Thermal modification of open heavy-flavour mesons from an effective hadronic theory

Glòria Montaña

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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, Phys.Rev.D 102 (2020)]
[GM, Olaf Kaczmarek, Laura Tolos, Angels Ramos, Eur.Phys.J.A 56 (2020)]
[Juan Torres-Rincon, GM, Angels Ramos, Laura Tolos, arXiv:2106.01156]

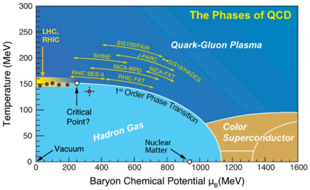
A Virtual Tribute to Quark Confinement and the Hadron Spectrum 2021

2-6 August 2021

UNIVERSITAT DE BARCELONA · ICCUB · EXCELENCIA MARÍA DE MAEZTU · GOBIERNO DE ESPAÑA · MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

Introduction

INTRODUCTION



- Matter at very high temperatures and vanishing baryon densities (QGP?) is produced in HICs at RHIC and LHC
  $\longrightarrow$ hot mesonic (pionic) matter after confinement transition

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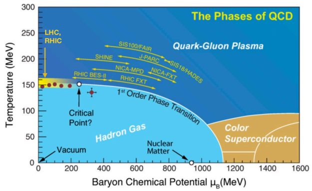

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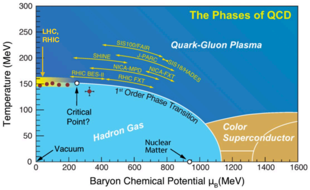
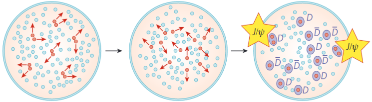


Color screening



Comover scattering

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- Heavy quarks are formed at the initial stage of the collision and have a large relaxation time
- Heavy mesons are a powerful probe of the QGP
  - Open heavy-flavour mesons created at the confinement transition
  - They iteract with the light mesons in the medium
  - Quarkonia suppression: color screening + comover scattering

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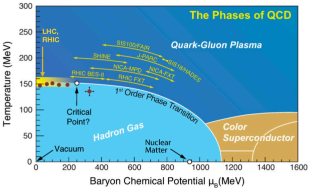

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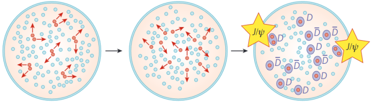

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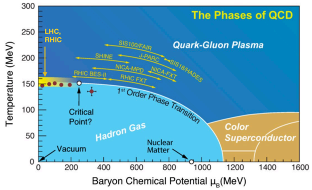

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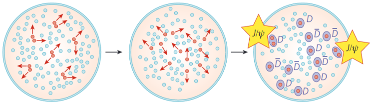

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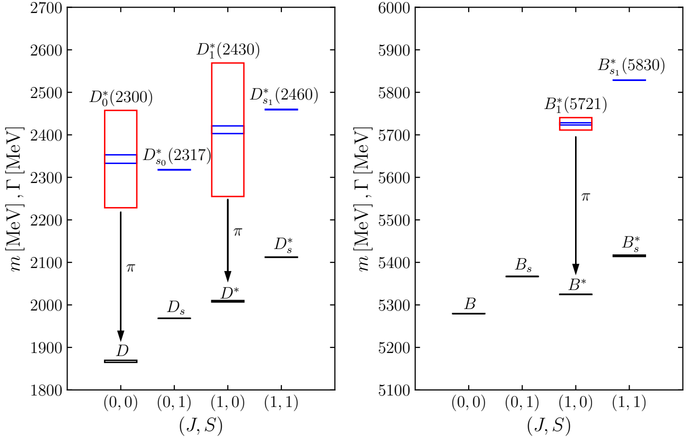
- Properties of hadrons and their thermal modification are contained in their spectral functions
- Spectral functions can be calculated with effective hadronic theories within a unitarized approach

OPEN HEAVY-FLAVOUR SPECTRUM



- Broad resonances with $S = 0$
- Narrow states with $S = 1$

[P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]

How do these states change with temperature?

Scattering of open heavy-flavour mesons off light mesons in free space

EFFECTIVE THEORY

Effective Lagrangian based on approximate chiral and heavy-quark spin symmetries

- Chiral expansion up to NLO: broken by light meson masses ($\Phi = \pi, K, \bar{K}, \eta$)
- Heavy-quark expansion up to LO: broken by physical heavy meson masses (D, D_s, D^*, D_s^*)

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

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

$$u = \exp\left(\frac{i\Phi}{\sqrt{2}f}\right), \quad \nabla^\mu = \partial^\mu - \frac{1}{2}(u^\dagger \partial^\mu u + u \partial^\mu u^\dagger), \quad u^\mu = i(u^\dagger \partial^\mu u - u \partial^\mu u^\dagger)$$

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

[Kolomeitsev and Lutz (2004)]
[Lutz and Soyeur (2008)]
[Guo, Hanhart and Meißner (2009)]
[Geng, Kaiser, Martin-Camalich and Weise (2010)]
...

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$$\begin{aligned}\mathcal{L}_{\rm NLO} = & - h_0 \langle D D^\dagger \rangle \langle \chi_+ \rangle + h_1 \langle D \chi_+ D^\dagger \rangle + h_2 \langle D D^\dagger \rangle \langle u^\mu u_\mu \rangle + h_3 \langle D u^\mu u_\mu D^\dagger \rangle \\ & + h_4 \langle \nabla_\mu D \nabla_\nu D^\dagger \rangle \langle u^\mu u^\nu \rangle + h_5 \langle \nabla_\mu D \{u^\mu, u^\nu\} \nabla_\nu D^\dagger \rangle + \{D \to D_\mu^*\}\end{aligned}$$

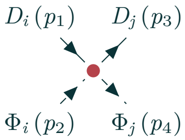
$$\text{LECs}: \; h_{0,\ldots,5}, \; \tilde{h}_{0,\ldots,5}$$

[Liu, Orginos, Guo, Hanhart and Meißner (2013)]
[Tolos and Torres-Rincon (2013)]
[Albaladejo, Fernandez-Soler, Guo and Nieves (2017)]
[Guo, Liu, Meißner, Oller and Rusetsky (2019)]

SCATTERING IN COUPLED CHANNELS

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

$$\mathcal{L} \to V^{ij}(s,t,u) = \frac{1}{f_\pi^2}\Big[\frac{1}{4} C_{\rm LO}^{ij}(s-u) - 4\, C_0^{ij} h_0 + 2\, C_1^{ij} h_1 - 2\, C_{24}^{ij}\Big(2h_2(p_2\cdot p_4) + h_4\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big) + 2\, C_{35}^{ij}\Big(h_3(p_2\cdot p_4) + h_5\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big)\Big],$$



C_n^{ij}: isospin coefficients

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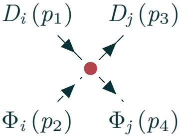

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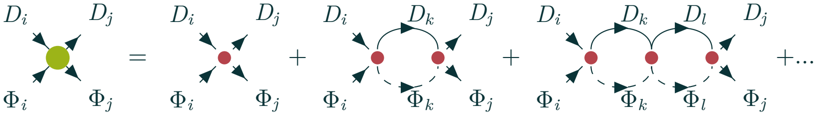
Unitarization: Bethe-Salpeter equation



$$T_{ij} = V_{ij} + V_{ik}G_kV_{kj} + V_{ik}G_kV_{kl}G_lV_{lj} + \ldots$$

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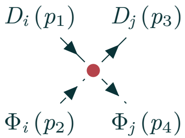

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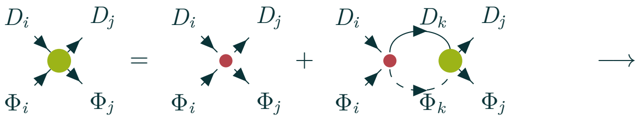

$$T_{ij} = V_{ij} + V_{ik} G_k T_{kj}$$

On-shell factorization of the T-matrix:

$$T = (1 - VG)^{-1}\,V$$

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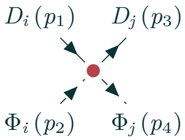
$$



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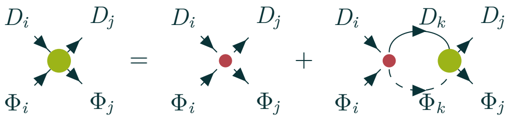

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- The two-meson propagator is regularized with a cutoff

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

- Poles in different Riemann sheets: bound states, resonances and virtual states, $m_R = {\rm Re}\, z_R\,, \Gamma_R = 2{\rm Im}\, z_R$
- Identification of the dynamically generated states with the experimental ones

RESULTS: DYNAMICALLY GENERATED OPEN-CHARM STATES

	$D_0^*(2300)$	$D_{s0}^*(2317)$	$D_1^*(2430)$	$D_{s1}^*(2460)$
M_R (MeV)	2343 ± 10	2317.8 ± 0.5	2412 ± 9	2459.5 ± 0.6
Γ_R (MeV)	229 ± 16	< 3.8	314 ± 29	< 3.5

J^P	(S, I)	Coupled channels			RS	Poles (MeV)	Couplings (GeV)
0^+	$(0, \frac{1}{2})$	$D\pi$	$D\eta$	$D_s\bar{K}$	$(-,+,+)$	$2081.9 - i86.0$	$\lvert g_{D\pi}\rvert = 8.9$, $\lvert g_{D\eta}\rvert = 0.4$, $\lvert g_{D_s\bar{K}}\rvert = 5.4$
		(2005.28)	(2415.10)	(2463.98)	$(-,-,+)$	$2529.3 - i145.4$	$\lvert g_{D\pi}\rvert = 6.7$, $\lvert g_{D\eta}\rvert = 9.9$, $\lvert g_{D_s\bar{K}}\rvert = 19.4$
	$(1,0)$	DK	$D_s\eta$		$(+,+)$	$2252.5 - i0.0$	$\lvert g_{DK}\rvert = 13.3$, $\lvert g_{D_s\eta}\rvert = 9.2$
		(2364.88)	(2516.20)				
1^+	$(0, \frac{1}{2})$	$D^*\pi$	$D^*\eta$	$D_s^*\bar{K}$	$(-,+,+)$	$2222.3 - i84.7$	$\lvert g_{D^*\pi}\rvert = 9.5$, $\lvert g_{D^*\eta}\rvert = 0.4$, $\lvert g_{D_s^*\bar{K}}\rvert = 5.7$
		(2146.59)	(2556.42)	(2607.84)	$(-,-,+)$	$2654.6 - i117.3$	$\lvert g_{D^*\pi}\rvert = 6.5$, $\lvert g_{D^*\eta}\rvert = 10.0$, $\lvert g_{D_s^*\bar{K}}\rvert = 18.5$
	$(1,0)$	D^*K	$D_s^*\eta$		$(+,+)$	$2393.3 - i0.0$	$\lvert g_{D^*K}\rvert = 14.2$, $\lvert g_{D_s^*\eta}\rvert = 9.7$
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Γ_R (MeV)	229 ± 16	< 3.8	314 ± 29	< 3.5

J^P	(S, I)	Coupled channels			RS	Poles (MeV)	Couplings (GeV)
0^+	$(0, \frac{1}{2})$	$D\pi$	$D\eta$	$D_s\bar{K}$	$(-,+,+)$	$2081.9 - i86.0$	$\lvert g_{D\pi}\rvert = 8.9$, $\lvert g_{D\eta}\rvert = 0.4$, $\lvert g_{D_s\bar{K}}\rvert = 5.4$
		(2005.28)	(2415.10)	(2463.98)	$(-,-,+)$	$2529.3 - i145.4$	$\lvert g_{D\pi}\rvert = 6.7$, $\lvert g_{D\eta}\rvert = 9.9$, $\lvert g_{D_s\bar{K}}\rvert = 19.4$
	$(1, 0)$	DK	$D_s\eta$		$(+,+)$	$2252.5 - i0.0$	$\lvert g_{DK}\rvert = 13.3$, $\lvert g_{D_s\eta}\rvert = 9.2$
		(2364.88)	(2516.20)				
1^+	$(0, \frac{1}{2})$	$D^*\pi$	$D^*\eta$	$D_s^*\bar{K}$	$(-,+,+)$	$2222.3 - i84.7$	$\lvert g_{D^*\pi}\rvert = 9.5$, $\lvert g_{D^*\eta}\rvert = 0.4$, $\lvert g_{D_s^*\bar{K}}\rvert = 5.7$
		(2146.59)	(2556.42)	(2607.84)	$(-,-,+)$	$2654.6 - i117.3$	$\lvert g_{D^*\pi}\rvert = 6.5$, $\lvert g_{D^*\eta}\rvert = 10.0$, $\lvert g_{D_s^*\bar{K}}\rvert = 18.5$
	$(1, 0)$	D^*K	$D_s^*\eta$		$(+,+)$	$2393.3 - i0.0$	$\lvert g_{D^*K}\rvert = 14.2$, $\lvert g_{D_s^*\eta}\rvert = 9.7$
		(2504.20)	(2660.06)				

RESULTS: DYNAMICALLY GENERATED OPEN-BEAUTY STATES

	$B_1^*(5721)$	$B_{s1}^*(5830)$
M_R (MeV)	$5725.9^{+2.5}_{-2.7}$	5828.7 ± 0.2
Γ_R (MeV)	$B_1^*(5721)^+ : 31 \pm 6$	0.5 ± 0.4
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		(5417.51)	(5827.34)	(5862.53)	$(-,-,+)$	$5848.0 - i65.9$	$\lvert g_{\bar{B}\pi}\rvert = 10.9$, $\lvert g_{\bar{B}\eta}\rvert = 18.0$, $\lvert g_{\bar{B}_s\bar{K}}\rvert = 32.0$
	$(1, 0)$	$\bar{B}K$	$\bar{B}_s\eta$		$(+,+)$	$5639.3 - i0.0$	$\lvert g_{\bar{B}K}\rvert = 35.6$, $\lvert g_{\bar{B}_s\eta}\rvert = 23.8$
		(5775.12)	(5914.75)				
1^+	$(0, \frac{1}{2})$	$\bar{B}^*\pi$	$\bar{B}^*\eta$	$\bar{B}_s^*\bar{K}$	$(-,+,+)$	$5528.6 - i72.3$	$\lvert g_{\bar{B}^*\pi}\rvert = 22.6$, $\lvert g_{\bar{B}^*\eta}\rvert = 0.8$, $\lvert g_{\bar{B}_s^*\bar{K}}\rvert = 14.4$
		(5462.69)	(5872.51)	(5911.04)	$(-,-,+)$	$5893.3 - i65.0$	$\lvert g_{\bar{B}^*\pi}\rvert = 10.7$, $\lvert g_{\bar{B}^*\eta}\rvert = 18.0$, $\lvert g_{\bar{B}_s^*\bar{K}}\rvert = 32.1$
	$(1, 0)$	$\bar{B}^*K$	$\bar{B}_s^*\eta$		$(+,+)$	$5686.0 - i0.0$	$\lvert g_{\bar{B}^*K}\rvert = 14.2$, $\lvert g_{\bar{B}_s^*\eta}\rvert = 9.7$
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Thermal Effective Field Theory

THERMAL MODIFICATION OF HEAVY MESONS IN A MESONIC BATH

- Imaginary-time formalism
  - Sum over Matsubara frequencies $\rightarrow$ Bose-Einstein distribution functions

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

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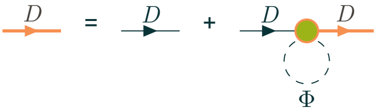
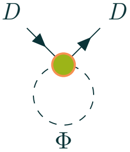
- Dressing the mesons in the loop function
  - Self-energy corrections
  - Pion mass varies slightly below T_c $\to$ only the heavy meson is dressed





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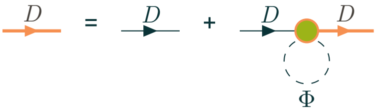
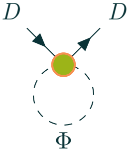
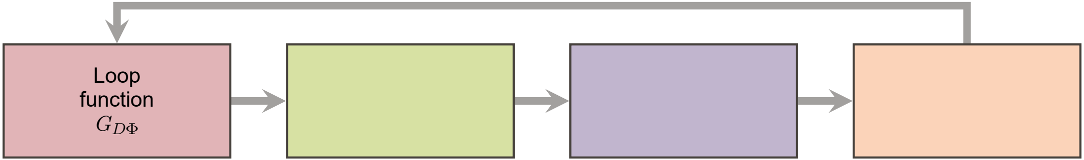




In the bath, processes that are forbidden in free space become possible: both production and absorption of heavy-light pairs.

SELF-CONSISTENT ITERATIVE PROCEDURE



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

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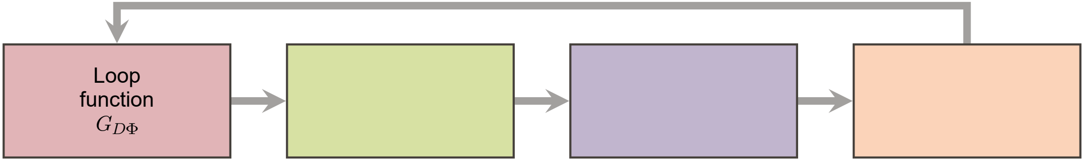

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Spectral functions

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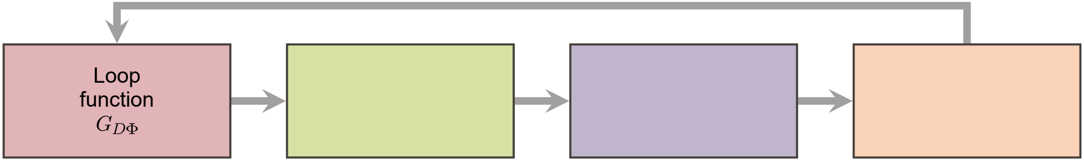

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Spectral functions

Bose distribution function at T: $f(\omega,T) = \frac{1}{e^{\omega/T}-1}$ (At zero temperature $f(\omega,T=0)=0$.)

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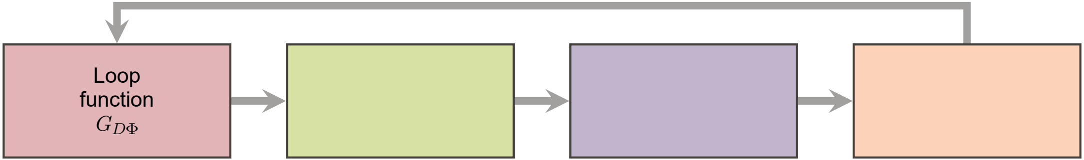

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Regularized with a cutoff Λ

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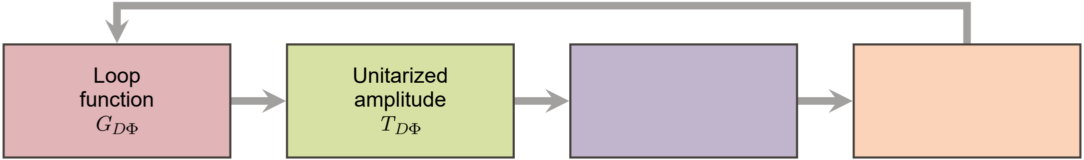
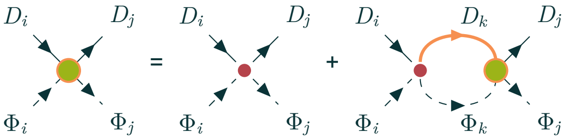


$$T_{ij} = V_{ij} + V_{ik} G_k T_{kj}$$



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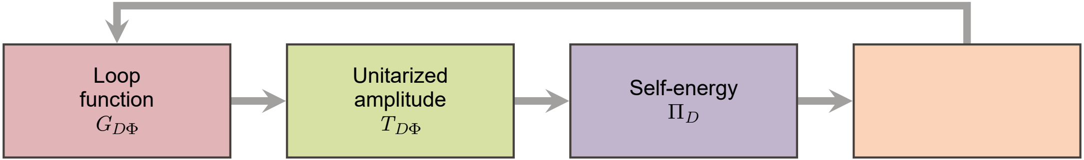
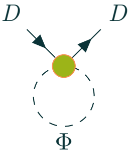


$$\Pi_D(E,\vec{p};T) = \frac{1}{\pi}\int \frac{d^3q}{(2\pi)^3}\int d\Omega \frac{E}{\omega_\Phi}\frac{f(\Omega,T) - f(\omega_\Phi,T)}{E^2-(\omega_\Phi-\Omega)^2+i\varepsilon}\,\mathrm{Im}\,T_{D\Phi}(\Omega,\vec{p}+\vec{q};T)$$



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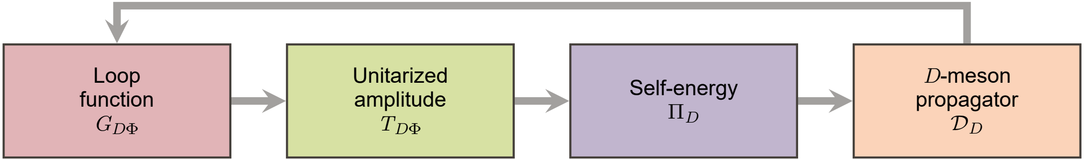
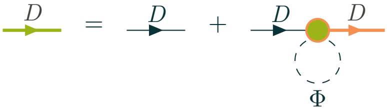


$$S_D(\omega,\vec{q};T) = -\frac{1}{\pi}\mathrm{Im}\,\mathcal{D}_D(\omega,\vec{q};T) = -\frac{1}{\pi}\mathrm{Im}\left(\frac{1}{\omega^2-\vec{q}^{\,2}-m_D^2-\Pi_D(\omega,\vec{q};T)}\right)$$

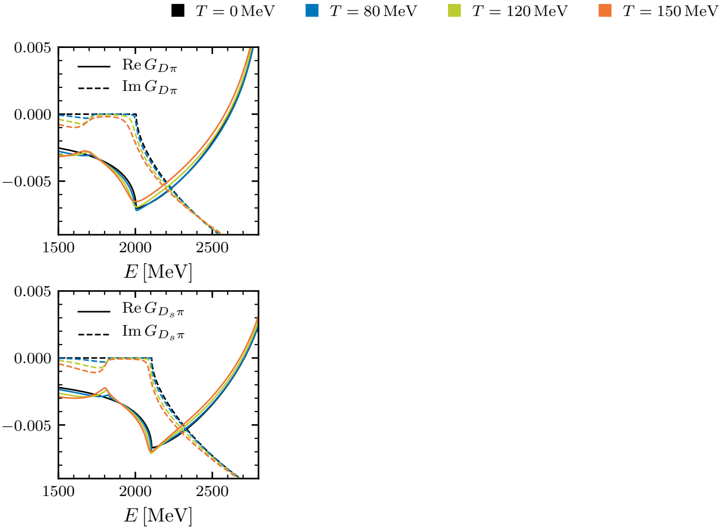


Results: Thermal modification of open-charm mesons

LOOP FUNCTIONS

Pionic bath

D and D_s with light mesons



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

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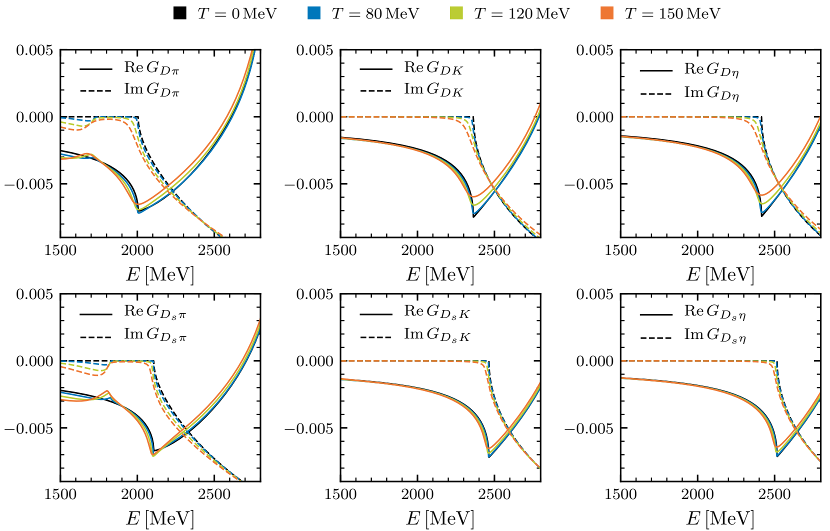

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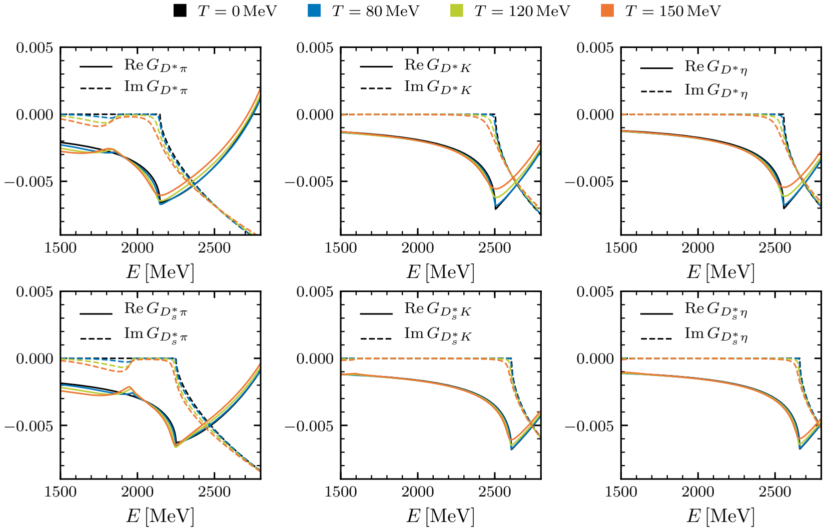
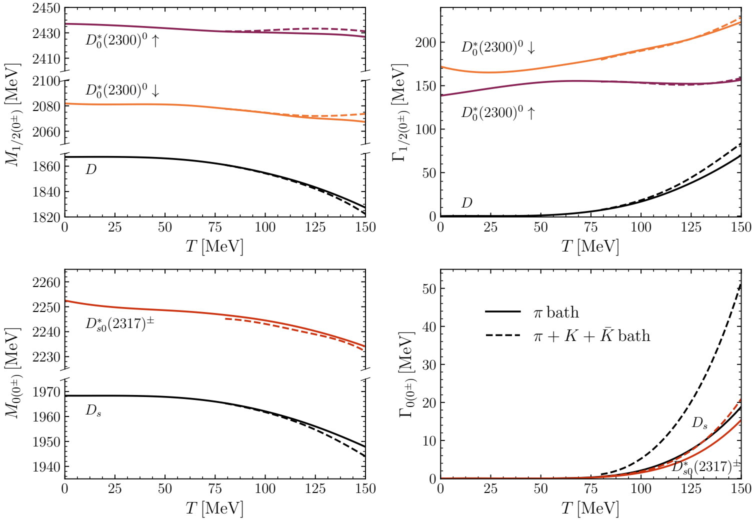


CHIRAL PARTNERS

Evolution of masses and widths

- Pionic bath (solid lines)
- Bath of $\pi, K, \bar{K}$ (dashed lines)

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



[GM, A. Ramos, L. Tolos, J. Torres-Rincon, Phys.Rev.D 102 (2020)]

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- Bath of $\pi, K, \bar{K}$ (dashed lines)

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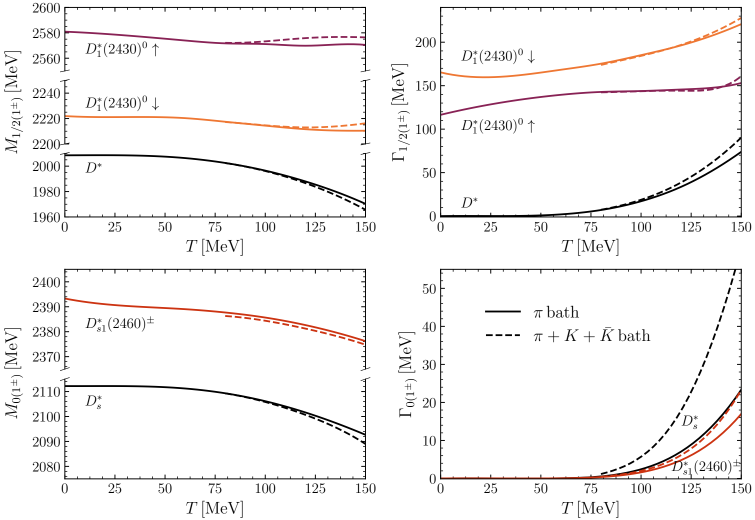


[GM, A. Ramos, L. Tolos, J. Torres-Rincon, Phys.Rev.D 102 (2020)]

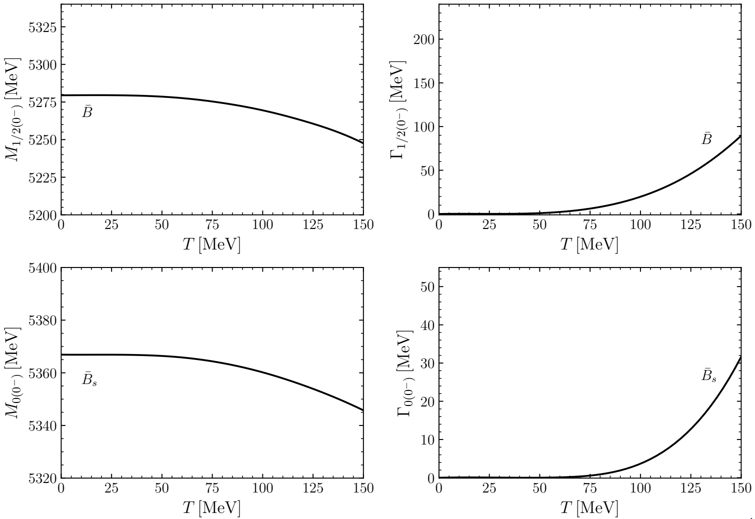
B MESONS

Evolution of masses and widths of the ground states

- Pionic bath

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

Similiar thermal effects for D and B mesons



Euclidean correlators: comparison with lattice QCD

FROM SPECTRAL FUNCTIONS TO EUCLIDEAN CORRELATORS

Spectral function $\rho(\omega, \vec{p}; T) \longrightarrow$ Euclidean correlator $G_E(\tau, \vec{p}; T)$

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

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Euclidean correlator $\longrightarrow$ Spectral function (ill-posed)

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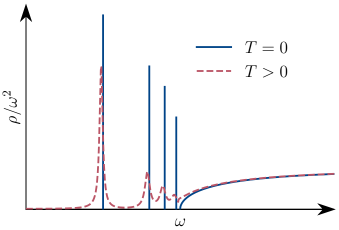

$$S_D(\omega, \vec{q}; T) = -\frac{1}{\pi} \mathrm{Im} \left(\frac{1}{\omega^2 - \vec{q}^2 - M_D^2 - \Pi_D(\omega, \vec{q}; T)} \right)$$

at unphysical meson masses (used in the lattice)

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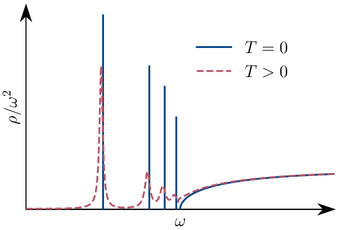

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at unphysical meson masses (used in the lattice)

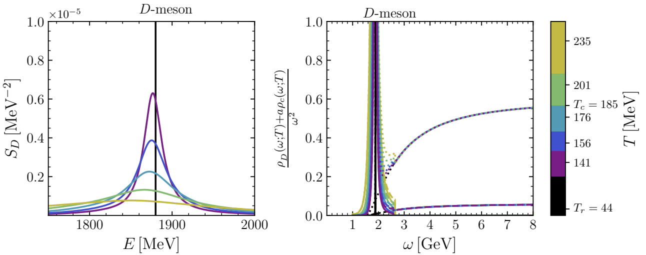
- Full: $\rho(\omega; T) = \rho_{\mathrm{gs}}(\omega; T) + a\rho_{\mathrm{cont}}(\omega; T)$

EUCLIDEAN CORRELATORS WITH EFT

[GM, O. Kaczmarek, L. Tolos, A. Ramos, Eur.Phys.J.A 56 (2020)]

$m_\pi = 384$ 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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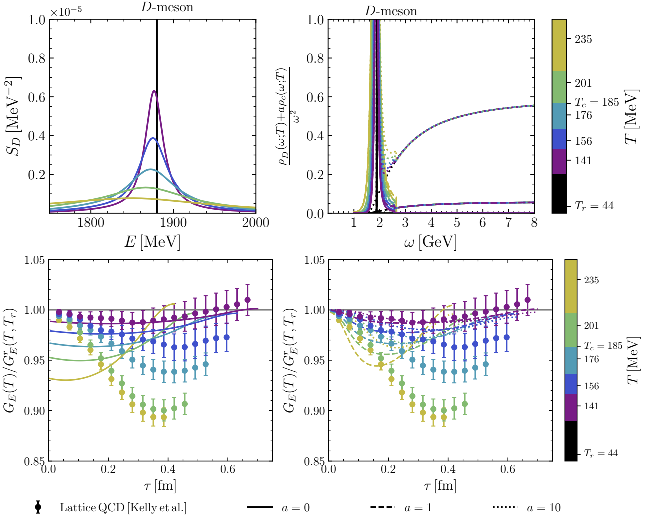
- The inclusion of the continuum improves the comparison at small τ
- Good agreement at the lowest temperature. At larger temperatures: excited states?
- Close and above T_c the EFT breaks down
- Similiar results for the D_s



Transport coefficients of an off-shell D meson

TRANSPORT COEFFICIENTS OF AN OFF-SHELL D-MESON

Fokker-Planck equation for the Green's function

$$\frac{\partial}{\partial t} G_D^{<}(t,k) = \frac{\partial}{\partial k^i} \left\{ \hat{A}(k;T)\, k^i G_D^{<}(t,k) + \frac{\partial}{\partial k^j} \left[\hat{B}_0(k;T)\, \Delta^{ij} + \hat{B}_1(k;T)\, \frac{k^i k^j}{\mathbf{k}^2} \right] G_D^{<}(t,k) \right\}$$

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Off-shell transport coefficients

- Drag force

$$\hat{A}(k^0,\mathbf{k};T) \equiv \frac{1}{2k^0}\int \frac{dk_1^0}{2\pi}\frac{d^3q}{(2\pi)^3}\, W(k^0,\mathbf{k},k_1^0,\mathbf{q})\,\frac{\mathbf{q}\cdot\mathbf{k}}{\mathbf{k}^2}$$

- Diffusion coefficients

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$$\frac{1}{2k^0}\int \frac{dk_1^0}{2\pi}\frac{d^3q}{(2\pi)^3} W(k^0,\mathbf{k},k_1^0,\mathbf{q}) = \frac{1}{2k^0}\sum_{\lambda,\lambda'=\pm}\lambda\lambda'\int_{-\infty}^{\infty} dk_1^0 \int \prod_{i=1}^{3}\frac{d^3k_i}{(2\pi)^3}\frac{1}{2E_2 2E_3} S_D(k_1^0,\mathbf{k}_1)$$
$$\times (2\pi)^4\delta^{(3)}(\mathbf{k}+\mathbf{k}_3-\mathbf{k}_1-\mathbf{k}_2)\delta(k^0+\lambda' E_3-\lambda E_2-k_1^0)$$
$$\times |T(k^0+\lambda' E_3,\mathbf{k}+\mathbf{k}_3)|^2 f^{(0)}(\lambda' E_3)\tilde{f}^{(0)}(\lambda E_2)\tilde{f}^{(0)}(k_1^0)$$

- ▶ Thermal effects in $|T|^2$ and E_k
- ▶ Landau cut
- ▶ Off-shell effects

RESULTS: D MESON TRANSPORT COEFFIECIENTS

In the static limit $\mathbf{k} \to 0$

For $k^0 = E_k$ solution of

$$E_k^2 - \mathbf{k}^2 - m_D^2 - \mathrm{Re}\,\Pi(E_k, \vec{k}; T) = 0$$

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$$2\pi T D_s(T) = \lim_{\mathbf{k}\to 0} \frac{2\pi T^3}{\hat{B}_0(E_k, \mathbf{k}; T)}$$

Momentum diffusion coefficient

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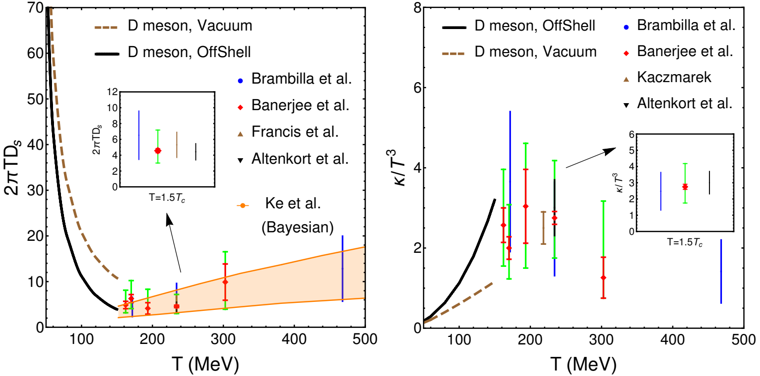

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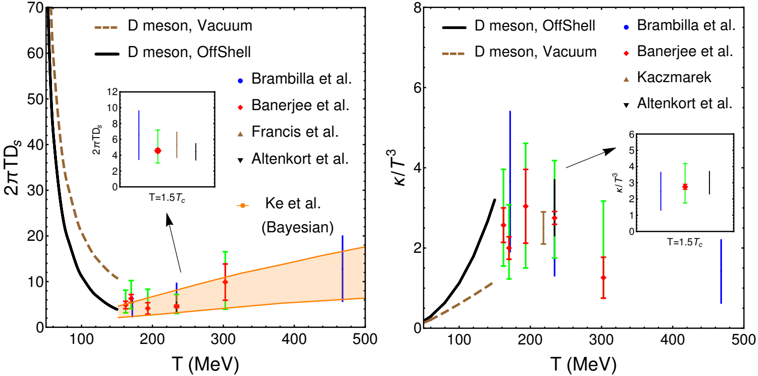

Good matching around T_c of our results with the lattice QCD data and a Bayesian analysis, specially when thermal and off-shell effects are included.

Conclusions

CONCLUSIONS

- We have described the scattering of open heavy-flavour mesons off light mesons including temperature corrections in a self-consistent manner.
- We have obtained spectral functions at various temperatures below T_c.
- The mass of the open heavy-flavour ground-state mesons decreases with temperature while they acquire a substantial width.
- Modification also of the dynamically generated resonances, but still far from chiral degeneracy at the temperatures explored.
- The largest effect comes form the pions in the bath. Heavier light mesons are less abundant.
- We have obtained Euclidean correlators from spectral functions at unphysical masses, which are in good agreement with LQCD results well below T_c. The the discrepancy close to T_c indicates the missing contribution of higher-excited states.
- We have introduced thermal and off-shell effects in the computattion of D-meson transport coefficients. The Landau Cut contributes sizeably at moderate temperatures.

Thermal modification of open heavy-flavour mesons from an effective hadronic theory

Glòria Montaña

University of Barcelona
Institute of Cosmos Sciences

[GM, Angels Ramos, Laura Tolos, Juan Torres-Rincon, Phys.Lett.B 806 (2020)]
[GM, Angels Ramos, Laura Tolos, Juan Torres-Rincon, Phys.Rev.D 102 (2020)]
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A Virtual Tribute to Quark Confinement and the Hadron Spectrum 2021

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