Properties of heavy mesons at finite temperature

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Outline

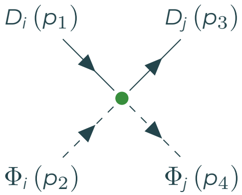
Motivation

- Heavy-ion-collision (HIC) programmes in on-going and upcoming experimental facilities (RHIC, LHC, FAIR) highly demand the theoretical study of hadronic properties under extreme conditions of temperature and density.
- We focus on finite-temperature mesonic (pionic) matter to study the high temperature and low density region of the QCD phase diagram (matter generated in HICs in RHIC and LHC).
- Heavy mesons ($D^{(*)}$, $D_s^{(*)}$, $B^{(*)}$, $B_s^{(*)}$) modify their properties in hot pionic matter.
- Consequences in the behaviour of excited mesonic states, such as $D_{s0}^*(2317)^{\pm}$ and $D_0^*(2300)^0$, dynamically generated in a heavy-light molecular model at finite temperature.

Model at $T = 0$

1

Chiral Lagrangian to NLO in the chiral expansion and LO in the heavy-quark expansion



$$\mathcal{L}(D^{(*)},\Phi) = \mathcal{L}_{\rm LO}(D^{(*)},\Phi) + \mathcal{L}_{\rm NLO}(D^{(*)},\Phi)$$

$$D = \begin{pmatrix} D^0 & D^+ & D_s^+ \end{pmatrix}, \quad D^*_\mu = \begin{pmatrix} D^{*0} & D^{*+} & D_s^{*+} \end{pmatrix}_\mu$$

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

$$\begin{aligned} V^{ij}(s,t,u) \quad &= \quad \frac{1}{f_\pi^2}\Big[\frac{C^{ij}_{\rm LO}}{4}(s-u) - 4C^{ij}_0 h_0 + 2C^{ij}_1 h_1 \\ &- \quad 2C^{ij}_{24}\Big(2h_2(p_2\cdot p_4) + h_4\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big) \\ &+ \quad 2C^{ij}_{35}\Big(h_3(p_2\cdot p_4) + h_5\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big)\Big] \end{aligned}$$

$C^{ij}_{\rm LO,0,1,24,35}$: isospin coefficients of the scattering amplitudes of $D^{(*)}$, $D_s^{(*)}$ mesons with π, K, $\bar{K}$, η mesons for the transition $i \to j$.

Model at $T = 0$

1

Chiral Lagrangian to NLO in the chiral expansion and LO in the heavy-quark expansion

$\mathcal{L}_{\mathrm{LO}}$

E.E. Kolomeitsev and M.F.M. Lutz, Phys. Lett. B 582, 39 (2004)

M.F.M. Lutz and M. Soyeur, Nucl. Phys. A 813, 14 (2008)

F.K. Guo, C. Hanhart and U.G. Meissner, Eur. Phys. J. A 40, 171 (2009)

L. S. Geng, N. Kaiser, J. Martin-Camalich and W. Weise, Phys. Rev. D 82, 054022 (2010)

$\mathcal{L}_{\mathrm{NLO}}$

LECs $h_0, \ldots, h_5$ fitted to Lattice QCD data

L. Liu, K. Orginos, F.K. Guo, C. Hanhart and U.G. Meissner, Phys. Rev. D 87, no. 1, 014508 (2013)

L. Tolos and J. M. Torres-Rincon, Phys. Rev. D 88, 074019 (2013)

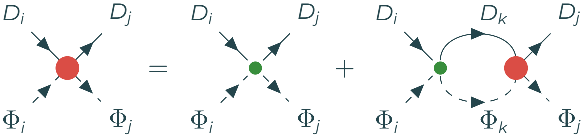
M. Albaladejo, P. Fernandez-Soler, F.K. Guo and J. Nieves, Phys. Lett. B 767, 465 (2017)

Z.H. Guo, L. Liu, U.G. Meißner, J.A. Oller and A. Rusetsky, Eur. Phys. J. C 79, no. 1, 13 (2019) ✓

Model at $T = 0$

2

Unitarization using the coupled-channel Bethe-Salpeter approach



$$T_{ij} = V_{ij} + V_{ik} G_k T_{kj} \quad \rightarrow \quad T = (1 - VG)^{-1} V$$

- Loop function

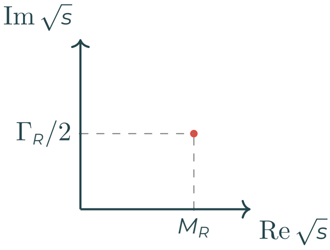
$$G_k = i \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_{D,k}^2 + i\varepsilon} \frac{1}{(P-q)^2 - m_{\Phi,k}^2 + i\varepsilon}$$

regularized with a cutoff $|\vec{q}| < \Lambda$

Meson-meson molecules

- Identification of resonances in the unitarized scattering amplitudes
- Analytical continuation and poles in the complex-energy plane:

- Mass
  $M_R = \mathrm{Re}\,\sqrt{s_R}$
- Half-width
  $\Gamma_R/2 = \mathrm{Im}\,\sqrt{s_R}$
- Coupling constants $|g_i|$
  strength of i^{th}-channel
  in the generation of
  the resonance
- Compositeness X_i
  amount of i^{th}-channel
  component of the resonance



Results at $T = 0$

Parameters of the model and poles: $D_0^*(2300)^0$ (before was $D_0^*(2400)^0$) and $D_{s0}^*(2317)^{\pm}$

h_0	h_1	h_2	h_3	$h_4 \bar{M}_D^{(*)}$	$h_5 \bar{M}_D^{(*)}$	Λ
0.033	0.45	-0.12	1.67	-0.02	-0.81	$800\,\mathrm{MeV}$

Values of the LECs and the cutoff Λ.

(C, S, I)	Channels	Threshold (MeV)
$(1, 0, 1/2)$	$D\pi$	2005.28
	$D\eta$	2415.10
	$D_s\bar{K}$	2463.98
$(1, 0, 3/2)$	$D\pi$	2005.28
$(1, 1, 0)$	DK	2364.88
	$D_s\eta$	2516.20
$(1, 1, 1)$	$D_s\pi$	2106.38
	DK	2364.88

Channels in isospin basis.

Results at $T = 0$

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	DK	2364.88

Channels in isospin basis.

(C, S, I)	RS	$M_R\,(\mathrm{MeV})$	$\Gamma_R/2\,(\mathrm{MeV})$	$\lvert g_i\rvert\,(\mathrm{GeV})$	X_i
$(1, 0, 1/2)$	$(-, +, +)$	2081.9	86.0	$\lvert g_{D\pi}\rvert = 8.9$	$X_{D\pi} = 0.29 - i\,0.27$
				$\lvert g_{D\eta}\rvert = 0.4$	$X_{D\eta} = 0.00 + i\,0.00$
				$\lvert g_{D_s\bar{K}}\rvert = 5.4$	$X_{D_s\bar{K}} = 0.01 + i\,0.05$
	$(-, -, +)$	2521.2	121.7	$\lvert g_{D\pi}\rvert = 6.4$	$X_{D\pi} = 0.02 + i\,0.09$
				$\lvert g_{D\eta}\rvert = 8.4$	$X_{D\eta} = 0.15 - i\,0.27$
				$\lvert g_{D_s\bar{K}}\rvert = 14.0$	$X_{D_s\bar{K}} = 0.43 + i\,0.49$
$(1, 1, 0)$	$(+, +, +)$	2252.5	0.0	$\lvert g_{DK}\rvert = 13.3$	$X_{DK} = 0.66 + i\,0.00$
				$\lvert g_{D_s\eta}\rvert = 9.2$	$X_{D_s\eta} = 0.17 + i\,0.00$

Poles, couplings and compositeness.

Finite temperature

M. Cleven, V. K. Magas and A. Ramos, Phys. Rev. C 96, no. 4, 045201 (2017)

M. Cleven, V. K. Magas and A. Ramos, arXiv:1906.06116

1

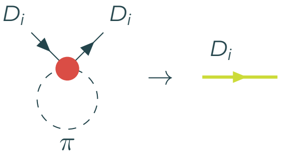
Finite temperature in the Matsubara formalism $(\beta = 1/T)$

$$q^0 \to \omega_n = \frac{i}{\beta} 2\pi n, \quad \int \frac{d^4q}{(2\pi^4)} \to \frac{i}{\beta} \sum_n \int \frac{d^3q}{(2\pi)^3} \quad \text{(bosons)}$$

2

Dressing the heavy meson in the loop function

- D-meson self-energy



Finite temperature

Loop function at $T \neq 0$

$$G_{D_i\Phi_i}(E,\vec{p};T) = \int \frac{d^3q}{(2\pi)^3} \int d\omega \int d\omega' \frac{S_{D_i}(\omega,\vec{q};T) S_{\Phi_i}(\omega',\vec{p}-\vec{q};T)}{E-\omega-\omega'+i\varepsilon} [1 + f(\omega,T) + f(\omega',T)]$$

Spectral functions:

$$S_{D_i}, \quad S_{\Phi_i} \to \frac{\omega_{\Phi_i}}{\omega'} \delta(\omega'^2 - \omega_{\Phi_i}^2), \quad \omega_M = \sqrt{q_M^2 + m_M^2}$$

Bose distribution function at T:

$$f(\omega,T) = \frac{1}{e^{\omega/T} - 1}$$

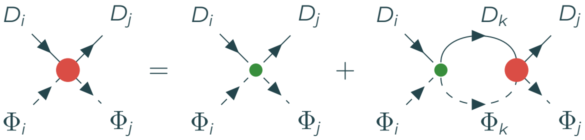
Regularized with a cutoff $|\vec{q}| < \Lambda$

Finite temperature

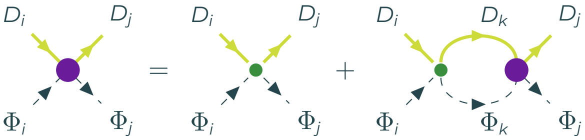
Unitarized T-matrix at $T \neq 0$

$$T_{ij} = V_{ij} + V_{ik} G_k T_{kj}$$

- Iteration 1 $\rightarrow$ Undressed mesons



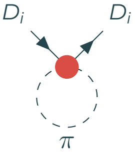
- Iteration > 1 $\rightarrow$ Dressed heavy meson



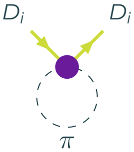
Self-energy at $T \neq 0$

$$\Pi_{D_i}(E,\vec{p};T) = \int \frac{d^3q}{(2\pi)^3} \int d\Omega \frac{E}{\omega_\pi} \frac{f(\Omega,T) - f(\omega_\pi,T)}{E^2 - (\omega_\pi - \Omega)^2 + i\varepsilon} \left(-\frac{1}{\pi} \right) \mathrm{Im}\, T_{D_i\pi}(\Omega, \vec{p}+\vec{q}; T)$$

- Iteration 1



- Iteration > 1

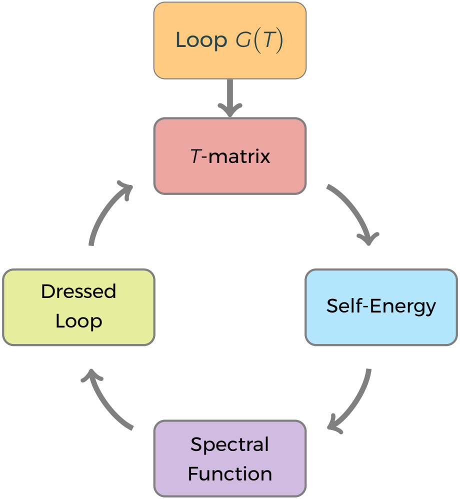


Spectral function

$$S_{D_i}(\omega,\vec{q};T) = -\frac{1}{\pi} \mathrm{Im}\, \mathcal{D}_{D_i}(\omega,\vec{q};T) = -\frac{1}{\pi} \mathrm{Im} \left(\frac{1}{\omega^2 - \vec{q}^2 - m_{D_i}^2 - \Pi_{D_i}(\omega,\vec{q};T)} \right)$$

Finite temperature

Self-consistent approach

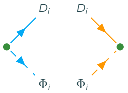


Finite temperature

Physical interpretation of the thermal bath

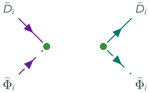
$\text{bath} \to \text{bath} + D_i\Phi_i \qquad \text{bath} + D_i\Phi_i \to \text{bath}$

$$G_{D_i\Phi_i}(E,\vec{p};T) \sim \Bigg\{ \frac{[1+f(\omega_{D_i},T)][1+f(\omega_{\Phi_i},T)] - f(\omega_{D_i},T)f(\omega_{\Phi_i},T)}{E-\omega_{D_i}-\omega_{\Phi_i}+i\varepsilon}$$



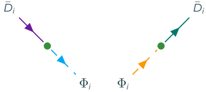
$\text{bath} + \bar{D}_i\bar{\Phi}_i \to \text{bath} \qquad \text{bath} \to \text{bath} + \bar{D}_i\bar{\Phi}_i$

$$+ \frac{f(\omega_{D_i},T)f(\omega_{\Phi_i},T) - [1+f(\omega_{D_i},T)][1+f(\omega_{\Phi_i},T)]}{E+\omega_{D_i}+\omega_{\Phi_i}+i\varepsilon}$$



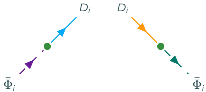
$\text{bath} + \bar{D}_i \to \text{bath} + \Phi_i \qquad \text{bath} + \Phi_i \to \text{bath} + \bar{D}_i$

$$+ \frac{f(\omega_{D_i},T)[1+f(\omega_{\Phi_i},T)] - f(\omega_{\Phi_i},T)[1+f(\omega_{D_i},T)]}{E+\omega_{D_i}-\omega_{\Phi_i}+i\varepsilon}$$



$\text{bath} + \bar{\Phi}_i \to \text{bath} + D_i \qquad \text{bath} + D_i \to \text{bath} + \bar{\Phi}_i$

$$+ \frac{f(\omega_{\Phi_i},T)[1+f(\omega_{D_i},T)] - f(\omega_{D_i},T)[1+f(\omega_{\Phi_i},T)]}{E-\omega_{D_i}+\omega_{\Phi_i}+i\varepsilon} \Bigg\}$$



At zero temperature $f(\omega, T=0)=0$

Finite temperature

Physical interpretation of the thermal bath

$$G_{D_i\Phi_i}(E,\vec{p};T) \sim \Bigg\{ \frac{[1+f(\omega_{D_i},T)][1+f(\omega_{\Phi_i},T)] - f(\omega_{D_i},T)f(\omega_{\Phi_i},T)}{E-\omega_{D_i}-\omega_{\Phi_i}+i\varepsilon}$$

First branch cut ($T=0$ cut):
$E \geq (m_{D_i}+m_{\Phi_i})$

$$+ \frac{f(\omega_{D_i},T)f(\omega_{\Phi_i},T) - [1+f(\omega_{D_i},T)][1+f(\omega_{\Phi_i},T)]}{E+\omega_{D_i}+\omega_{\Phi_i}+i\varepsilon}$$

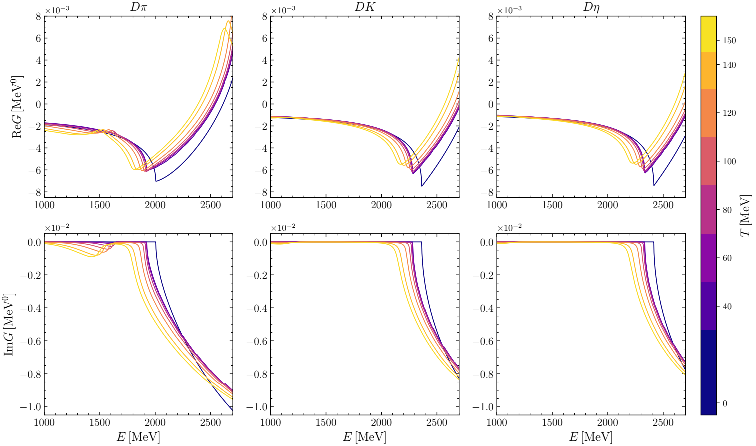
$$+ \frac{f(\omega_{D_i},T)[1+f(\omega_{\Phi_i},T)] - f(\omega_{\Phi_i},T)[1+f(\omega_{D_i},T)]}{E+\omega_{D_i}-\omega_{\Phi_i}+i\varepsilon}$$

$$+ \frac{f(\omega_{\Phi_i},T)[1+f(\omega_{D_i},T)] - f(\omega_{D_i},T)[1+f(\omega_{\Phi_i},T)]}{E-\omega_{D_i}+\omega_{\Phi_i}+i\varepsilon} \Bigg\}$$

Additional branch cut (*Landau* cut):
$E \leq (m_{D_i}-m_{\Phi_i})$

Results at $T \neq 0$

Loop functions at finite temperature: *D* with light mesons

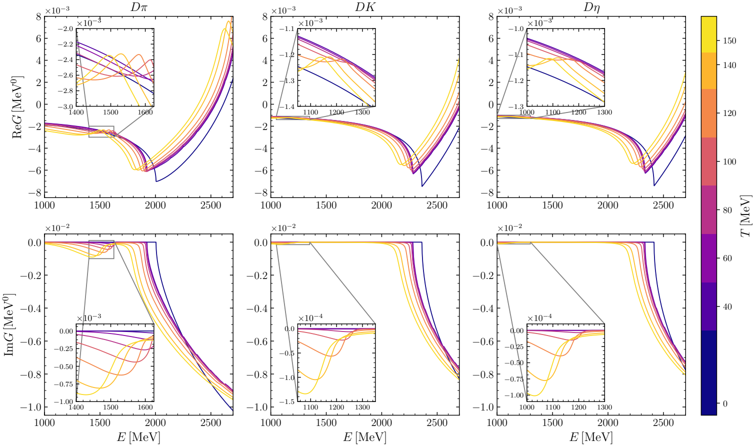


First branch cut ($T = 0$ cut): $E \geq \left(\tilde{m}_D + m_{\Phi_i}\right)$

Additional branch cut (*Landau* cut): $E \leq \left(\tilde{m}_D - m_{\Phi_i}\right)$

Results at $T \neq 0$

Loop functions at finite temperature: D with light mesons

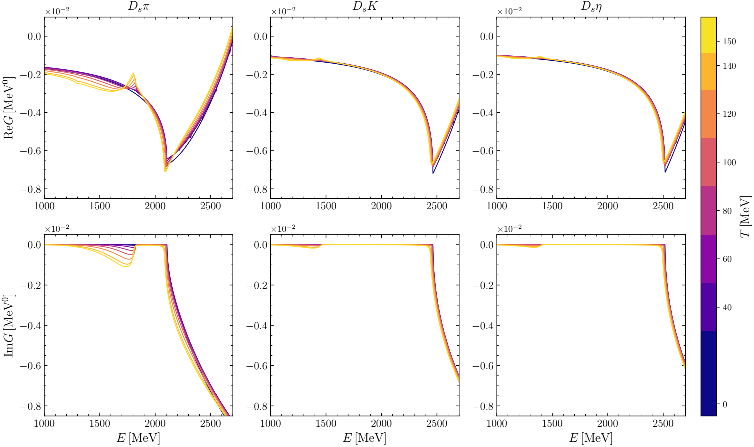


First branch cut ($T = 0$ cut): $E \geq \left(\tilde{m}_D + m_{\Phi_i}\right)$

Additional branch cut (*Landau* cut): $E \leq \left(\tilde{m}_D - m_{\Phi_i}\right)$

Results at $T \neq 0$

Loop functions at finite temperature: D_s with light mesons

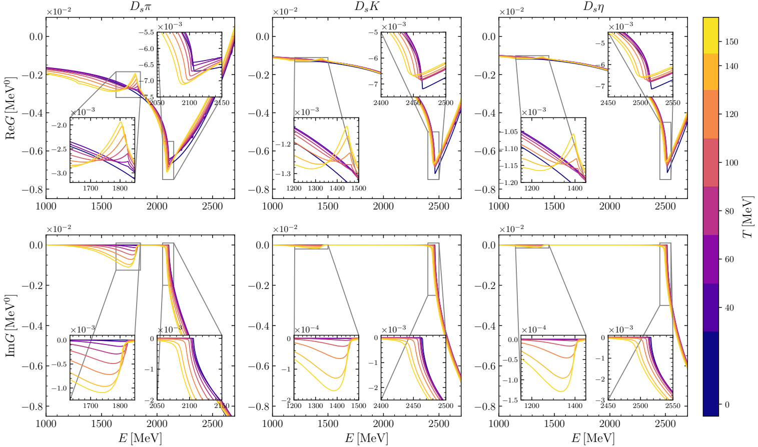


First branch cut ($T = 0$ cut): $E \geq \left(\tilde{m}_{D_s} + m_{\Phi_i}\right)$

Additional branch cut (*Landau* cut): $E \leq \left(\tilde{m}_{D_s} - m_{\Phi_i}\right)$

Results at $T \neq 0$

Loop functions at finite temperature: D_s with light mesons



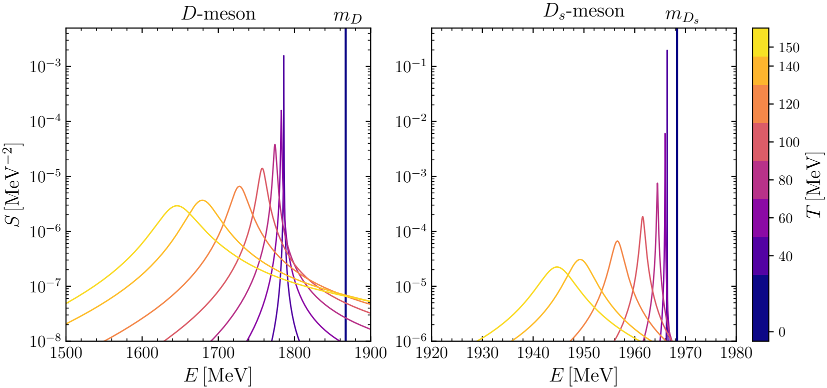
First branch cut ($T = 0$ cut): $E \geq (\tilde{m}_{D_s} + m_{\Phi_i})$

Additional branch cut (*Landau* cut): $E \leq (\tilde{m}_{D_s} - m_{\Phi_i})$

Results at $T \neq 0$

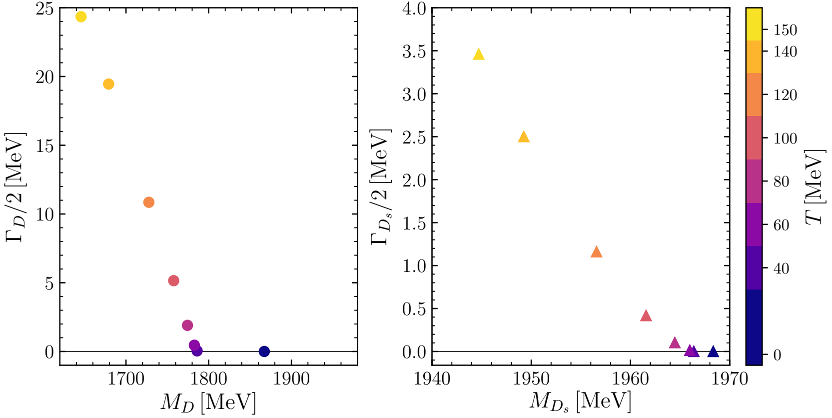
Spectral functions

- Mass shift and width acquisition of the $D_{(s)}$-mesons in a thermal bath



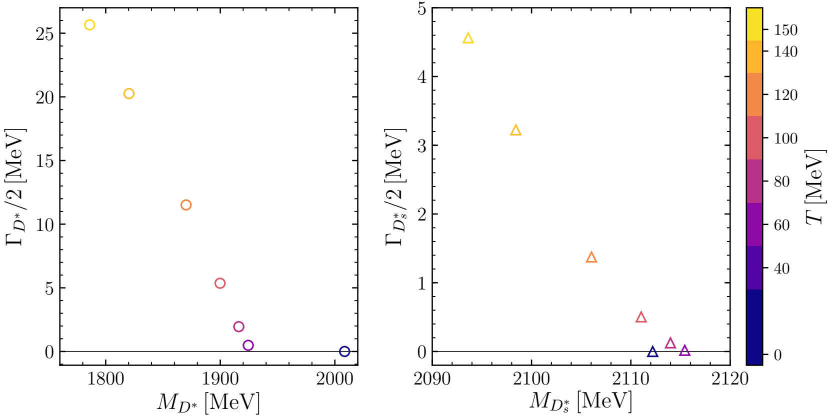
Results at $T \neq 0$

- Mass shift and width acquisition of the $D_{(s)}$-mesons in a thermal bath



Results at $T \neq 0$

- Mass shift and width acquisition of the $D^*_{(s)}$-mesons in a thermal bath



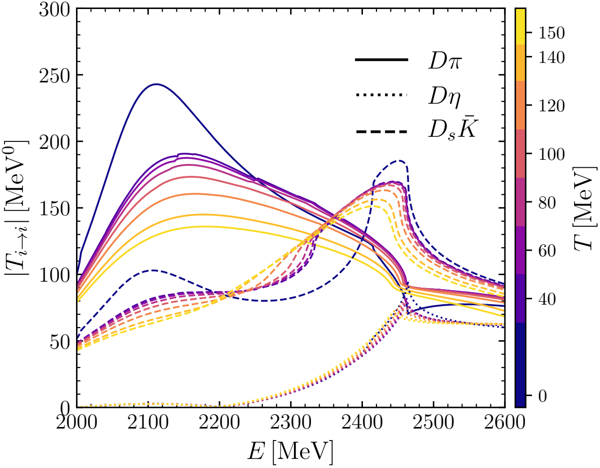
Results at $T \neq 0$

Dynamically generated resonances at finite temperature

Two poles of the $\boldsymbol{D_0^*(2300)^0}$ (before was $D_0^*(2400)^0$)

T-matrix in sector
$(C, S, I) = (1, 0, 1/2)$

Experimental values
$M = 2300 \pm 19\,\mathrm{MeV}$
$\Gamma = 274 \pm 40\,\mathrm{MeV}$

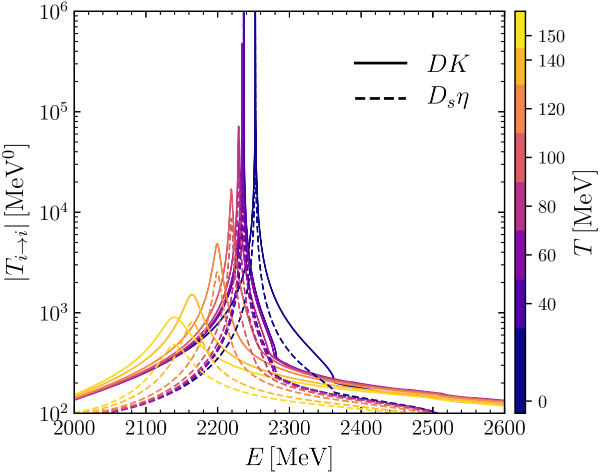


Dynamically generated resonances at finite temperature

$D^*_{s0}(2317)^{\pm}$

T-matrix in sector
$(C, S, I) = (1, 1, 0)$

Experimental values
$M = 2317.8 \pm 0.5\,\mathrm{MeV}$
$\Gamma < 3.8\,\mathrm{MeV}$



Conclusions and Outlook

- We have introduced finite-temperature corrections to the description of the interaction of open charm mesons with light mesons in a self-consistent manner.
- The mass of the charmed $D^{(*)}$- and $D_s^{(*)}$-mesons decrease monotonically with temperature ($\sim 10-13\%$ for the $D^{(*)}$ and $\sim 1\%$ for the $D_s^{(*)}$ at $T = 150\,\mathrm{MeV}$) while they acquire a substantial width ($\sim 50\,\mathrm{MeV}$ for the $D^{(*)}$ and $\sim 7-10\,\mathrm{MeV}$ for the $D_s^{(*)}$ at $T = 150\,\mathrm{MeV}$).
- The dynamically generated resonances shift their mass and get wider as temperature increases.

In the near future we aim to:

- Explore the hidden-charm sector.
- Study transport properties of heavy mesons at finite temperature.
- Extend our calculations to the bottom sector.
- Test our results against Lattice QCD calculations.