Thermal modification of open-charm mesons from an effective hadronic theory

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University of Barcelona
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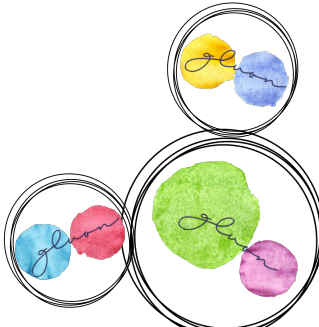
[GM, Angels Ramos, Laura Tolos, Juan Torres-Rincon, Phys.Lett.B 806 (2020)]
[GM, Angels Ramos, Laura Tolos, Juan Torres-Rincon, arXiv:2007.12601]
[GM, Olaf Kaczmarek, Laura Tolos, Angels Ramos, arXiv:2007.15690]

Theory Seminar - Jefferson Lab
September 14, 2020



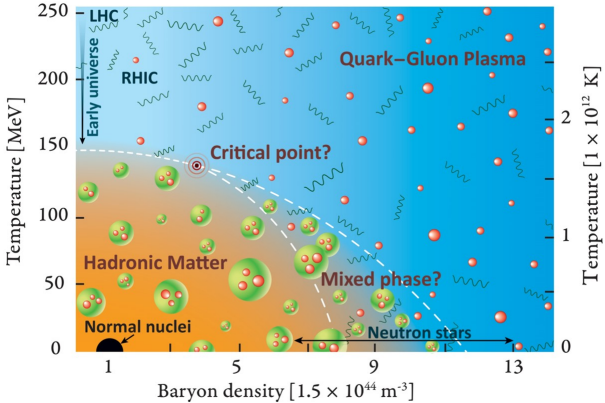
OUTLINE

1. Motivation
2. Hadronic molecular model:
Effective hadronic interaction & Unitarization
3. Results I:
Dynamically generated states at $T = 0$
4. Finite temperature corrections
5. Results II: Thermal modifications
6. Euclidean correlators: comparison with lattice QCD
7. Results III: Open-charm Euclidean correlators
8. Conclusions and Outlook

Motivation

MOTIVATION (I)

→ 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**.



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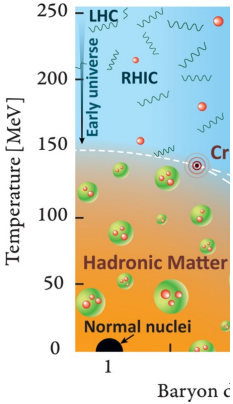

Theoretical tools to study the matter at high temperatures:

- Perturbative theories
- Lattice QCD
- Non-perturbative effective hadronic theories

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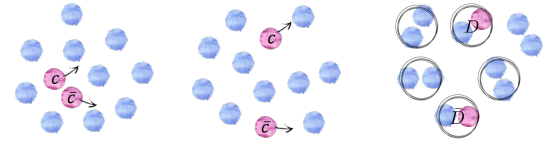

Start of the collision QGP Hadronization

Comover scattering

Quarkonia suppression

- Color screening
- Comover scattering

MOTIVATION (II)

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- Consequences in the behavior of **excited mesonic states**, such as the non-strange $D_0^*(2300)$ and $D_1^*(2430)$ and the strange $D_{s0}^*(2317)$ and $D_{s1}^*(2460)$, dynamically generated in a heavy-light molecular model at finite temperature.

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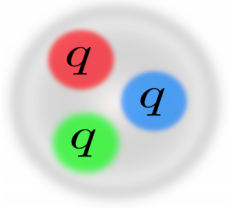
- Spectral functions can be obtained at unphysical meson masses and used to calculate **Euclidean correlators** to compare with lattice QCD results.

Hadronic molecular model:
Effective hadronic interaction & Unitarization

QUARK MODEL

Although the basic constituents in QCD are quarks and gluons, the **conventional quark model** (Gell-Mann, 1964; Zweig, 1964) has been very successful in describing hadron structure.

Baryon



p, n, Λ, Δ, Ξ_c, ...

Meson

π, K, D, B, J/ψ, ...

EXOTIC HADRONS

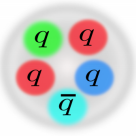
There are many (excited) hadrons that do not accommodate in the qqq or $q\bar{q}$ picture.

Other configurations allowed by QCD, e.g., $q\bar{q}q\bar{q}$, $qqq\bar{q}$, etc., are called **exotic**.

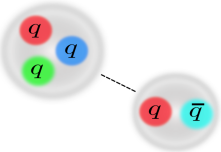
Baryonic systems

Pentaquarks $qqqq\bar{q}$

Compact pentaquark



Meson-baryon molecule



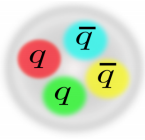
$\Lambda(1405)$, $\Lambda_c(2595)$, $\Lambda_c(2625)$, $P_c(4380)$, $P_c(4450)$, ...

EXOTIC HADRONS

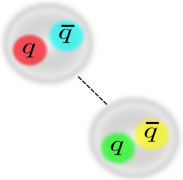
Mesonic systems

Tetraquarks $q\bar{q}q\bar{q}$

Compact tetraquark

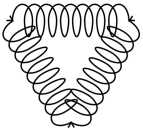


Meson-meson molecule



Hybrid

Glueball



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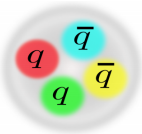
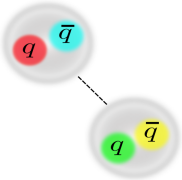
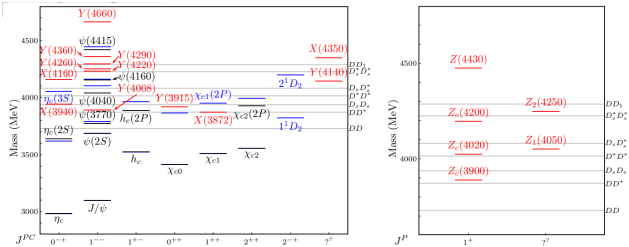


Meson-meson molecule





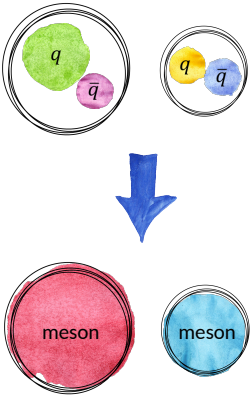
A. Esposito et al. Int.J.Mod.Phys. A30 (2015) 1530002

$D_0^*(2300)$, $D_s^*(2317)$, $X(3872)$, charged Z states, ...

HADRONIC MOLECULES

Hadronic molecules are deuteron-like **quasi-bound states** of two mesons (tetraquark), a meson and a baryon (pentaquark) or two baryons (hexaquark).

- → Dynamically generated via multiple scattering of their meson/baryon components.
- → Located near threshold $m_1 + m_2$
- → Studied using effective hadronic theories.
- → Mesons and baryons are the degrees of freedom.



EFFECTIVE HADRONIC THEORY

The most general effective Lagrangian, up to a given order, **consistent with the symmetries** of the underlying theory.

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Heavy-light meson-meson interaction → Symmetries of QCD :

- **Chiral symmetry** in the limit $m_u,\ m_d,\ m_s \to 0$
- **Heavy-quark symmetry** in the limit $m_c,\ m_b \to \infty$

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Interaction of $D^{(*)}$ and $D_s^{(*)}$ with light mesons:

→ Lagrangian at NLO in the chiral expansion and LO in the heavy-quark expansion

$$\mathcal{L} = \mathcal{L}_{\mathrm{LO}} + \mathcal{L}_{\mathrm{NLO}}$$

INTERACTION LAGRANGIAN (LO)

Lagrangian at NLO in the chiral expansion and LO in the heavy-quark expansion

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$$\begin{aligned}\mathcal{L}_{\rm LO} = \ & \langle \nabla^\mu D \nabla_\mu D^\dagger \rangle - m_D^2 \langle D D^\dagger \rangle \ - \langle \nabla^\mu D^{*\nu} \nabla_\mu D^{*\dagger}_\nu \rangle + m_D^2 \langle D^{*\nu} D^{*\dagger}_\nu \rangle \\ & + i\, g \langle D^{*\mu} u_\mu D^\dagger - D u^\mu D^{*\dagger}_\mu \rangle + \frac{g}{2 m_D} \langle D^*_\mu u_\alpha \nabla_\beta D^{*\dagger}_\nu - \nabla_\beta D^*_\mu u_\alpha D^{*\dagger}_\nu \rangle \epsilon^{\mu\nu\alpha\beta}\end{aligned}$$

$$\nabla_\mu D^{(*)} = \partial_\mu D^{(*)} - D^{(*)} \Gamma^\mu \qquad \Gamma_\mu = \frac{1}{2}(u^\dagger \partial_\mu u + u \partial_\mu u^\dagger)$$

$$u_\mu = i\,(u^\dagger \partial_\mu u - u \partial_\mu u^\dagger) \qquad u = \sqrt{U} = \exp\left(\frac{i\,\Phi}{\sqrt{2} f_\pi}\right)$$

[Kolomeitsev and Lutz (2004)]
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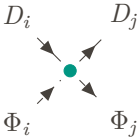
D mesons:

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



Light mesons:

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

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$$\chi_+ = u^\dagger\chi u^\dagger + u\chi u \qquad \chi = \mathrm{diag}(m_\pi^2, m_\pi^2, 2m_K^2 - m_\pi^2) \qquad \text{LECs}: \ h_{0,\ldots,5},\ \tilde{h}_{0,\ldots,5}$$

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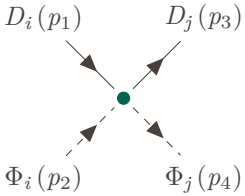

Tree-level scattering amplitude of $D^{(*)}$, $D_s^{(*)}$ mesons with π, K, $\bar{K}$, η mesons:

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

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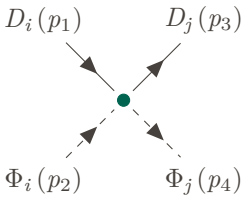

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$C^{ij}_{\rm LO,0,1,24,35}$: isospin coefficients for the transition $i \to j$

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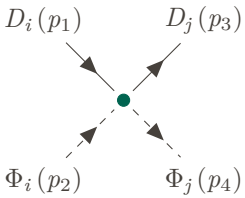


Tree-level scattering amplitude of $D^{(*)}$, $D_s^{(*)}$ mesons with π, K, $\bar{K}$, η mesons:

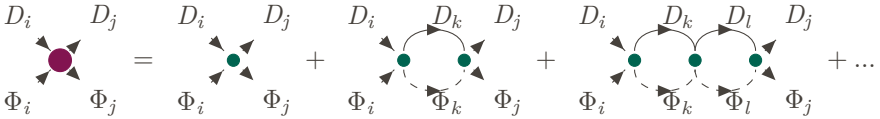
$$\begin{aligned} V^{ij}(s,t,u) \;=\; & \frac{1}{f_\pi^2}\Big[\frac{1}{4}\, C^{ij}_{\rm LO}\,(s-u) - 4\, C^{ij}_0\, h_0 + 2\, C^{ij}_1\, h_1 \\ & - 2\, C^{ij}_{24}\Big(2\, h_2\,(p_2\cdot p_4) + h_4\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big) \\ & + 2\, C^{ij}_{35}\Big(h_3\,(p_2\cdot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

LECs fitted to LQCD data of scattering lengths

[Guo, Liu, Meißner, Oller Rusetsky (2019)]

UNITARIZATION

Bethe-Salpeter equation in coupled-channels:



$$T_{ij} = V_{ij} + V_{ik} G_k V_{kj} + V_{ik} G_k V_{kl} G_l V_{lj} + \ldots$$

UNITARIZATION

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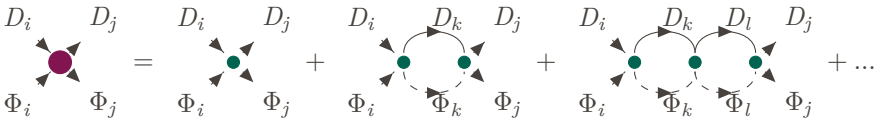

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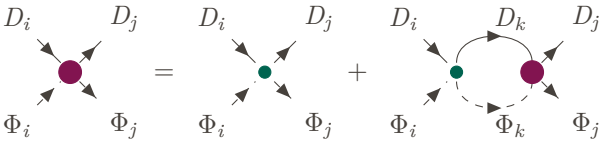


$$T_{ij} = V_{ij} + V_{ik} G_k T_{kj} \quad \rightarrow \quad T = (1 - VG)^{-1} V \quad \text{(On-shell factorization)}$$

LOOP FUNCTION

The two-meson propagator

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

has to be regularized:

→ Dimensional regularization: subtraction constants $a_k(\mu)$

→ **Cutoff regularization** with $|\vec{q}| < \Lambda$

At threshold: $\sqrt{s_{\rm thr}} = m_1 + m_2$

$$G_{\rm DR}(\sqrt{s_{\rm thr}}, a_l(\mu)) = G_\Lambda(\sqrt{s_{\rm thr}}, \Lambda)$$

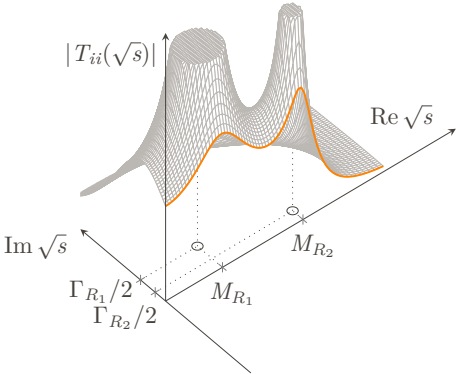
DYNAMICALLY GENERATED STATES

→ Identification of **states** in the unitarized scattering amplitudes

→ **Analytical continuation** and **poles** in the complex-energy plane

→ Bound states, resonances and virtual states in different **Riemann sheets**

- Mass $M_R = \mathrm{Re}\sqrt{s_R}$
- Half-width $\frac{\Gamma_R}{2} = \mathrm{Im}\sqrt{s_R}$
- Coupling constants $|g_i|$
- Compositeness $X_i = \left|g_i^2 \frac{\partial G_i(z_p)}{\partial z}\right|$



Results I:
Dynamically generated states at $T = 0$

COUPLED CHANNELS

In isospin basis:

(S, I)	Channels $J^P = 0^- \oplus 0^-$	Threshold (MeV)
$(-1, 0)$	$D\bar{K}$	2364.88
$(-1, 1)$	$D\bar{K}$	2364.88
$(0, \frac{1}{2})$	$D\pi$	2005.28
	$D\eta$	2415.10
	$D_s\bar{K}$	2463.98
$(0, \frac{3}{2})$	$D\pi$	2005.28
$(1, 0)$	DK	2364.88
	$D_s\eta$	2516.20
$(1, 1)$	$D_s\pi$	2106.38
	DK	2364.88
$(2, \frac{1}{2})$	D_sK	2463.98

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$(-1, 0)$	$D^*\bar{K}$	2504.20
$(-1, 1)$	$D^*\bar{K}$	2504.20
$(0, \frac{1}{2})$	$D^*\pi$	2146.59
	$D^*\eta$	2556.42
	$D_s^*\bar{K}$	2607.84
$(0, \frac{3}{2})$	$D^*\pi$	2146.59
$(1, 0)$	D^*K	2504.20
	$D_s^*\eta$	2660.06
$(1, 1)$	$D_s^*\pi$	2250.24
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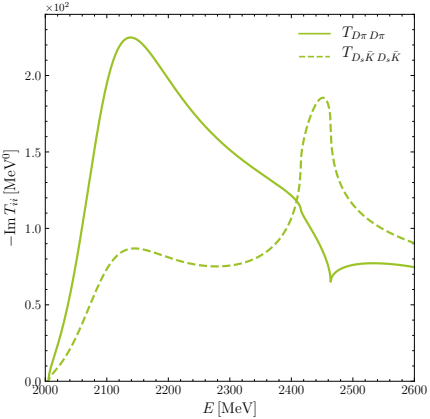
DYNAMICALLY GENERATED STATES

Scalars ($J^P = 0^+$): $D_0^*(2300)$ and $D_{s0}^*(2317)$

(S, I)	RS	M_R (MeV)	$\Gamma_R/2$ (MeV)	$\lvert g_i \rvert$ (GeV)	χ_i
$(0, \frac{1}{2})$	$(-,+,+)$	2081.9	86.0	$\lvert g_{D\pi}\rvert = 8.9$	$\chi_{D\pi} = 0.40$
				$\lvert g_{D\eta}\rvert = 0.4$	$\chi_{D\eta} = 0.00$
				$\lvert g_{D_s\bar{K}}\rvert = 5.4$	$\chi_{D_s\bar{K}} = 0.05$
	$(-,-,+)$	2529.3	145.4	$\lvert g_{D\pi}\rvert = 6.7$	$\chi_{D\pi} = 0.10$
				$\lvert g_{D\eta}\rvert = 9.9$	$\chi_{D\eta} = 0.40$
				$\lvert g_{D_s\bar{K}}\rvert = 19.4$	$\chi_{D_s\bar{K}} = 1.63$
$(1, 0)$	$(+,+)$	2252.5	0.0	$\lvert g_{DK}\rvert = 13.3$	$\chi_{DK} = 0.66$
				$\lvert g_{D_s\eta}\rvert = 9.2$	$\chi_{D_s\eta} = 0.17$



Experimental values:

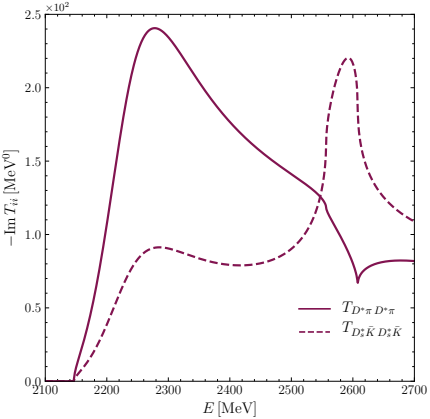
$M_R = 2300 \pm 19$ MeV, $\quad \Gamma_R = 274 \pm 40$ MeV

$M_R = 2317.8 \pm 0.5$ MeV, $\quad \Gamma_R < 3.8$ MeV

DYNAMICALLY GENERATED STATES

Axial vectors ($J^P = 1^+$): $D_1^*(2430)$ and $D_{s1}^*(2460)$

(S, I)	RS	M_R (MeV)	$\Gamma_R/2$ (MeV)	$\lvert g_i \rvert$ (GeV)	χ_i
$(0, \frac{1}{2})$	$(-,+,+)$	2222.3	84.7	$\lvert g_{D^*\pi} \rvert = 9.5$	$\chi_{D^*\pi} = 0.40$
				$\lvert g_{D^*\eta} \rvert = 0.4$	$\chi_{D^*\eta} = 0.00$
				$\lvert g_{D_s^*\bar{K}} \rvert = 5.7$	$\chi_{D_s^*\bar{K}} = 0.05$
	$(-,-,+)$	2654.6	117.3	$\lvert g_{D^*\pi} \rvert = 6.5$	$\chi_{D^*\pi} = 0.09$
				$\lvert g_{D^*\eta} \rvert = 10.0$	$\chi_{D^*\eta} = 0.40$
				$\lvert g_{D_s^*\bar{K}} \rvert = 18.5$	$\chi_{D_s^*\bar{K}} = 1.47$
$(1, 0)$	$(+,+)$	2393.3	0.0	$\lvert g_{D^*K} \rvert = 14.2$	$\chi_{D^*K} = 0.68$
				$\lvert g_{D_s^*\eta} \rvert = 9.7$	$\chi_{D_s^*\eta} = 0.17$



Experimental values:

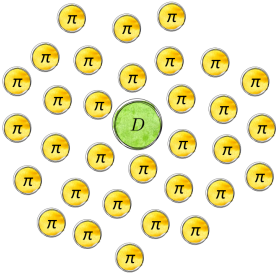
$M_R = 2427 \pm 40$ MeV, $\quad \Gamma_R = 384^{+130}_{-110}$ MeV

$M_R = 2459.5 \pm 0.6$ MeV, $\quad \Gamma_R < 3.5$ MeV

Finite temperature corrections

MESONIC BATH

- → Mesonic matter at a temperature $0 < T < T_c$
- → Vanishing baryon density
- → Heavy mesons behave as Brownian particles
- → Modification of the properties of the D mesons



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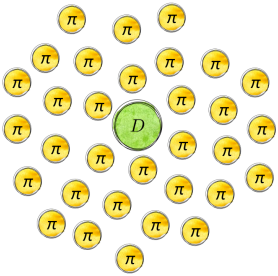

Both **production** and **absorption** processes of heavy-light pairs are possible

MODIFICATION OF HEAVY MESONS IN A HOT MEDIUM

Imaginary time formalism

- Sum over Matsubara frequencies

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

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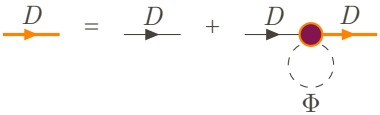
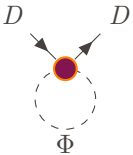
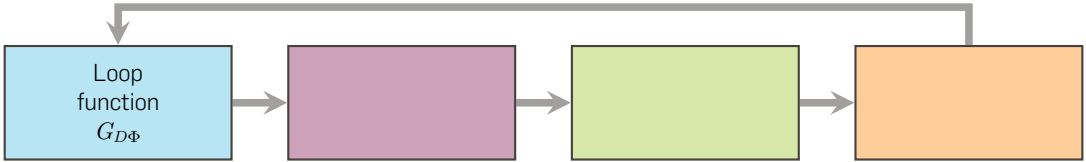
Dressing the mesons in the loop function

- Self-energy corrections
- Pion mass slightly varies below T_c $\quad\to\quad$ only heavy meson is dressed



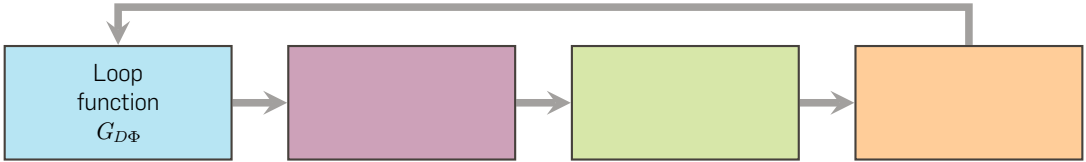


SELF-CONSISTENCY



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

SELF-CONSISTENCY



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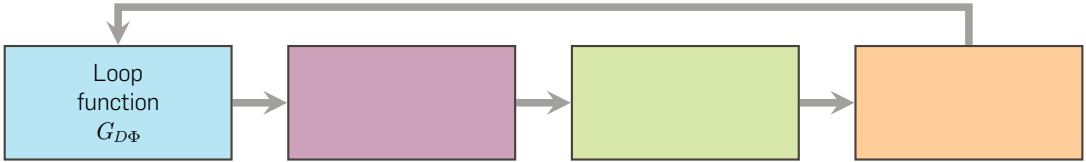
Spectral functions: $S_D, \quad S_\Phi \to \frac{\omega_\Phi}{\omega'}\delta(\omega'^2-\omega_\Phi^2), \quad \omega_\Phi = \sqrt{q_\Phi^2+m_\Phi^2}$

SELF-CONSISTENCY



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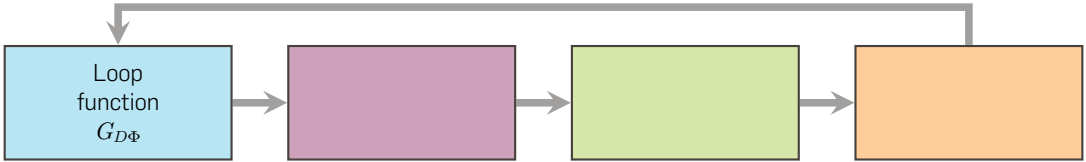
Bose distribution function at T: $f(\omega,T) = \frac{1}{e^{\omega/T}-1}$

SELF-CONSISTENCY



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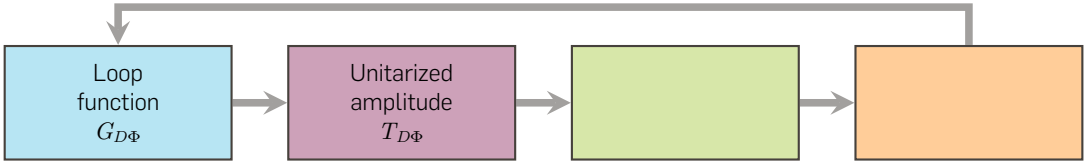
Regularized with a cutoff $|\vec{q}| < \Lambda$

SELF-CONSISTENCY



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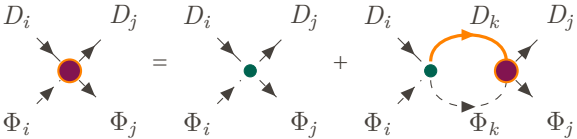
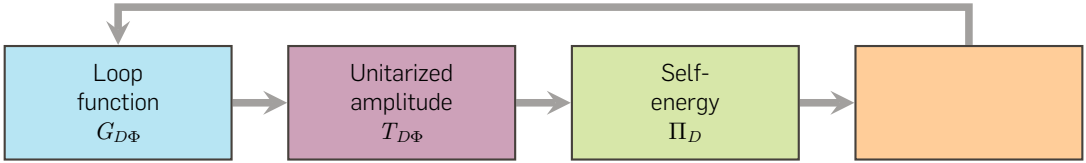
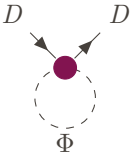


SELF-CONSISTENCY



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



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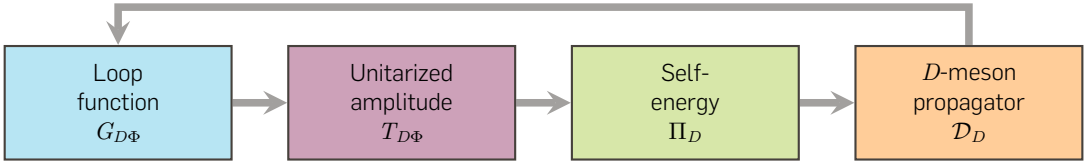
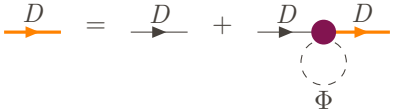
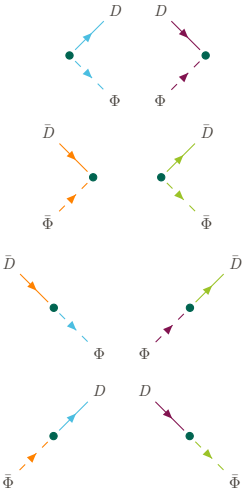


$$S_D(\omega, \vec{q}; T) = -\frac{1}{\pi}\mathrm{Im}\, \mathcal{D}_D(\omega, \vec{q}; T) = -\frac{1}{\pi}\mathrm{Im}\left(\frac{1}{\omega^2 - \vec{q}^2 - m_D^2 - \Pi_D(\omega, \vec{q}; T)}\right)$$



PHYSICAL INTERPRETATION OF THE THERMAL BATH

$$G_{D\Phi}(E,\vec{p};T) \sim \left\{ \begin{array}{l} \text{bath} \to \text{bath} + D\Phi \qquad \text{bath} + D\Phi \to \text{bath} \\ \dfrac{[1+f(\omega_D,T)][1+f(\omega_\Phi,T)] - f(\omega_D,T)f(\omega_\Phi,T)}{E-\omega_D-\omega_\Phi+i\varepsilon} \\ \text{bath} + \bar{D}\bar{\Phi} \to \text{bath} \qquad \text{bath} \to \text{bath} + \bar{D}\bar{\Phi} \\ + \dfrac{f(\omega_D,T)f(\omega_\Phi,T) - [1+f(\omega_D,T)][1+f(\omega_\Phi,T)]}{E+\omega_D+\omega_\Phi+i\varepsilon} \\ \text{bath} + \bar{D} \to \text{bath} + \Phi \qquad \text{bath} + \Phi \to \text{bath} + \bar{D} \\ + \dfrac{f(\omega_D,T)\,[1+f(\omega_\Phi,T)] - f(\omega_\Phi,T)\,[1+f(\omega_D,T)]}{E+\omega_D-\omega_\Phi+i\varepsilon} \\ \text{bath} + \bar{\Phi} \to \text{bath} + D \qquad \text{bath} + D \to \text{bath} + \bar{\Phi} \\ + \dfrac{f(\omega_\Phi,T)\,[1+f(\omega_D,T)] - f(\omega_D,T)\,[1+f(\omega_\Phi,T)]}{E-\omega_D+\omega_\Phi+i\varepsilon} \end{array} \right\}$$



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

PHYSICAL INTERPRETATION OF THE THERMAL BATH

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

$$+\frac{f(\omega_D,T)f(\omega_\Phi,T) \;-\; [1+f(\omega_D,T)][1+f(\omega_\Phi,T)]}{E+\omega_D+\omega_\Phi+i\varepsilon}$$

$$+\frac{f(\omega_D,T)\;\;[1+f(\omega_\Phi,T)] \;-\; f(\omega_\Phi,T)\;\;[1+f(\omega_D,T)]}{E+\omega_D-\omega_\Phi+i\varepsilon}$$

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

First branch cut
($T=0$ unitary cut):
$E \geq (m_D + m_\Phi)$

Additional branch cut
(Landau cut):
$E \leq (m_D - m_\Phi)$

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

Results II: Thermal modifications

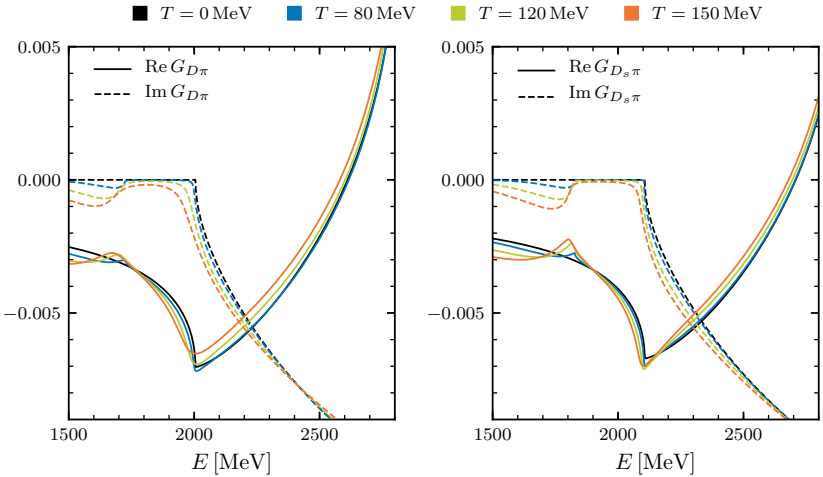
LOOP FUNCTIONS

Pionic bath

D and D_s with light mesons

Unitary cut:
$E \geq (m_D + m_\Phi)$

Landau cut:
$E \leq (m_D - m_\Phi)$



LOOP FUNCTIONS

Pionic bath

D^* and D_s^* with light mesons

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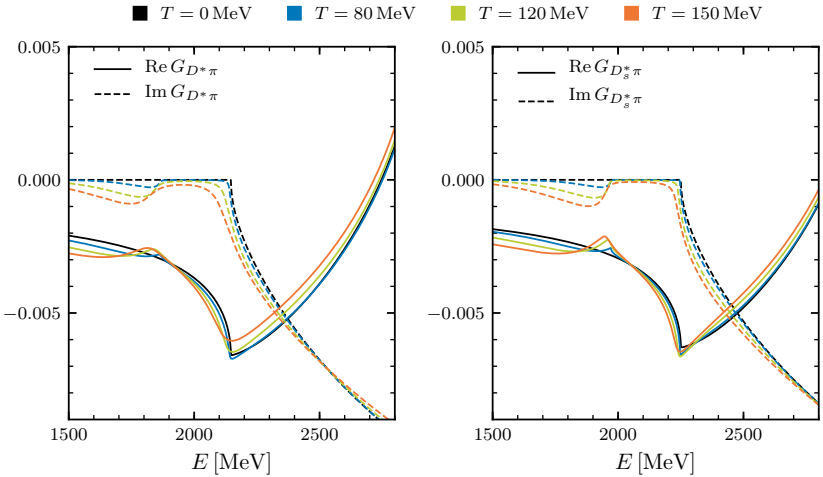
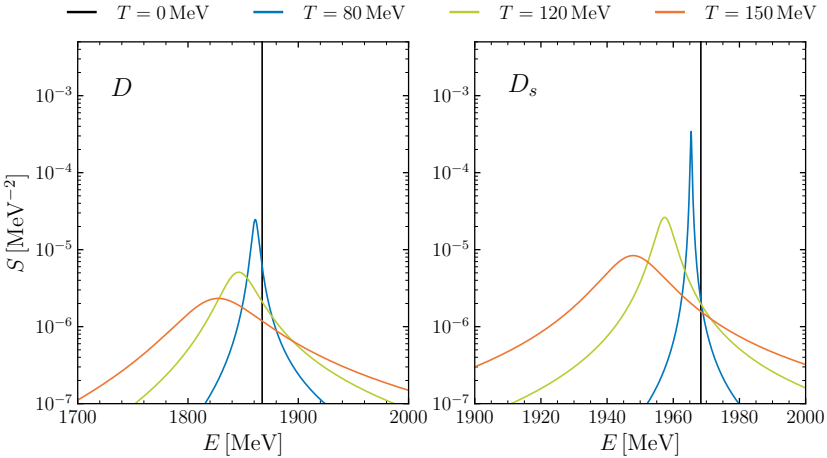
Landau cut:
$E \leq (m_{D^*} - m_\Phi)$



SPECTRAL FUNCTIONS

Open-charm **pseudoscalar mesons** in a pionic bath

$$S_D(\omega, \vec{q}; T) = -\frac{1}{\pi}\mathrm{Im}\,\mathcal{D}_D(\omega, \vec{q}; T)$$



Mass shift and width acquisition of the D and D_s mesons in a thermal bath

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Open-charm
vector mesons
in a pionic bath

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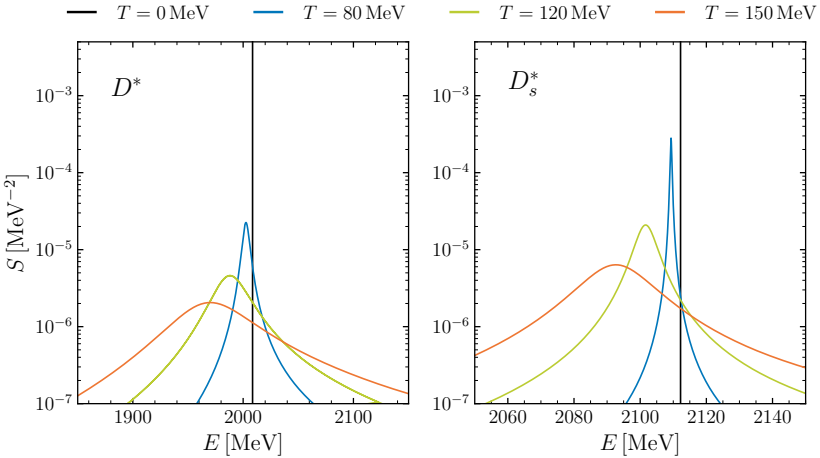


Mass shift and width acquisition of the D^* and D_s^* mesons in a thermal bath

DYNAMICALLY GENERATED STATES

Scalars ($J^P = 0^+$):

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

→ Two-pole structure of the $D_0^*(2300)$

Experimental values:

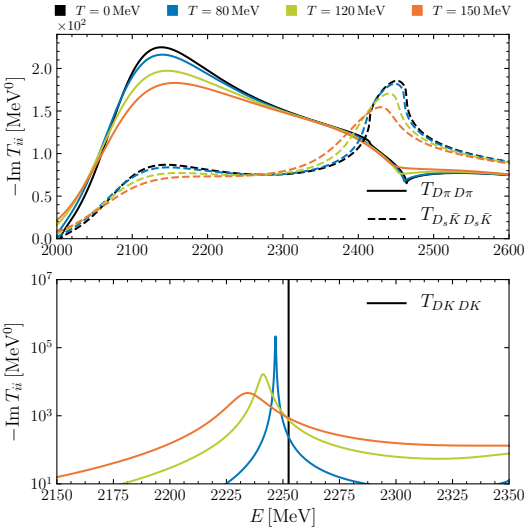
$M_R = 2300 \pm 19$ MeV, $\Gamma_R = 274 \pm 40$ MeV

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

→ $D_{s0}^*(2317)$

Experimental values:

$M_R = 2317.8 \pm 0.5$ MeV, $\Gamma_R < 3.8$ MeV



DYNAMICALLY GENERATED STATES

Axial vectors ($J^P = 1^+$):

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

→ Two-pole structure of the $D_1^*(2430)$

Experimental values:

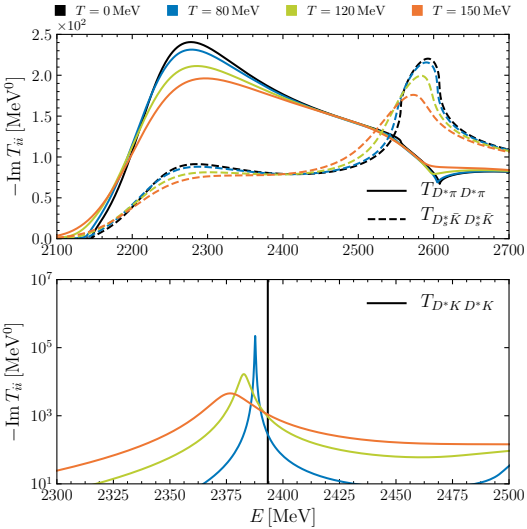
$M_R = 2427 \pm 40$ MeV, $\Gamma_R = 384^{+130}_{-110}$ MeV

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

→ $D_{s1}^*(2460)$

Experimental values:

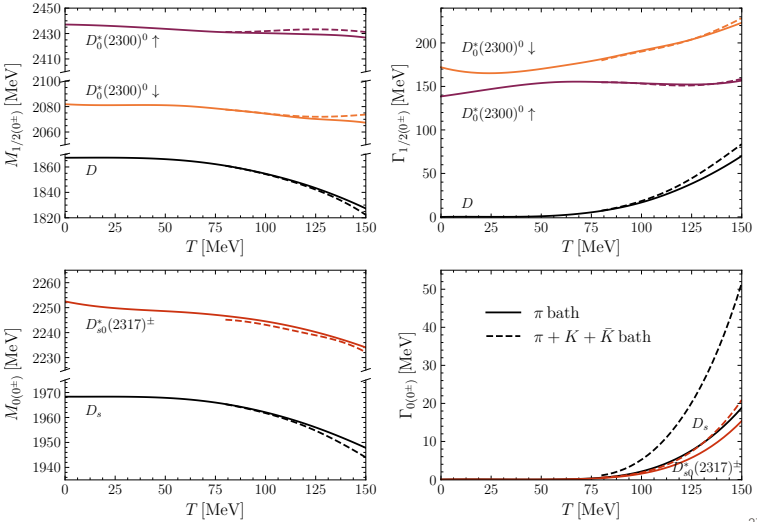
$M_R = 2459.5 \pm 0.6$ MeV, $\Gamma_R < 3.5$ MeV



CHIRAL PARTNERS

Evolution of masses and widths of the open-charm mesons in a pionic (or $\pi + K + \bar{K}$) bath

$$I(J^P) = \frac{1}{2}(0^\pm),\ 0(0^\pm)$$



[GM, A. Ramos, L. Tolos, J. Torres-Rincon, arXiv:2007.12601]

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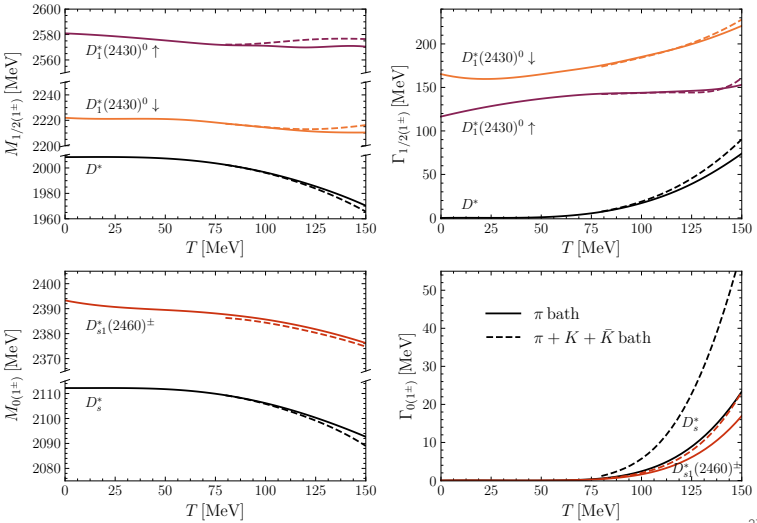

[GM, A. Ramos, L. Tolos, J. Torres-Rincon, arXiv:2007.12601]

Euclidean correlators: comparison with lattice QCD

FROM SPECTRAL FUNCTIONS TO EUCLIDEAN CORRELATORS

Spectral function $\rightarrow$ **Euclidean correlator**

$$G_E(\tau, \vec{p}; T) = \int_0^\infty d\omega \; K(\tau, \omega; T) \;\; \rho(\omega, \vec{p}; T)$$

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- Bayesian methods (e.g. MEM)
- Fitting Ansätze

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- Bayesian methods (e.g. MEM)
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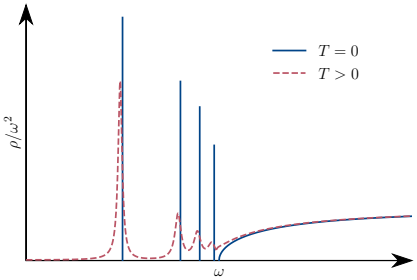
Reconstructed correlator

$$G_E^r(\tau; T, T_r) = \int_0^\infty d\omega K(\tau, \omega; T)\rho(\omega; T_r) \quad \rightarrow \quad \frac{G_E(\tau; T)}{G_E^r(\tau; T, T_r)}$$

EUCLIDEAN CORRELATORS WITH EFT



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at unphysical meson masses (used in the lattice)

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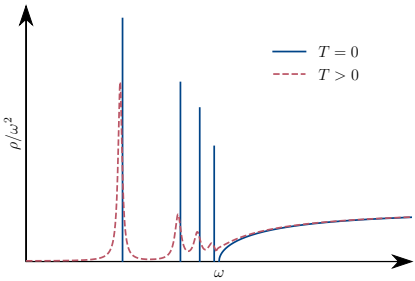

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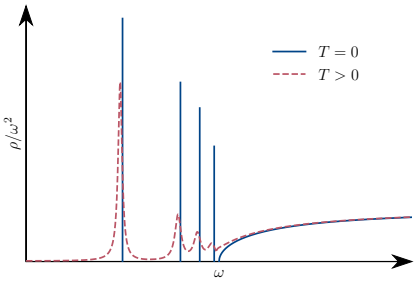

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Full: $\rho(\omega; T) = \rho_{\mathrm{gs}}(\omega; T) + \ a \ \ \rho_{\mathrm{cont}}(\omega; T)$

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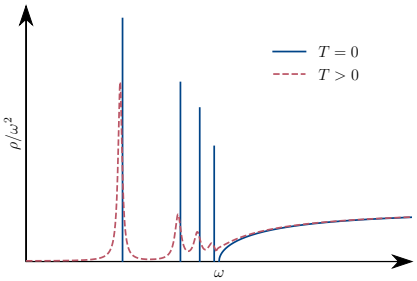

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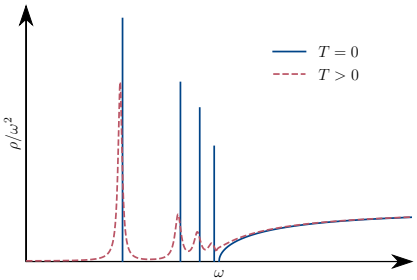

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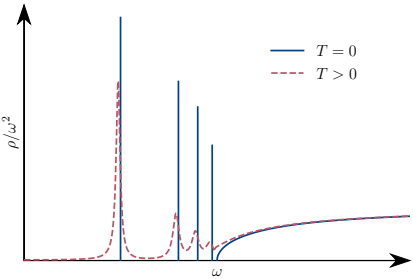
$$\times\, 2\left(1 - \frac{(m_1 - m_2)^2}{\omega^2}\right)$$
$$\times\, [n(-\omega_0, T) - n(\omega - \omega_0, T)]\,\theta(\omega - (m_1 + m_2))$$

EUCLIDEAN CORRELATORS WITH EFT



$$m_1 = m_c = 1.5 \text{ GeV}$$
$$m_2 = m_l = 0,\ m_2 = m_s = 100 \text{ MeV}$$

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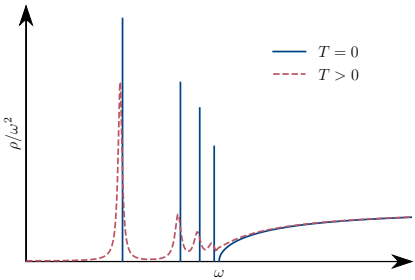

a : weight factor

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Results III: Open-charm Euclidean correlators

EFT SPECTRAL FUNCTIONS AT UNPHYSICAL MASSES

$m_\pi = 384$ MeV

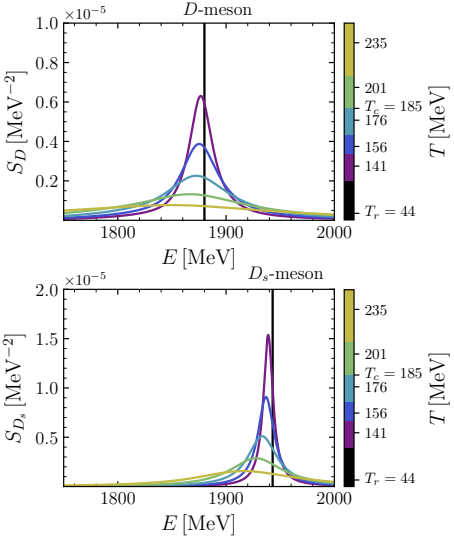
$m_K = 546$ MeV

$m_\eta = 589$ MeV

$m_D = 1880$ MeV

$m_{D_s} = 1943$ MeV

[Kelly, Rothkopf, Skullerud (2018)]



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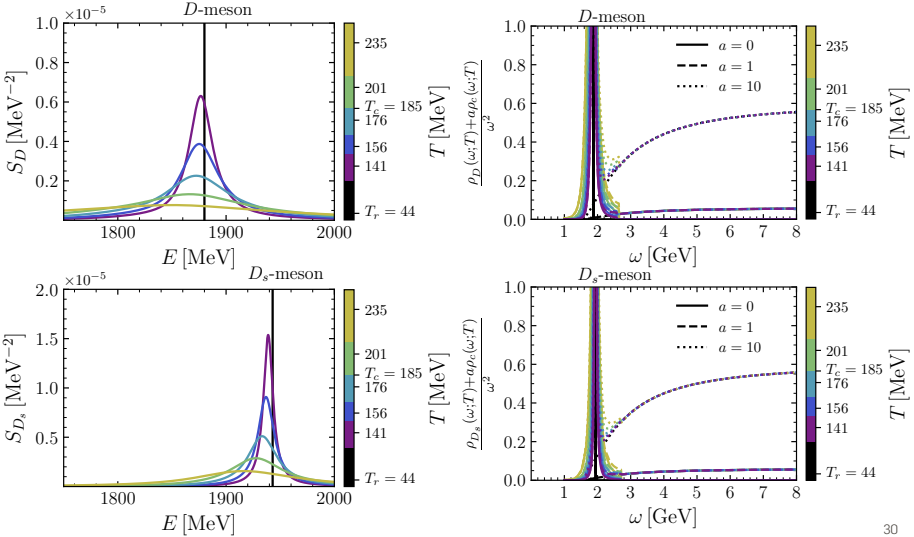
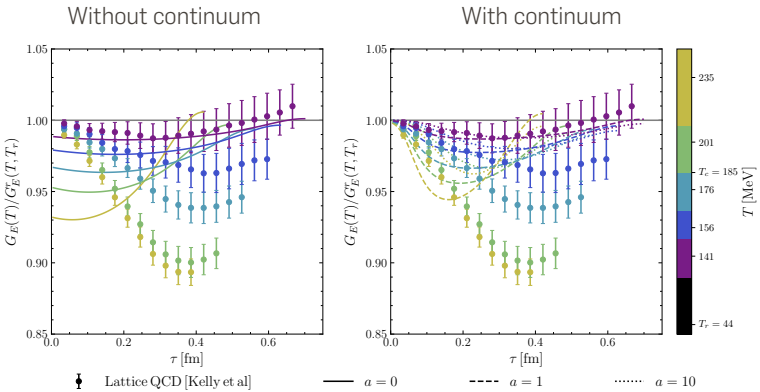


COMPARISON WITH LQCD

D **meson**



→ Inclusion of the continuum improves the matching at small τ

→ Very good agreement at the lowest temperature. At larger temperatures: excited states?

→ Close and above T_c the EFT breaks down.

[GM, O. Kaczmarek, L. Tolos, A. Ramos, arXiv:2007.15690]

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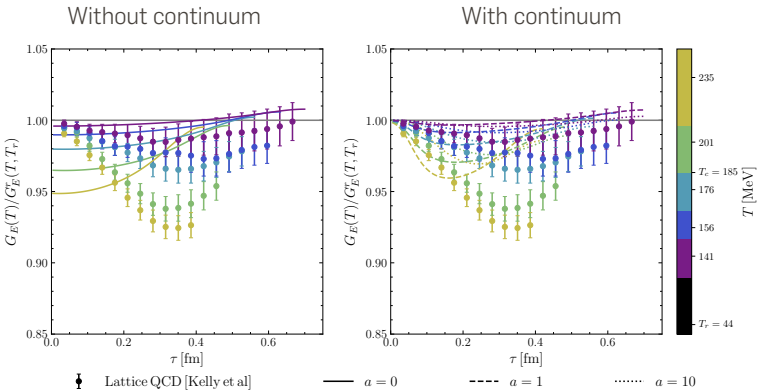

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- The effect of the addition of **kaons in the bath** is mild.
- We have calculated **Euclidean correlators** from spectral functions at the unphysical masses used in the lattice. **Well below Tc there is a good agreement with LQCD results**, whereas close or above T_c the discrepancy indicates the missing contribution of higher-excited states.

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In the near future we aim to:

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- → Further test our results against **lattice QCD** calculations and make predictions at the physical point

Thank you!

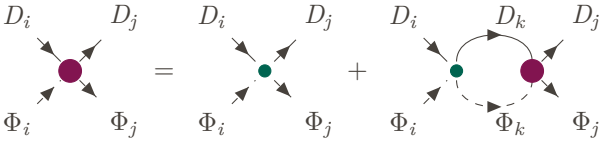
Gràcies!

Backup slides

UNITARIZED T-MATRIX AT $T \neq 0$

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

- Iteration 1: Undressed mesons



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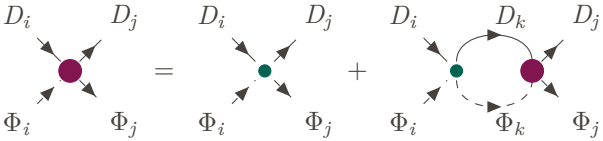
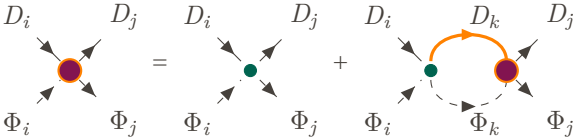


- Iteration > 1: Dressed heavy meson



LOOP FUNCTION AT $T > 0$

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

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Spectral functions:

$$S_D, \quad S_\Phi \to \frac{\omega_\Phi}{\omega'} \delta(\omega'^2 - \omega_\Phi^2), \quad \omega_\Phi = \sqrt{q_\Phi^2 + m_\Phi^2}$$

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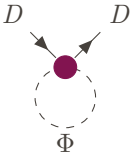
Regularized with a cutoff $|\vec{q}| < \Lambda$

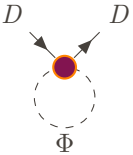
SELF-ENERGY AT $T > 0$

$$\Pi_D(E, \vec{p}; T) = -\frac{1}{\pi} \int \frac{d^3 q}{(2\pi)^3} \int d\Omega \frac{E}{\omega_\Phi} \frac{f(\Omega, T) - f(\omega_\Phi, T)}{E^2 - (\omega_\Phi - \Omega)^2 + i\varepsilon} \operatorname{Im} T_{D\Phi}(\Omega, \vec{p} + \vec{q}; T)$$

Iteration 1



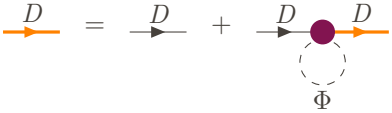
Iteration > 1



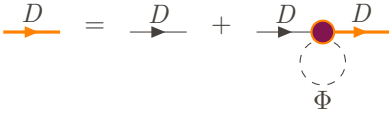
SPECTRAL FUNCTION

$$S_D(\omega, \vec{q}; T) = -\frac{1}{\pi}\mathrm{Im}\, \mathcal{D}_D(\omega, \vec{q}; T) = -\frac{1}{\pi}\mathrm{Im}\left(\frac{1}{\omega^2 - \vec{q}^2 - m_D^2 - \Pi_D(\omega, \vec{q}; T)}\right)$$

Iteration 1



Iteration > 1



SELF-CONSISTENCY

Loop function $G_{D\Phi}$

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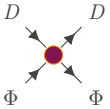
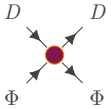
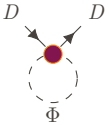
Loop function $G_{D\Phi}$ → Unitarized amplitude $T_{D\Phi}$ →



SELF-CONSISTENCY

Loop function $G_{D\Phi}$ → Unitarized amplitude $T_{D\Phi}$ → Self-energy Π_D →





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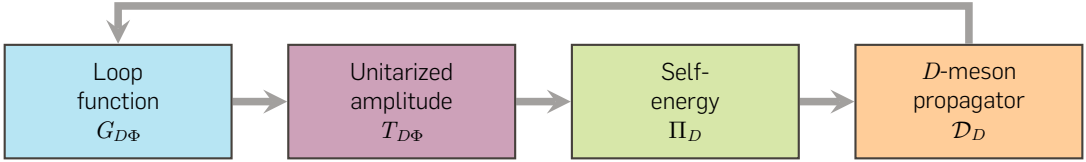
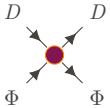
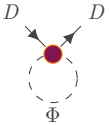
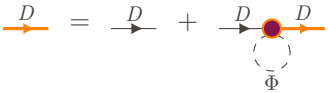








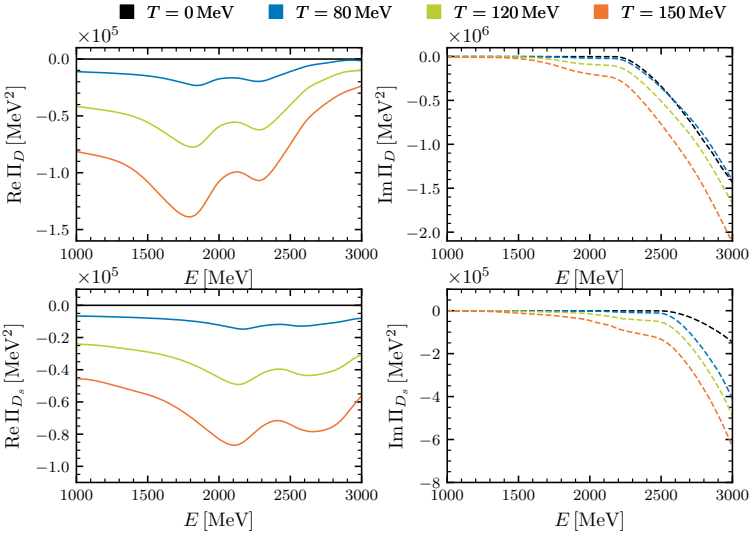
SELF-ENERGY

Pionic bath

D and D_s with light mesons

First opening:
$E \geq (m_D - 2m_\pi)$

Second opening:
$E \leq (m_D + 2m_\pi)$



SELF-ENERGY

Pionic bath

D^* and D_s^* with light mesons

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Second opening:
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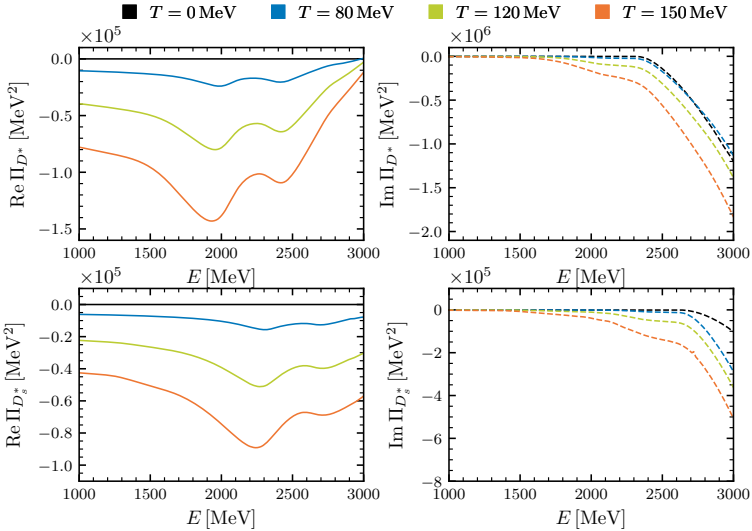


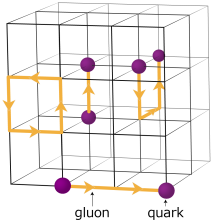
LATTICE EUCLIDEAN CORRELATORS

Temperature of the system on a lattice of size $N_\sigma^3 \times N_\tau \rightarrow$ related to the temporal extent:

$$T = \frac{1}{aN_\tau}, \quad a : \text{Lattice spacing}$$

Euclidean correlators of some operators $\widehat{O}$:

$$\langle \widehat{O}_1(\tau, \vec{x}) \widehat{O}_2(0, \vec{0}) \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}[U]\mathcal{D}[\bar{\psi}, \psi] \widehat{O}_2[U, \bar{\psi}, \psi] \widehat{O}_1[U, \bar{\psi}, \psi] e^{-S_F[U, \bar{\psi}, \psi] - S_G[U]}$$



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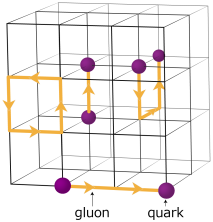
$\mathcal{Z}$: partition function



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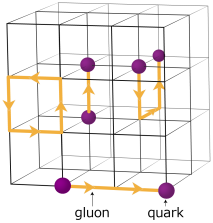
$S_F[U, \bar{\psi}, \psi]$ and $S_G[U]$: fermion and gluon parts of the discritized QCD action



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$$\langle J(\tau, \vec{x}) J(0, \vec{0}) \rangle = -\frac{1}{\mathcal{Z}} \int \mathcal{D}[U] e^{-S_G[U]} \det[M] \mathrm{Tr}\left[\Gamma_H \; M^{-1}(0, \vec{0}; \tau, \vec{x}) \; \Gamma_H \; M^{-1}(\tau, \vec{x}; 0, \vec{0}) \right],$$

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$\Gamma_H = 1, \gamma_5, \gamma_\mu, \gamma_5\gamma_\mu$: for scalar, pseudoscalar, vector and axial vector channels

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M^{-1} : fermion propagator