Effective Field Theories for Hadron Spectroscopy

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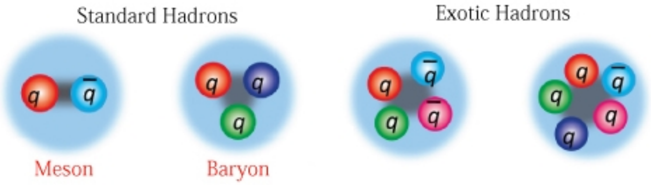
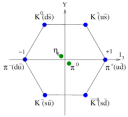
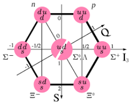
Intro



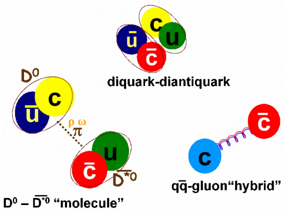
- 'Regular' hadrons: $q\bar{q}$, qqq



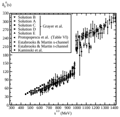


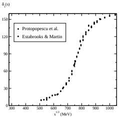
- Exotics: $q\bar{q}q\bar{q}$, $qqqq\bar{q}$, $qqg, \ldots$

  Not $q\bar{q}$: $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$



Light hadrons





Close to ...

$\longrightarrow$ PP th. $\pi\pi$, $K\bar{K}$... PB $K\Lambda$,$\pi\Sigma$, $\bar{K}N$...

$\longrightarrow$ PV th. $K\bar{K}^*$, $\pi\rho$, $\pi\omega$, $\eta\omega$... SB σN...

$\longrightarrow$ VV th. $\rho\rho$, $K^*\bar{K}^*$... VB $\rho(\omega)N$, K^*N...

$\longrightarrow$ Hybrid, Glueball candidate

Particle	J^P	overall
N	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	***

Particle	J^P	Overall status	Status as seen in — $N\bar{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi$, $\Lambda\gamma$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi$, $\Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi$, $\Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	
$\Lambda(1800)$	$1/2^-$	***	***	**	$\Lambda\pi\pi$, $\Sigma(1385)\pi$, $N\bar{K}^*$
$\Lambda(1810)$	$1/2^+$	***	**	**	$N\bar{K}_2^*$
$\Lambda(1820)$	$5/2^+$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	****	****	**	$\Sigma(1385)\pi$, $N\bar{K}^*$
$\Lambda(2000)$	$1/2^-$	*	*	*	

LIGHT UNFLAVORED MESONS ($S = C = B = 0$)

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

See related reviews:

- Form Factors for Radiative Pion and Kaon Decays
- Scalar Mesons below 2 GeV
- $\rho(770)$
- Pseudoscalar and Pseudovector Mesons in the 1400
- $\rho(1450)$ and $\rho(1700)$

Particle	$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(500)$ aka σ; was $f_0(600)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $h_1(1415)$ was $h_1(1380)$	$0^-(1^{+-})$
$a_1(1420)$	$1^-(1^{++})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$

• $f_1(1510)$
• $f_2'(1525)$
$f_2(1565)$
$\rho(1570)$
$h_1(1595)$
• $\pi_1(1600)$
• $a_1(1640)$
$f_2(1640)$
• $\eta_2(1645)$
• $\omega(1650)$
• $\omega_3(1670)$
• $\pi_2(1670)$
• $\phi(1680)$
• $\rho_3(1690)$
• $\rho(1700)$
• $a_2(1700)$
• $f_0(1710)$
$\eta(1760)$
• $\pi(1800)$
$f_2(1810)$
$X(1835)$
• $\phi_3(1850)$

Methods: EFT's, Chiral symmetry, Unitarity

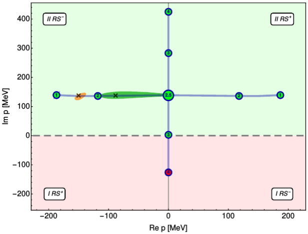
General properties of the scattering amplitudes: Analyticity, Unitarity, Crossing symmetry, applied often in combination with EFT (chiral symmetry)

- Unitarized Chiral Perturbation Theory. Oller, Oset, Pelaez (1997)
- Inverse Amplitude Method. Truon, Herrero, Dobado, Pelaez (1988)
- Roy-Steiner equations based on dispersion relations. Roy, Steiner, Hite (1971)
- N/D method, Oller (1998)
- Bethe-Salpeter ...

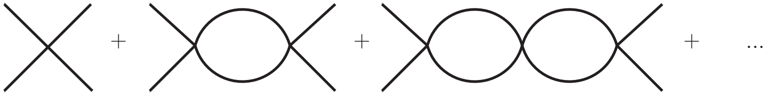
and LQCD!

Example of Application in combination with LQCD data

σ meson. Guo, Alexandru, Molina, Mai, Döring, PRD98 (2018)



Dynamically generated resonances



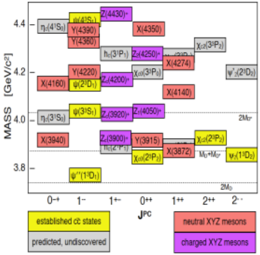
Many suggestions of dynamically generated resonances...

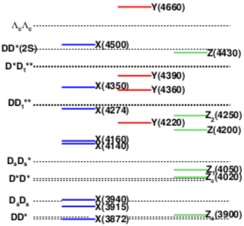
- Oller, Oset, Pelaez, Ramos, Hanhart, Krewald, Speth, Nieves, Inoue, Ruiz-Arriola, Meissner, Vicente-Vacas, Garcia-Recio, Molina, Roca, Geng, Alvarez-Ruso, Alarcon, Albaladejo, Nícola ...
  ... and a very long list of authors!...´

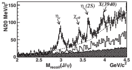
However, no clear statement for them in the light sector since ...

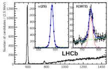
- Most of these exotic candidates can overlap with $q\bar{q}/qqq$ except for those with non-$q\bar{q}$ quantum numbers like $\pi_1(1400)$, $\pi_1(1600)$ ...

Heavy hadrons

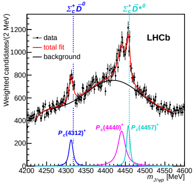








State	M_0 [MeV]	Γ[MeV]
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$



Clear evidence of exotic states!

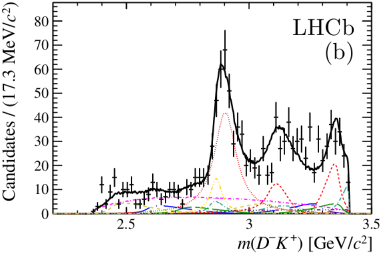
- Hidden-charm charged tetraquarks $Z_c^+ \sim c\bar{d}u\bar{c}$ $(D^{(*)}\bar{D}^{(*)})$.
  Hidden-strange candidate? $a_0(980)$? ... more?
- Hidden-charm (strange) pentaquarks $P_{c(s)}^+ \sim c\bar{c}uud(s)$, $(\bar{D}^{(*)}\Sigma_c^{(*)}(\Xi_c^{(*)}))$.
  Hidden-strange candidate? $N^*(1535)$, (strange) $\Lambda(1405)$, ...more?

Flavor exotic tetraquark $T_{cs}(2900)$

LHCb (2020)

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

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

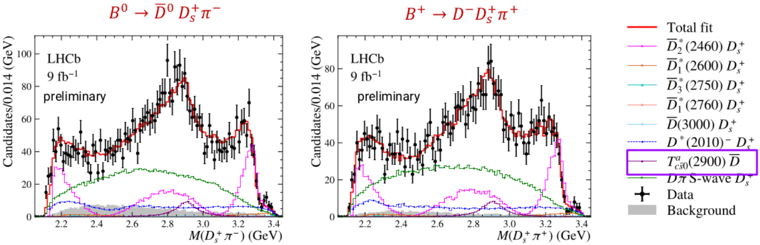


R. Aaij et al. (LHCb Collaboration), PRL125(2020), PRD102(2020)

New exotic tetraquark seen in $D_s^+\pi^+$

LHCb (2022)

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



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

arXiv:2212.02717

D^*K^* th.: 2903 MeV

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

Local-Hidden-Gauge Formalism

The hidden gauge formalism

Bando, Kugo, Yamawaki, PRL54,1215

Lagrangian

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

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

Upon expansion of $[V_\mu - \frac{i}{g}\Gamma_\mu]^2$, $\mathcal{L}'s$

$$\mathcal{L}_{V\gamma} = -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q \rangle, \mathcal{L}_{VPP} = -ig \langle V^\mu [P, \partial_\mu P] \rangle, \mathcal{L}_{\gamma PP} = ieA_\mu \langle Q[P, \partial_\mu P] \rangle, \ldots$$

$$\frac{F_V}{M_V} = \frac{1}{\sqrt{2}g}, \qquad \frac{G_V}{M_V} = \frac{1}{2\sqrt{2}g}, \qquad F_V = \sqrt{2}f, \qquad G_V = \frac{f}{\sqrt{2}}, \qquad g = \frac{M_V}{2f}$$

Vector-vector scattering Bando,Kugo,Yamawaki

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

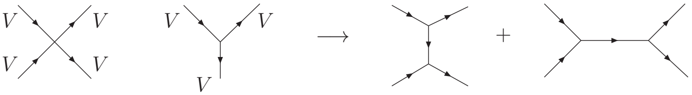
$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle$$

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

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu]$$

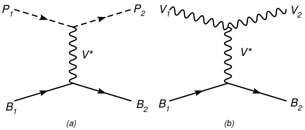
$$g = \frac{M_V}{2f}$$

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



a) b) c) d)

PB and VB interaction



$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu [V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)$$

$$t_{P_1P_2V} = g_{15_F}\, C_{15_F}(15 \otimes 15)\,(q_1+q_2)_\mu \epsilon^\mu$$

$$t_{B_1\bar{B}_2V} = \{g_{15_1}\, C_{15_1}(20' \otimes \bar{20}') + g_{15_2}\, C_{15_2}(20' \otimes \bar{20}')$$

$$+ g_1\, C_1(20' \otimes \bar{20}')\}\bar{u}_{r'}(p_2)\gamma \cdot \epsilon\, u_r(p_1)$$

with $g_{15_F} = -2\sqrt{2}g$. g_{15_1}, g_{15_2} and g_1 are evaluated demanding

1) The couplinga $p\bar{p} \to J/\psi$, $p\bar{p} \to \phi$ should be zero by OZI rules,
2) The coupling $p\bar{p} \to \rho^0$ should be the one obtained in SU(3).

$$g_{15_1} = -g; \qquad g_{15_2} = 2\sqrt{3}\,g; \qquad g_1 = 3\sqrt{5}\,g\ .$$

Bethe-Salpeter equation

$$T = [I - VG]^{-1}V$$

New exotic hadrons

Pentaquark states

Wu, Molina, Oset, Zou (2010)

$$V_{ab(P_1 B_1 \to P_2 B_2)} = \frac{C_{ab}}{4f^2}(q_1^0 + q_2^0)$$

$$V_{ab(V_1 B_1 \to V_2 B_2)} = \frac{C_{ab}}{4f^2}(q_1^0 + q_2^0)\vec{\epsilon}_1 \cdot \vec{\epsilon}_2$$

	$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	ρN	ωN	ϕN	$K^*\Sigma$	$K^*\Lambda$
$\bar{D}^*\Sigma_c$	-1	0	$-1/2$	$\sqrt{3}/2$	0	1	0
$\bar{D}^*\Lambda_c^+$		1	$-3/2$	$-\sqrt{3}/2$	0	0	1

C_{ab} for the VB system in the sector $I = 1/2$, $S = 0$.

	$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c^{'}$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$\bar{K}^*N$	$K^*\Xi$
$\bar{D}_s^*\Lambda_c^+$	0	$-\sqrt{2}$	0	0	0	-1	$-\sqrt{3}$	0
$\bar{D}^*\Xi_c$		-1	0	$-3/2$	$-1/2$	0	0	$\sqrt{3/2}$
$\bar{D}^*\Xi_c^{'}$			-1	$\sqrt{3}/2$	$\sqrt{3}/2$	0	0	$1/\sqrt{2}$

C_{ab} for the VB system in the sector $I = 0$, $S = -1$.

PB resonances (units in MeV)

(I,S)	M	Γ	Γ_i					
$(1/2,0)$			πN	ηN	$\eta' N$	$K\Sigma$		$\eta_c N$
	4261	56.9	3.8	8.1	3.9	17.0		23.4
$(0,-1)$			$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$\eta'\Lambda$	$K\Xi$	$\eta_c\Lambda$
	4209	32.4	15.8	2.9	3.2	1.7	2.4	5.8
	4394	43.3	0	10.6	7.1	3.3	5.8	16.3

VB resonances

(I,S)	M	Γ	Γ_i					
$(1/2,0)$			ρN	ωN	$K^*\Sigma$			$J/\psi N$
	4412	47.3	3.2	10.4	13.7			19.2
$(0,-1)$			$\bar{K}^*N$	$\rho\Sigma$	$\omega\Lambda$	$\phi\Lambda$	$K^*\Xi$	$J/\psi\Lambda$
	4368	28.0	13.9	3.1	0.3	4.0	1.8	5.4
	4544	36.6	0	8.8	9.1	0	5.0	13.8

$\Lambda_b \to p + J/\psi + K^-$

Experimental P_c states (LHCb, 2019)

M (MeV)	Γ (MeV)
$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2^{+5.7}_{-1.9}$
P_{cs} states (LHCb, 2020)	
$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$

Pentaquarks states

LHCb 2015.

$P_c^+(4380)$, $M = (4380 \pm 8 \pm 29)$ MeV, $\Gamma = (205 \pm 18 \pm 86)$ MeV, and
$P_c^+(4450)$, $M = (4449.8 \pm 1.7 \pm 2.5)$ MeV, $\Gamma = (39 \pm 5 \pm 19)$ MeV
Assignments: $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ are possible.

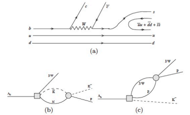


FIG. 1: Mechanisms for the $\Lambda_b \to J/\psi K^- p$ reaction implementing the final state interaction

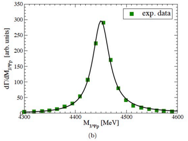
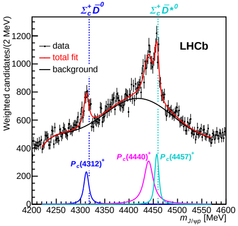


FIG. 2: Results for the $K^- p$ and $J/\psi\, p$ invariant mass distributions compared to the data of ref. [24].

The theoretical analysis of the $\Lambda_b \to J/\psi K^- p$ Roca, Nieves, Oset, PRD92 (2015)supports the $J^P = 3/2^-$ assignment of the pentaquark state, and its nature as $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ molecule.



In 2019 the new experimental analysis shows one more pentaquark, $P_c(4312)$ and $P_c(4450)$ splits into two.

Pentaquark states

- Generalized HGF formalism with HQSS Xiao, Nieves, Oset (2013,2019)

Mass	Width	Main channel	J^P	Experiment
4306.4	15.2	$\bar{D}\Sigma_c$	$1/2^-$	$P_c(4312)$
4453.0	23.4	$\bar{D}^*\Sigma_c$	$1/2^-$	$P_c(4440)$
4452.5	3.0	$\bar{D}^*\Sigma_c$	$3/2^-$	$P_c(4457)$

  Heavy quarks act as spectators if we exchange light vectors. Heavy quark spin symmetry is automatically fulfilled.

- OMEP, Interaction given by One-Meson-Exchange Potential, Yamaguchi, Santopinto, PRD96 (2017)
- Coupling meson-baryon with compact $5q$ state, Hosaka, Tacheuchi, Takizawa, Yamaguchi, Santopionto (2017)
- Analysis of the J/ψ data with coupled-channel involving both one-pion exchange as well as short-range interaction, Du, Baru, Guo, Hanhart, Meissner, Wang PRL124 (2020)

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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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 $D^*_sD^*$ 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.

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- 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 $D^*D^*_s$ $c\bar{q}c\bar{s}$

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	$\sqrt{s}_{\rm exp}$	$\Gamma_{\rm exp}$
$1, -1$	$D^* \bar{K}^*$	$0[0^+]$	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: 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 $\alpha = -1.6$.

D^*D^* and $D^*D_s^*$ states

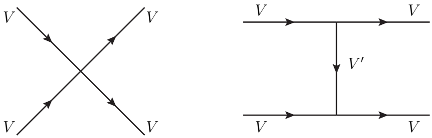
T_{cc} states from D^*D^*, $D^*D_s^*$ Dai,Molina,Oset, PRD105(2022)

DD^*: $T_{cc}(3875)$, LHCb, Nature(2022), $\delta m = -360 \pm 40^{+4}_{-0}$ KeV, $\Gamma = 48 \pm 2^{+0}_{-14}$ KeV

Signature in LQCD Virtual bound state, $m_\pi \simeq 280$ MeV, Padmanath, Prelovsek PRL129(2022)

See Eulogio's talk on Thursday, 2.30pm

Feijoo, Liang, Oset, PRD104 (2021) Local Hidden-Gauge Approach D^0D^{*+}, D^+D^{*0} correlation functions; Inverse problem, Vidana, Feijoo, Albaladejo, Oset, Nieves, 2303.06079, 2304.01870 (2023)



(a) (b)

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

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

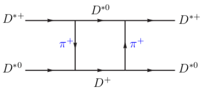
Repulsion for $I = 1$

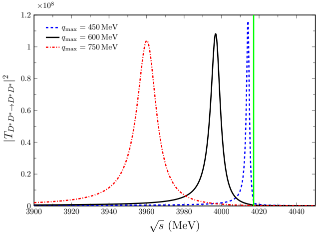
J	Amplitude	Contact	V-exchange	$\sim$ Total
1	$D^*D^* \to D^*D^*$	0	$\frac{g^2}{4}\left(\frac{2}{m^2_{J/\psi}} + \frac{1}{m^2_\omega} - \frac{3}{m^2_\rho}\right)\{(p_1+p_3).(p_2+p_4) + (p_1+p_4).(p_2+p_3)\}$	$-25.4g^2$
1	$D_s^*D^* \to D_s^*D^*$	0	$-\frac{g^2(p_1+p_4)(p_2+p_3)}{m^2_{K^*}} + \frac{g^2(p_1+p_3)(p_2+p_4)}{m^2_{J/\psi}}$	$-19.5g^2$

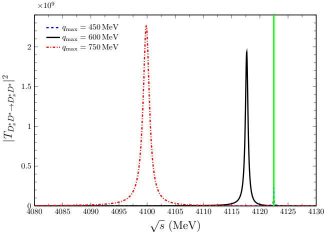
T_{cc} states from $D^*D^*/D^*D_s^*$

$V \rightarrow V + i\, ImV_{\rm box}(DD^*)$

$T^{-1} = V^{-1} - G$







	$q_{\rm max} = 450$ MeV	$q_{\rm max} = 420$ MeV
$M_{D^*D^*}$	4014.08 MeV	4015.54 MeV
$B_{D^*D^*}$	3.23 MeV	1.56 MeV
$\Gamma_{D^*D^*}$	2.3 MeV	1.5 MeV
$M_{D_s^*D^*}$	4122.46 MeV (cusp)	4122.46 MeV (cusp)
$\Gamma_{D_s^*D^*}$	$70 - 100$ KeV	$70 - 100$ KeV

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

Local Hidden Gauge Approach

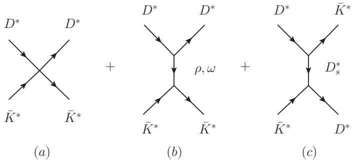


Figure 1: $D^*\bar{K}^* \to D^*\bar{K}^*$ interaction

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 $I = 0$.

Attractive for $I = 0$ and repulsive for $I = 1$.

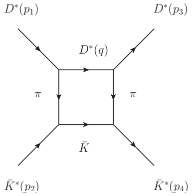
Decay of the $T_{cs}(2900)$ to $D^*\bar{K}$

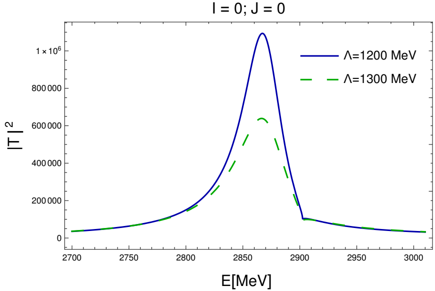
Molina, Oset PLB811 2020, $\alpha = -1.474$, $\Lambda = 1300$.

$I(J^P)$	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 3: New results including the width of the D^*K channel.

$$T = [I - VG]^{-1} V$$





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).

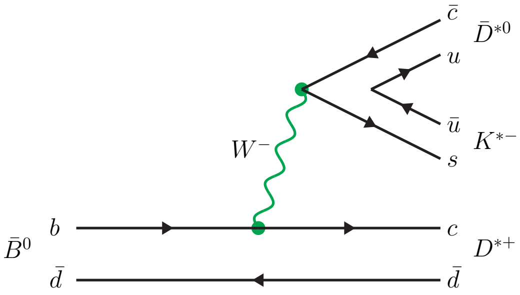


Figure 2: Diagrammatic decay of the $\bar{B}^0 \to \bar{D}^{*0}D^{*+}K^{*-}$ at the quark level.

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

Hadronization + decay; $\bar{B}^0 \to D^{*+}\bar{D}^{*0}K^-$

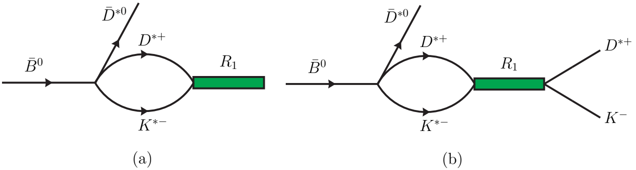


Figure 3: (a) Rescattering of $D^{*+}K^{*-}$ to produce R_1; (b) Decay of R_1 to $D^{*+}K^-$. Dai, Molina and Oset, PLB832 (2022)

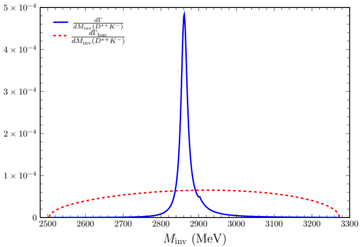
$$\frac{d\Gamma}{dM_{\rm inv}(D^{*+}K^-)} = \frac{1}{(2\pi)^3}\frac{1}{4M^2_{\bar{B}^0}}\, p_{\bar{D}^{*0}}\tilde{p}_{K^-} \sum |t'|^2$$

See also:

$\bar{B}^0 \to D^{*+}K^-\bar{K}^{*0}$, PRD105(2022);

2^+: $B^+ \to D^+D^-K^+$,

PLB833(2022), Bayar, Oset.



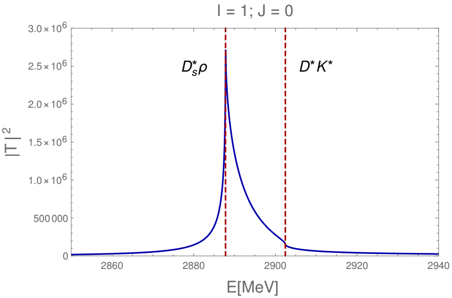
The $T_{c\bar{s}}(2900)$

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

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
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
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
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 $I=1$. $C=1; S=1; I=1$.

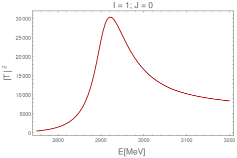
The interaction is attractive for both $I=0$ and $I=1$, favoring a $J^P = 2^+$ state. (see PRD82 (2010) Molina, Branz, Oset, for $I=0$)

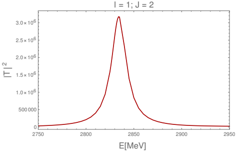
$C = 1, S = 1, I = 1$ The $T_{c\bar{s}}(2900)$

New results, $\alpha = -1.474$ to obtain the $T_{cs}(2900)$ state in $D^*\bar{K}^*$.

Convolution due to the vector meson mass distribution ρ, K^*

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



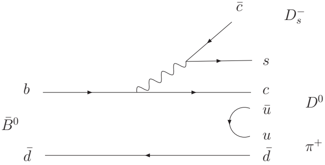


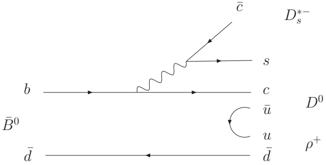
$I(J^P)$	M[MeV]	Γ[MeV]	Coupled channels	state
$1(0^+)$	2920	130	$D^*K^*, D_s\rho$	$T_{c\bar{s}}(2900)$
$1(1^+)$	2922	145		?
$1(2^+)$	2835	20		?

Table 5: PRD107(2023), Exp. $(m, \Gamma) = (2908 \pm 11 \pm 20, 136 \pm 23 \pm 11)$ MeV

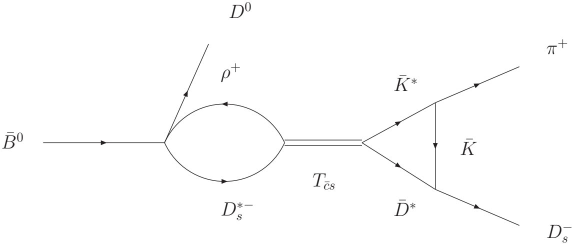
Production of the $T_{\bar{c}s}(2900)$

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





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

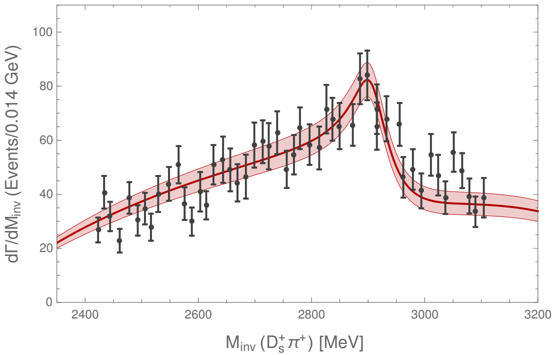


Production of the $T_{\bar{c}s}(2900)$ in B decays

$$T(E) = aG(E)_{D_s^*\rho}\, t_{D_s^*\rho\to\bar{D}^*\bar{K}^*}(E)\, t_L(E) + b \quad (3)$$

$E = M_{inv}(\pi^+ D_s^-)$; a, b parameters; t_L amplitude for the triangle loop.

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



$D_{s0}(2317)$ quark mass dependence

Quark mass dependence of the $D(D^*)$ mesons

Heavy Hadron Chiral Perturbation Theory (HHχPT)

E. Jenkins, NPB412 (1994)

$$\frac{1}{4}(D+3D^*) = m_H + \alpha_a - \sum_{X=\pi,K,\eta} \beta_a^{(X)} \frac{M_X^3}{16\pi f^2} + \sum_{X=\pi,K,\eta} \left(\gamma_a^{(X)} - \lambda_a^{(X)}\alpha_a\right) \frac{M_X^2}{16\pi^2 f^2} \log\left(M_X^2/\mu^2\right) + c_a$$

$$(D^* - D) = \Delta + \sum_{X=\pi,K,\eta} \left(\gamma_a^{(X)} - \lambda_a^{(X)}\Delta\right) \frac{M_X^2}{16\pi^2 f^2} \log\left(M_X^2/\mu^2\right) + \delta c_a$$

$\mu = 770$ MeV; $g^2 = 0.55$ MeV (Decay of the D^* meson)

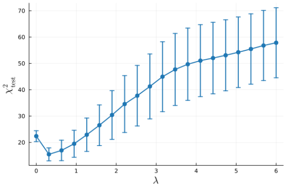
$$\left.\begin{aligned} \frac{1}{4}(D+3D^*) &= m_H + f(\sigma, a, b, c, d) \\ (D^* - D) &= \Delta + g(\Delta^{(\sigma)}, \Delta^{(a)}) \end{aligned}\right\}$$

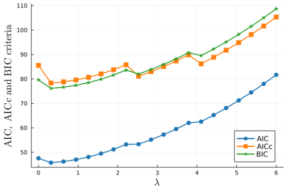
9 parameters, but different collaborations/scale settings, $7 + 2 \times 7 = 21$ parameters, ~ 80 data points

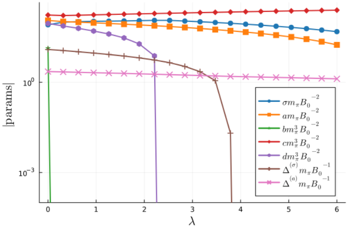
ETMC, PACS, HSC, CLS, RQCD, S.Prelovsek, MILC

LASSO + information criteria;

$$\chi^2_P = \chi^2 + \lambda \sum_i^n |p_i|; \quad \text{Data} = \text{Training}\,(70\%) + \text{Test}\,(30\%) \tag{4}$$







$$\frac{1}{4}(m_D + 3m_{D^*}) = m_H + f(\sigma, a, \not{b}, c, d)$$

$$m_{D^*} - m_D = \Delta + g(\Delta^{(\sigma)}, \Delta^{(a)})$$

$D(D^*)$ quark mass dependence

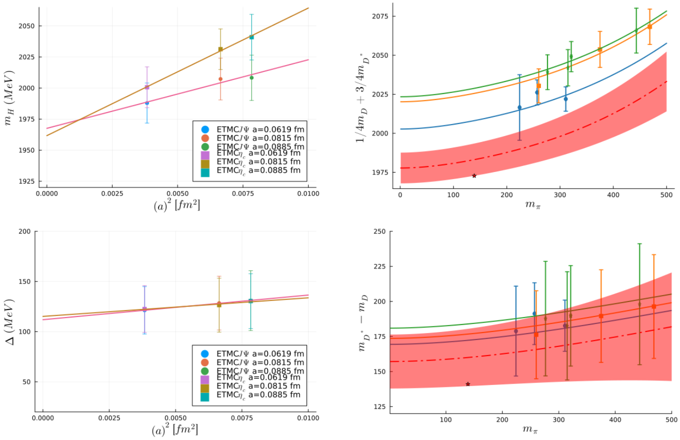


Figure 5: Extrapolation to the physical point of the ETMC data.

Quark mass dependence of the $D_{s0}(2317)$ resonance in DK

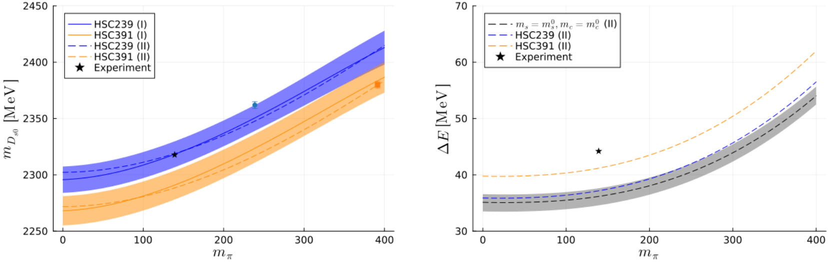
Potential $V(s)$ consistent with HQSS, See Fernando's talk at 2.30pm

See also L.S. Geng and Albaladejo's talk about $D_{s0}(2317)$ (Femtoscopy)

$$V(s) = V_{DK}(s) + V_{\rm ex}(s); \qquad 1 - Z \simeq 0.7 - 0.8$$

2306.01848

$$V_{DK} = -\frac{s-u}{2f^2} \quad ; V_{\rm ex} = \frac{V_{c\bar{s}}^2}{s - m_{c\bar{s}}^2} \tag{5}$$



$m_\pi = 236$ MeV; $a_t^{-1} = 5.667$ GeV; $a_t M_{\eta_c} = 0.2412$, $M_{\eta_c} = 2986$ MeV;

$m_\pi = 391$ MeV; $a_t^{-1} = 6.079$ GeV; $a_t M_{\eta_c} = 0.2735$; $M_{\eta_c} = 2963$ MeV;

Decay width of the $D_{s0}^*(2317)$ to $D_s^+\pi^0$

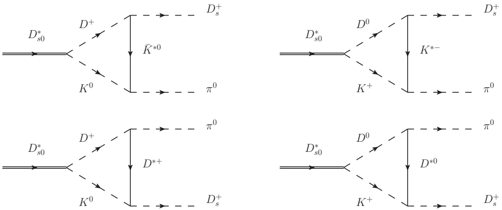


Figure 6: Feynman diagrams of the $D_s^{*0} \to D_s^+\pi^0$.

$\pi^0 - \eta$ mixing

$$\tilde{\pi}^0 = \pi^0 \cos\tilde{\epsilon} + \eta_8 \sin\tilde{\epsilon}$$

$$\tilde{\eta} = -\pi^0 \sin\tilde{\epsilon} + \eta_8 \cos\tilde{\epsilon}$$

with $\eta_8 = \frac{2\sqrt{2}}{3}\eta - \frac{1}{3}\eta'$

$$g_X = \frac{g_{DK}^{(I=0)}}{\sqrt{2}}$$

$$\Gamma_X = |\vec{p}_f| \frac{|t|^2}{8\pi m_X^2} \qquad (6)$$

$$\boxed{\Gamma_{D_{s0}^*} = 100 \pm 30 \ \mathrm{KeV}}$$

H. L. Fu et al., 120^{+18}_{-4} MeV, EPJA58(2022), M. Cleven,

$c\bar{s}$ state: $\Gamma = 7.83^{+1.97}_{-1.55}$ KeV

M. Han et al., 2305.04250 (2023)

Conclusions

Conclusions

- The HGF has predicted many exotic states. Some of them discovered. A new table of exotic particles is coming ...
- The $X_0(2866)$ or $T_{cs}(2900)$ is compatible with a $D^*\bar{K}^*$ resonance decaying to $D\bar{K}$. Proposed reactions to observe the 1^+ state:
  $\bar{B}^0 \to D^{*+}\bar{D}^{*0}K^-$, PLB832 (2022), Dai, Molina, Oset,
  $\bar{B}^0 \to D^{*+}K^-\bar{K}^{*0}$, PRD105 (2022); and the 2^+ state:
  $B^+ \to D^+D^-K^+$, PLB833 (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 combination of LQCD with EFT's is a usefool tool to extract the properties or esonances with high accuracy
- The study of the pion mass dependence of the $D_{s0}(2317)$ supports the DK molecular picture