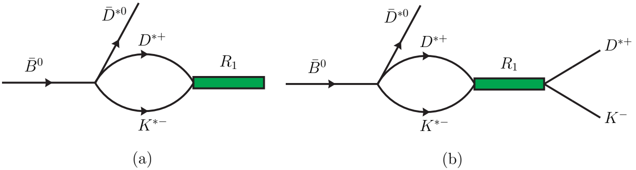


Figure 5: (a) Rescattering of $D^{*+}K^{*-}$ to give the resonance R_1 of $I = 0, J^P = 1^+$; (b) Further decay of R_1 to $D^{*+}K^-$.

$$|D^*\bar{K}^*; I=0\rangle = -\frac{1}{\sqrt{2}}(D^{*+}K^{*-} + D^{*0}\bar{K}^{*0})\,. \qquad (12)$$

$\bar{B}^0 \to \bar{D}^{*0}D^{*+}K^{*-}$ vertex: $(1)\bar{D}^{*0}$, $(2)D^{*+}$, $(3)K^{*-}$

$$(s-wave) \quad -i\,t = -i\,C\,\boldsymbol{\epsilon}^{(1)}\cdot(\boldsymbol{\epsilon}^{(2)}\times\boldsymbol{\epsilon}^{(3)}) = -i\,C\,\epsilon_{ijk}\epsilon_i^{(1)}\epsilon_j^{(2)}\epsilon_k^{(3)}$$

$R_I \to VV$ vertex: $-\frac{1}{\sqrt{2}}g_{R,D^*\bar{K}^*}\mathcal{P}^{(J=1)}$; $\quad \mathcal{P}^{(J=1)} = \frac{1}{2}(\epsilon_i^{(2)}\epsilon_j^{(3)} - \epsilon_j^{(2)}\epsilon_i^{(3)})$

How can we observe the $J^P = 1^+$ $T_{cs}(2900)$ state?

$$\sum_{pol} \epsilon_i^{(1)} \epsilon_{ii'j'} \epsilon_m^{(1)} \epsilon_{mi'j'} = \epsilon_{ii'j'} \epsilon_{ii'j'} = \delta_{ii'} \delta_{jj'} - \delta_{i'j'} \delta_{j'i'} = 9 - 3 = 6$$

$$\sum_{pol} |t'|^2 = \frac{6}{4} C^2 |g_{R_1, D^* \bar{K}^*}|^2 |G_{D^* \bar{K}^*}(M_{\rm inv})|^2 |g_{R_1, D^* \bar{K}}|^2 \left| \frac{1}{M^2_{\rm inv}(R_1) - M^2_{R_1} + i M_{R_1} \Gamma_{R_1}} \right|^2$$

with $M^2_{\rm inv} = (P_{D^{*+}} + P_{K^-})^2$. The effective $|g_{R_1, D^* \bar{K}}|^2$ coupling is obtained from the $R_1 \to D^* \bar{K}$ width.

$$\boxed{\frac{d\Gamma}{dM_{\rm inv}(D^{*+}K^-)} = \frac{1}{(2\pi)^3} \frac{1}{4M^2_{\bar{B}^0}} p_{\bar{D}^{*0}} \tilde{p}_{K^-} \sum |t'|^2} \qquad (13)$$

where $\tilde{p}_{K^-} = \frac{\lambda^{1/2}(M^2_{\rm inv}(D^{*+}K^-), m^2_{D^*}, m^2_{\bar{K}})}{2M_{\rm inv}(D^{*+}K^-)}$, $p_{\bar{D}^{*0}} = \frac{\lambda^{1/2}(M^2_{\bar{B}^0}, m^2_{\bar{D}^{*0}}, M^2_{\rm inv}(D^{*+}K^-))}{2M_{\bar{B}^0}}$.

Background for $\bar{B}^0 \to \bar{D}^{*0} D^{*+} K^-$ $\quad -it = -iC \boldsymbol{\epsilon}(D^{*0}) \cdot \boldsymbol{\epsilon}(D^{*+})$

$$\frac{d\Gamma_{\rm bac}}{dM_{\rm inv}(D^{*+}K^-)} = \frac{1}{(2\pi)^3} \frac{1}{4M^2_{\bar{B}^0}} p_{\bar{D}^{*0}} \tilde{p}_{\bar{K}}\, 3\, C^2 \qquad (14)$$

How can we observe the $J^P = 1^+$ state?

Dai, Molina and Oset, Phys. Lett. B832 (2022)

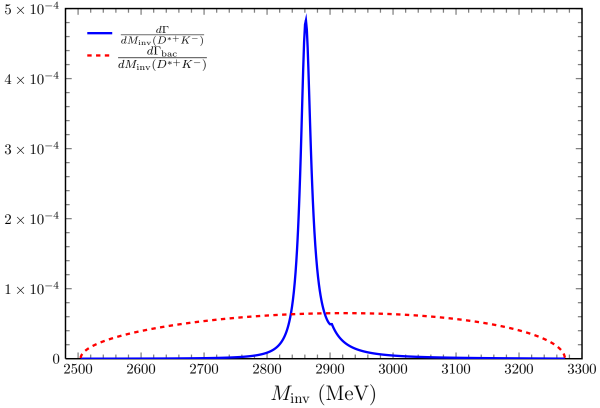


Figure 6: $\frac{d\Gamma}{dM_{\rm inv}}$ for the R_1 production versus the background, $\frac{d\Gamma_{\rm bac}}{dM_{\rm inv}}$, in the $\bar{B}^0 \to \bar{D}^{*0} D^{*+} K^{*-}$ reaction in a global arbitrary normalization. $M_{\rm inv}$ is the invariant mass of $D^{*+}K^-$. $\mathcal{B}_R(R_1; R_1 \to D^{*+}K^-) = 4.24 \times 10^{-3}$.

How can we observe the $J^P = 1^+$ state?

Similar results for the $\bar{B}^0 \to D^{*+} K^{*-} K^{*0} \to R_1 K^{*0} \to D^{*+} K^- K^{*0}$ process. Dai, Molina and Oset, Phys. Rev. D105 (2022)

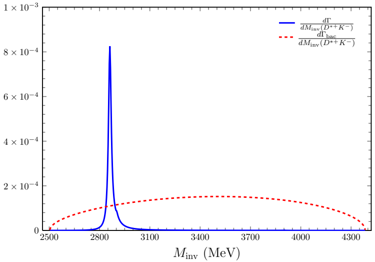


Figure 7: $\frac{d\Gamma}{dM_{\rm inv}}$ for R_1 production and $\frac{d\Gamma_{\rm bac}}{dM_{\rm inv}}$ for background in the $\bar{B}^0 \to K^{*0} D^{*+} K^-$ reaction in global arbitrary units versus the $D^{*+} K^-$ invariant mass.

The $T_{cs}(2900)$ can also be seen in:

$\bar{B}^0 \to K^0 D^{*+} K^{*-} \to K^0 X_0 \to K^0 D^+ K^-$ Phys. Rev. D105 (2022)

$B^- \to D^- D^{*+} K^{*-} \to D^- X_0 \to D^- D^+ K^-$ Phys. Lett. B832 (2022)

Conclusions

Conclusions

- The $X_0(2866)$ or $T_{cs}(2900)$ is compatible with a $D^*\bar{K}^*$ resonance decaying to $D\bar{K}$. Its spin partners can be also searched for in B decays. Proposed reactions to observe the 1^+ state:
  $\bar{B}^0 \to D^{*+}\bar{D}^{*0}K^-$, Phys. Lett. B832 (2022), Dai, Molina, Oset,
  $\bar{B}^0 \to D^{*+}K^-\bar{K}^{*0}$, Phys. Rev. D105 (2022); and the 2^+ state:
  $B^+ \to D^+D^-K^+$, Phys. Lett. B833 (2022), Bayar and Oset.
- The $T_{c\bar{s}}(2900)$ is more likely to be a failed bound state, or cusp structure around the $D^*K^*, D_s^*\rho$ thresholds. The width of the ρ is responsible for most of its width. There should be a bound state for $J^P = 2^+$ with mass of around 2830 MeV and width 20 MeV.