Thermal effects on open heavy-flavor mesons

Glòria Montaña

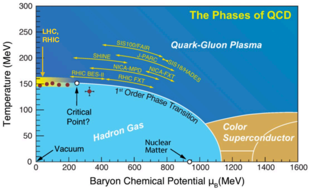
University of Barcelona
Institute of Cosmos Sciences

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

Second Strong2020 online Workshop
14-16 September 2021

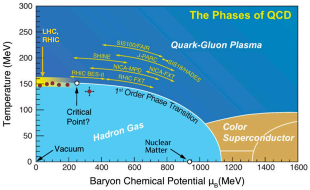
Introduction

INTRODUCTION



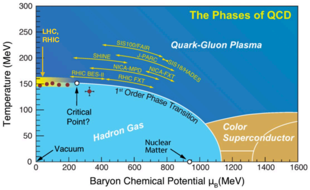
- Matter at very high temperatures and vanishing baryon densities (QGP?) is produced in HICs at RHIC and LHC
  $\longrightarrow$ hot mesonic (pionic) matter after confinement transition

INTRODUCTION

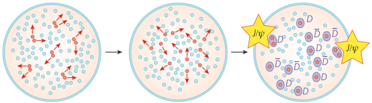


- ▶ Matter at very high temperatures and vanishing baryon densities (QGP?) is produced in HICs at RHIC and LHC
  $\longrightarrow$ hot mesonic (pionic) matter after confinement transition
- ▶ Heavy quarks are formed at the initial stage of the collision and have a large relaxation time

INTRODUCTION



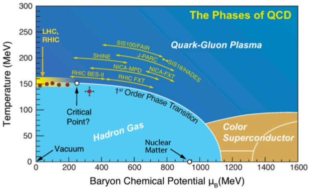
Color screening



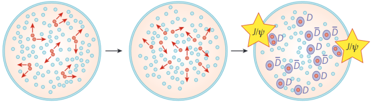
Comover scattering

- Matter at very high temperatures and vanishing baryon densities (QGP?) is produced in HICs at RHIC and LHC
  ⟶ hot mesonic (pionic) matter after confinement transition
- 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-flavor mesons created at the confinement transition
  - They iteract with the light mesons in the medium
  - Quarkonia suppression: color screening + comover scattering

INTRODUCTION



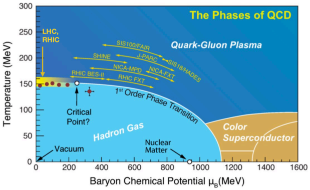
Color screening



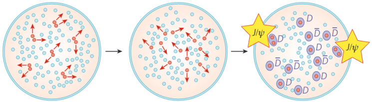
Comover scattering

- 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
- 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-flavor mesons created at the confinement transition
  - ◁ They iteract with the light mesons in the medium
  - ◁ Quarkonia suppression: color screening + comover scattering
- Properties of hadrons and their thermal modification are contained in their spectral functions

INTRODUCTION



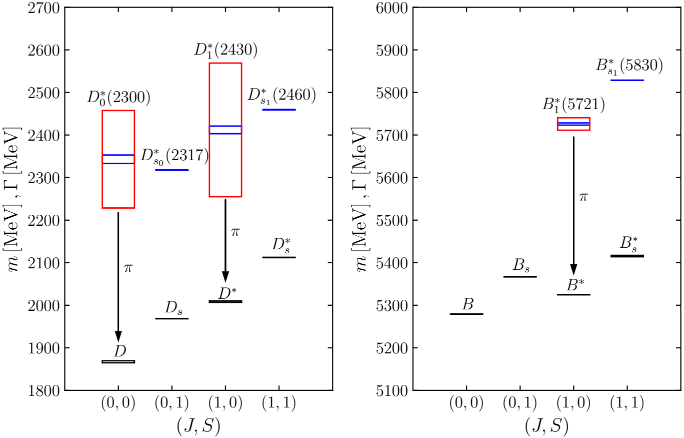
Color screening



Comover scattering

- Matter at very high temperatures and vanishing baryon densities (QGP?) is produced in HICs at RHIC and LHC
  ⟶ hot mesonic (pionic) matter after confinement transition
- 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-flavor mesons created at the confinement transition
  - They iteract with the light mesons in the medium
  - Quarkonia suppression: color screening + comover scattering
- 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

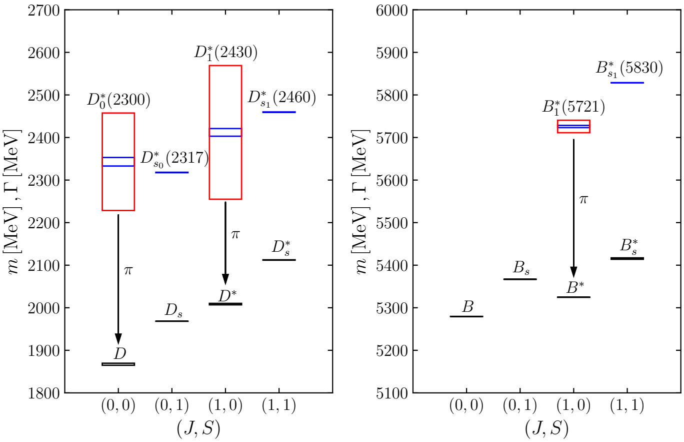
OPEN HEAVY-FLAVOR SPECTRUM



- 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)]

OPEN HEAVY-FLAVOR 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-flavor 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^*)

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

$$\mathcal{L}_{\rm LO} = \langle \nabla^\mu D \nabla_\mu D^\dagger \rangle - m_D^2 \langle D D^\dagger \rangle - \langle \nabla^\mu D^{*\nu} \nabla_\mu D_\nu^{*\dagger} \rangle + m_D^2 \langle D^{*\nu} D_\nu^{*\dagger} \rangle$$

$$+\, i\, g \langle D^{*\mu} u_\mu D^\dagger - D u^\mu D_\mu^{*\dagger} \rangle + \frac{g}{2m_D} \langle D_\mu^* u_\alpha \nabla_\beta D_\nu^{*\dagger} - \nabla_\beta D_\mu^* u_\alpha D_\nu^{*\dagger} \rangle \epsilon^{\mu\nu\alpha\beta}$$

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

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

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

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

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^*)

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

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

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

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

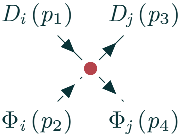
$${\rm LECs:}\ h_{0,\ldots,5},\ \tilde{h}_{0,\ldots,5}$$

[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:

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

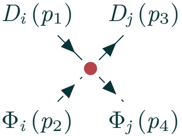


C_n^{ij}: isospin coefficients

SCATTERING IN COUPLED CHANNELS

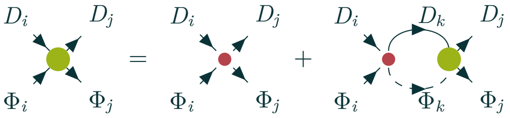
s-wave scattering amplitude of $D^{(*)}$, $D_s^{(*)}$ mesons with π, K, $\bar{K}$, η:

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



C_n^{ij}: isospin coefficients

Unitarization: Bethe-Salpeter equation



$\longrightarrow$

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

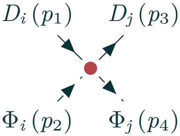
On-shell factorization of the T-matrix:

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

SCATTERING IN COUPLED CHANNELS

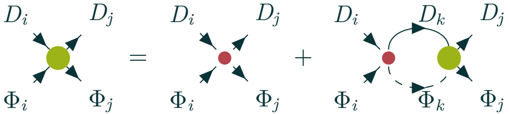
s-wave scattering amplitude of $D^{(*)}$, $D_s^{(*)}$ mesons with π, K, $\bar{K}$, η:

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



C_n^{ij}: isospin coefficients

Unitarization: Bethe-Salpeter equation



$\longrightarrow$

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

On-shell factorization of the T-matrix:

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

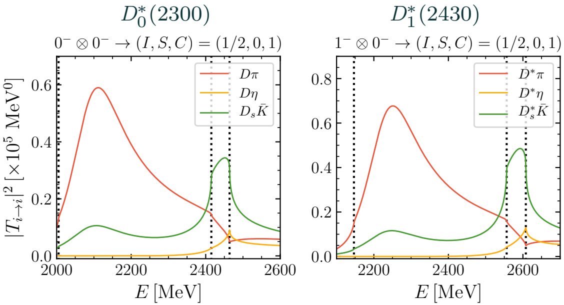
- The two-meson propagator is regularized with a cutoff

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

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

RESULTS: DYNAMICALLY GENERATED STATES WITH OPEN HEAVY FLAVOR

Open charm



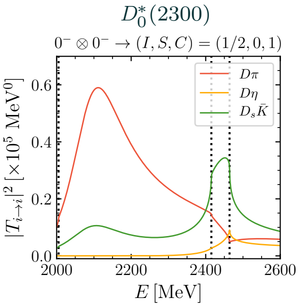
$(I,S) = (0,1)$:

DK bound state at 2252.5 MeV $\to D_{s0}^*(2317)$
D^*K bound state at 2393.3 MeV $\to D_{s1}^*(2460)$

RESULTS: DYNAMICALLY GENERATED STATES WITH OPEN HEAVY FLAVOR

$$\text{LECS:} \quad \frac{h^B_{0,\dots,3}}{\hat{M}_B} = \frac{h^D_{0,\dots,3}}{\hat{M}_D} \;, \quad h^B_{4,5}\,\hat{M}_B = h^D_{4,5}\,\hat{M}_D$$

Open charm

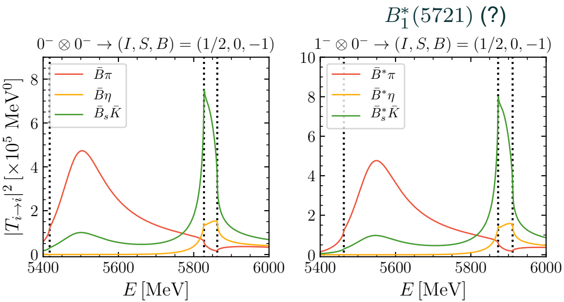


$(I, S) = (0, 1)$:

DK bound state at 2252.5 MeV → $D^*_{s0}(2317)$

D^*K bound state at 2393.3 MeV → $D^*_{s1}(2460)$

Open beauty



$(I, S) = (0, 1)$:

$\bar{B}K$ bound state at 5639.3 MeV

$\bar{B}^*K$ bound state at 5686.0 MeV → $B^*_{s1}(5830)$ (?)

Thermal Effective Field Theory

THERMAL MODIFICATION OF HEAVY MESONS IN A MESONIC BATH

- Imaginary-time formalism
  - Sum over Matsubara frequencies → Bose-Einstein distribution functions

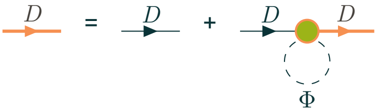
$$q^0 \to i\omega_n = \frac{i}{\beta} 2\pi n \,, \quad \int \frac{d^4 q}{(2\pi^4)} \to \frac{i}{\beta} \sum_n \int \frac{d^3 q}{(2\pi)^3} \quad \text{(bosons)}$$

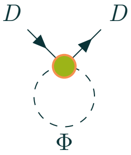
THERMAL MODIFICATION OF HEAVY MESONS IN A MESONIC BATH

- Imaginary-time formalism
  - Sum over Matsubara frequencies → Bose-Einstein distribution functions

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

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



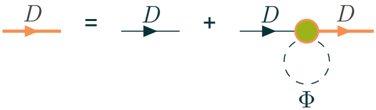


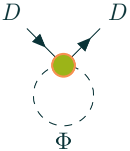
THERMAL MODIFICATION OF HEAVY MESONS IN A MESONIC BATH

- Imaginary-time formalism
  - Sum over Matsubara frequencies → Bose-Einstein distribution functions

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

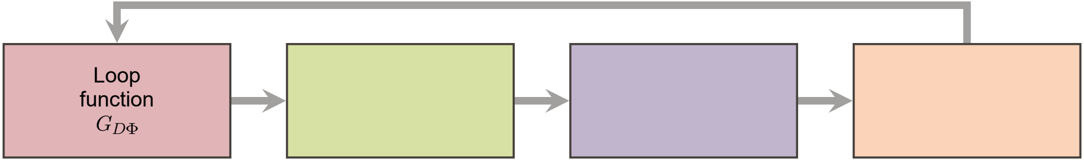
- Dressing the mesons in the loop function
  - Self-energy corrections
  - Pion mass varies slightly below T_c → only the heavy meson is dressed





New processes that are absent in free space are now possible: real mesons present in the thermal medium can be absorbed.

SELF-CONSISTENT ITERATIVE PROCEDURE


Loop function $G_{D\Phi}$

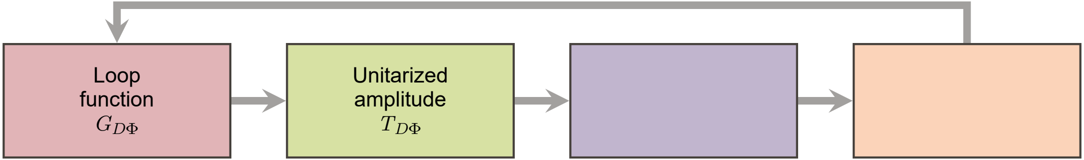
$$G_{D\Phi}(E,\vec{p};T) = \int \frac{d^3q}{(2\pi)^3} \int d\omega \int d\omega' \frac{S_D(\omega,\vec{q};T)\, S_\Phi(\omega',\vec{p}-\vec{q};T)}{E-\omega-\omega'+i\varepsilon}[1+f(\omega,T)+f(\omega',T)]$$

D-meson spectral function

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

Regularized with a cutoff Λ

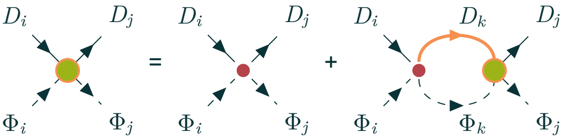
SELF-CONSISTENT ITERATIVE PROCEDURE



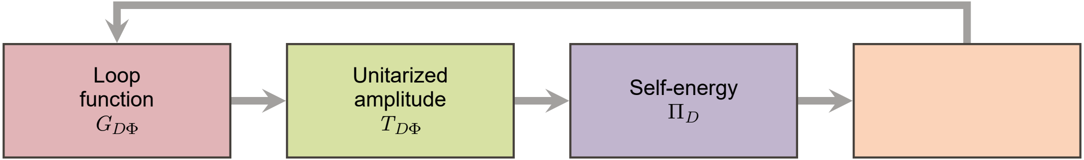
Loop function $G_{D\Phi}$

Unitarized amplitude $T_{D\Phi}$

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



SELF-CONSISTENT ITERATIVE PROCEDURE

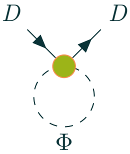


Loop function $G_{D\Phi}$

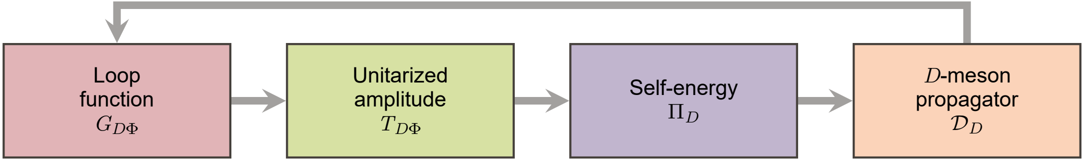
Unitarized amplitude $T_{D\Phi}$

Self-energy Π_D

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



SELF-CONSISTENT ITERATIVE PROCEDURE



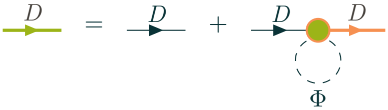
Loop function $G_{D\Phi}$

Unitarized amplitude $T_{D\Phi}$

Self-energy Π_D

D-meson propagator $\mathcal{D}_D$

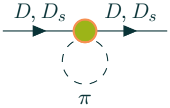
$$S_D(\omega, \vec{q}; T) = -\frac{1}{\pi}\mathrm{Im}\ \mathcal{D}_D(\omega, \vec{q}; T) = -\frac{1}{\pi}\mathrm{Im}\left(\frac{1}{\omega^2 - \vec{q}^2 - m_D^2 - \Pi_D(\omega, \vec{q}; T)}\right)$$



Results: Thermal modification of open-charm mesons

LOOP FUNCTIONS

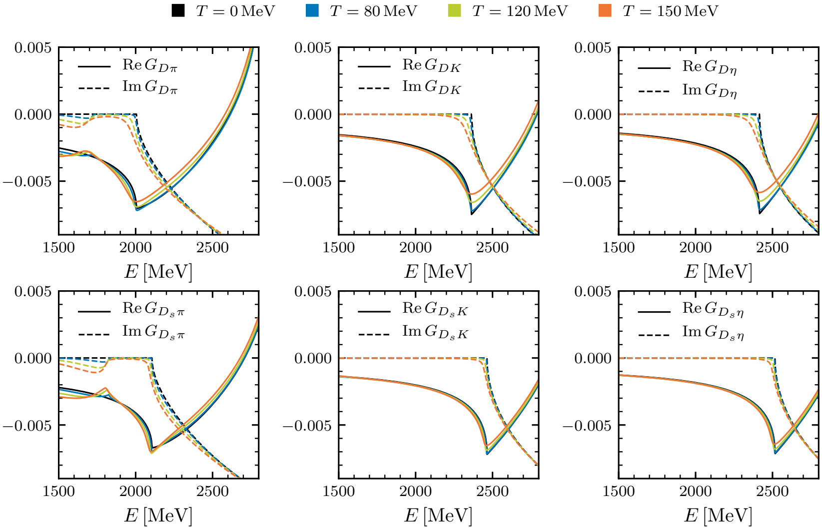
Pionic bath



Loops D and D_s
with $\Phi = \{\pi,\ K,\ \eta\}$

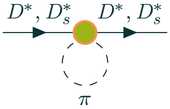
Unitary cut:
$E \geq (m_D + m_\Phi)$

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



LOOP FUNCTIONS

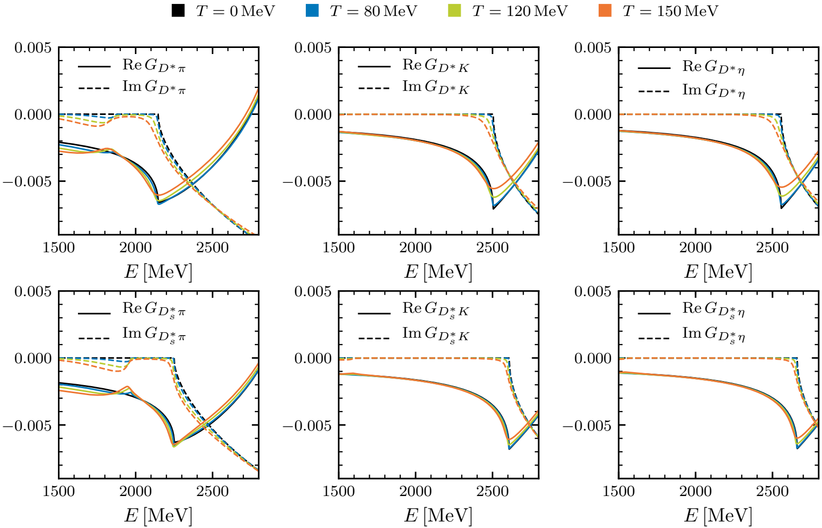
Pionic bath



Loops D^* and D_s^* with $\Phi = \{\pi,\ K,\ \eta\}$

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

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

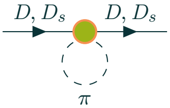


D MESONS: MASSES AND WIDTHS. CHIRAL PARTNERS

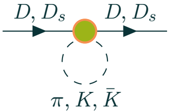
Evolution of masses and widths

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

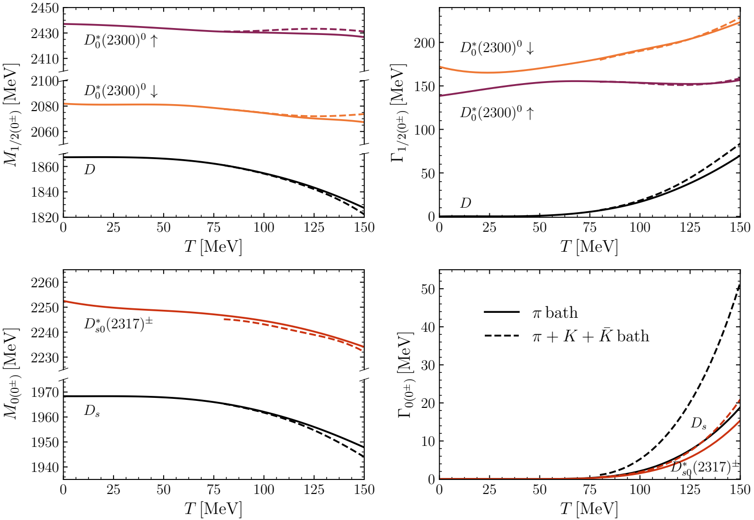
- Solid lines



- Dashed lines



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

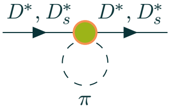


D MESONS: MASSES AND WIDTHS. CHIRAL PARTNERS

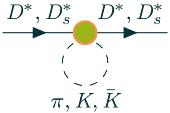
Evolution of masses and widths

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

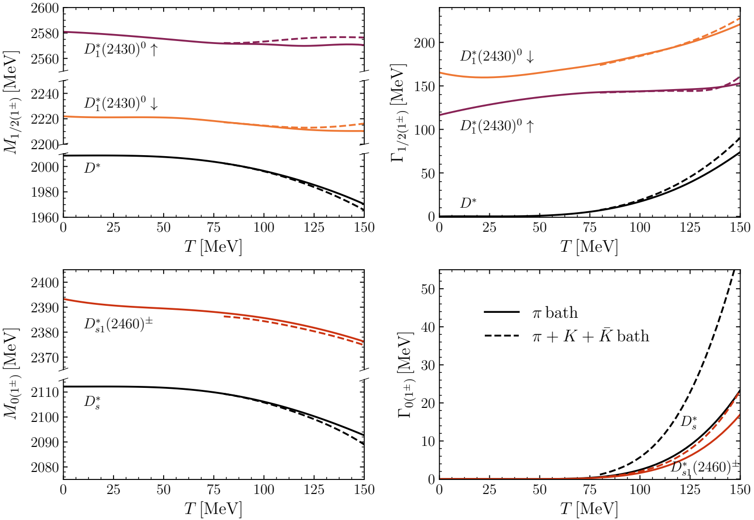
- Solid lines



- Dashed lines



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

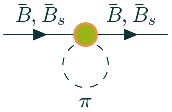


B MESONS: MASSES AND WIDTHS

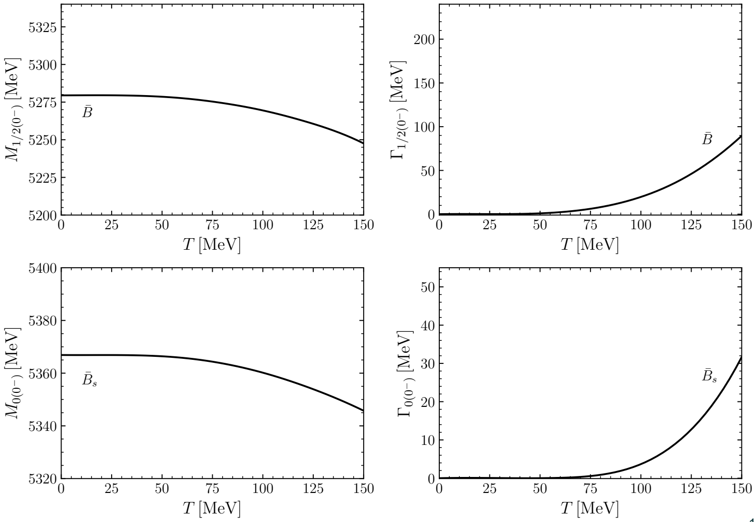
Evolution of masses and widths of the ground states

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

- Pionic bath



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 $G_E(\tau, \vec{p}; T)$

$$G_E(\tau, \vec{p}; T) = \int_0^\infty d\omega K(\tau, \omega; T)\rho(\omega, \vec{p}; T) \ , \qquad K(\tau, \omega; T) = \frac{\cosh[\omega(\tau - \frac{1}{2T})]}{\sinh(\frac{\omega}{2T})}$$

FROM SPECTRAL FUNCTIONS TO EUCLIDEAN CORRELATORS

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

$$G_E(\tau, \vec{p}; T) = \int_0^\infty d\omega K(\tau, \omega; T)\rho(\omega, \vec{p}; T) \ , \qquad K(\tau, \omega; T) = \frac{\cosh[\omega(\tau - \frac{1}{2T})]}{\sinh(\frac{\omega}{2T})}$$

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

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

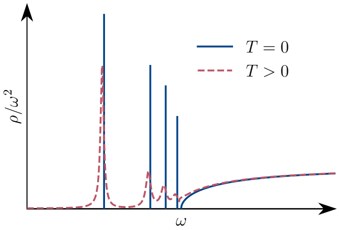
FROM SPECTRAL FUNCTIONS TO EUCLIDEAN CORRELATORS

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

$$G_E(\tau, \vec{p}; T) = \int_0^\infty d\omega K(\tau, \omega; T)\rho(\omega, \vec{p}; T) \, , \qquad K(\tau, \omega; T) = \frac{\cosh[\omega(\tau - \frac{1}{2T})]}{\sinh(\frac{\omega}{2T})}$$

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

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



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

at unphysical meson masses (used in the lattice)

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

EUCLIDEAN CORRELATORS WITH EFT

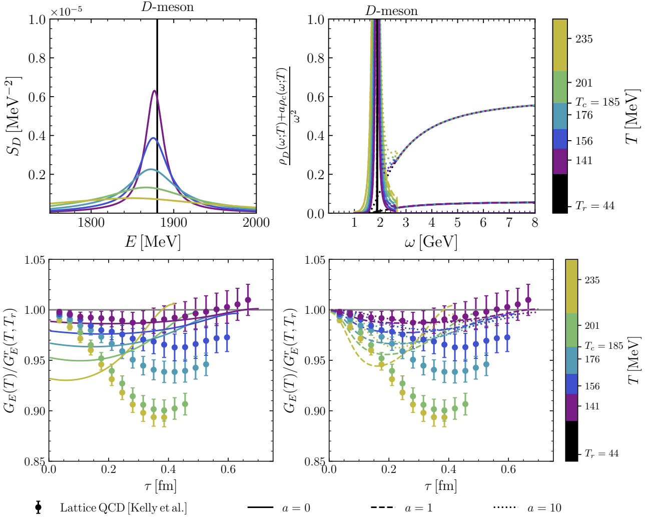
[GM, O. Kaczmarek, L. Tolos, A. Ramos, Eur.Phys.J.A 56 (2020)]

$m_\pi = 384$ MeV
$m_K = 546$ MeV
$m_\eta = 589$ MeV
$m_D = 1880$ MeV
$m_{D_s} = 1943$ MeV

[Kelly, Rothkopf, Skullerud (2018)]

- Behavior at small τ improved by the continuum
- Good agreement at low temperatures

  At larger temperatures: excited states?
- $\sim T_c$ 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

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

TRANSPORT COEFFICIENTS OF AN OFF-SHELL D-MESON

Fokker-Planck equation for the Green's function

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

Off-shell transport coefficients

- Drag force

$$\hat{A}(k^0, \mathbf{k};\, T) \equiv \left\langle 1 - \frac{\mathbf{k}\cdot\mathbf{k}_1}{\mathbf{k}^2} \right\rangle$$

- Diffusion coefficients

$$\hat{B}_0(k^0, \mathbf{k};\, T) \equiv \frac{1}{4}\left\langle {\mathbf{k}_1}^2 - \frac{(\mathbf{k}\cdot\mathbf{k}_1)^2}{\mathbf{k}^2} \right\rangle$$

$$\hat{B}_1(k^0, \mathbf{k};\, T) \equiv \frac{1}{2}\left\langle \frac{(\mathbf{k}\cdot(\mathbf{k}-\mathbf{k}_1)^2}{\mathbf{k}^2} \right\rangle$$

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

$$\langle \mathcal{F}(\mathbf{k},\mathbf{k}_1)\rangle = \frac{1}{2k^0}\sum_{\lambda=\pm}\lambda\int_{-\infty}^{\infty} dk_1^0 \int \prod_{i=1}^{3}\frac{d^3k_i}{(2\pi)^3}\,\frac{1}{2E_2 2E_3}\; S_D(k_1^0,\mathbf{k}_1)\;\times(2\pi)^4\delta^{(3)}(\mathbf{k}+\mathbf{k}_3-\mathbf{k}_1-\mathbf{k}_2)\,\mathcal{F}(\mathbf{k},\mathbf{k}_1)$$

$$\Big\{\, |T(k^0+E_3,\mathbf{k}+\mathbf{k}_3)|^2\;\delta(k^0+E_3-\lambda E_2-k_1^0)[1+f(k_1^0)][1+f(\lambda E_2)]\,f(E_3)$$

$$+\,|T(k^0-E_3,\mathbf{k}+\mathbf{k}_3)|^2\;\delta(k^0-E_3-\lambda E_2-k_1^0)[1+f(k_1^0)][1+f(\lambda E_2)][1+f(E_3)]\Big\}$$

TRANSPORT COEFFICIENTS OF AN OFF-SHELL D-MESON

Fokker-Planck equation for the Green's function

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

Off-shell transport coefficients

- Drag force

$$\hat{A}(k^0,\mathbf{k};\,T) \equiv \left\langle 1 - \frac{\mathbf{k}\cdot\mathbf{k}_1}{\mathbf{k}^2}\right\rangle$$

- Diffusion coefficients

$$\hat{B}_0(k^0,\mathbf{k};\,T) \equiv \frac{1}{4}\left\langle {\mathbf{k}_1}^2 - \frac{(\mathbf{k}\cdot\mathbf{k}_1)^2}{\mathbf{k}^2}\right\rangle$$

$$\hat{B}_1(k^0,\mathbf{k};\,T) \equiv \frac{1}{2}\left\langle \frac{(\mathbf{k}\cdot(\mathbf{k}-\mathbf{k}_1)^2}{\mathbf{k}^2}\right\rangle$$

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

$$\langle \mathcal{F}(\mathbf{k},\mathbf{k}_1)\rangle = \frac{1}{2k^0}\sum_{\lambda=\pm}\lambda\int_{-\infty}^{\infty} dk_1^0 \int\prod_{i=1}^{3}\frac{d^3k_i}{(2\pi)^3}\,\frac{1}{2E_2 2E_3}\; S_D(k_1^0,\mathbf{k}_1)\;\times(2\pi)^4\delta^{(3)}(\mathbf{k}+\mathbf{k}_3-\mathbf{k}_1-\mathbf{k}_2)\,\mathcal{F}(\mathbf{k},\mathbf{k}_1)$$

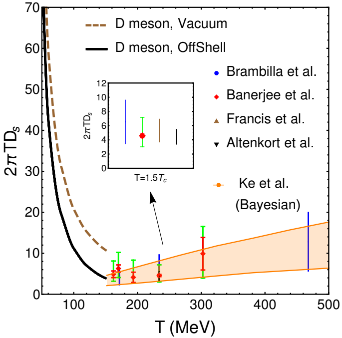
$$\Big\{\,|T(k^0+E_3,\mathbf{k}+\mathbf{k}_3)|^2\;\delta(k^0+E_3-\lambda E_2-k_1^0)[1+f(k_1^0)][1+f(\lambda E_2)]\,f(E_3)$$

$$+\,|T(k^0-E_3,\mathbf{k}+\mathbf{k}_3)|^2\,\delta(k^0-E_3-\lambda E_2-k_1^0)[1+f(k_1^0)][1+f(\lambda E_2)][1+f(E_3)]\Big\}$$

RESULTS: D-MESON TRANSPORT COEFFIECIENTS

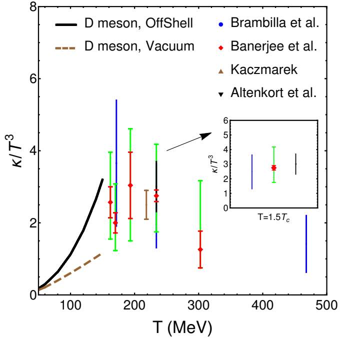
Spatial diffusion coefficient

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



Momentum diffusion coefficient

$$\kappa(T) = 2\hat{B}_0(E_k, \mathbf{k}\to 0;\, T)$$



Comparison with:

- lattice QCD calculations
- Bayesian analysis

Good matching at T_c,

specially when thermal and off-shell effects are included (black solid lines)

[J. Torres-Rincon, GM, A. Ramos, L. Tolos, arXiv:2106.01156]

Summary

SUMMARY

- We have extended the EFT describing the scattering of open heavy-flavor mesons off light mesons to finite temperature in a self-consistent way.

- Thermal effects: masses decrease moderately while the widths increase substantially with increasing temperatures. Pions contribute the most (most abundant mesons in the bath).

- The thermal modification of chiral partners is comparable, being far from chiral degeneracy at the temperatures explored.

- Euclidean correlators computed from spectral functions at unphysical masses are in good agreement with LQCD results well below T_c. Discrepancies close to T_c possibly indicate the missing contribution of higher-excited states.

- D-meson transport coefficients below T_c from an off-shell kinetic theory including thermal effects. The new contribution coming from the Landau Cut of the loop function improves considerably the comparison with lattice QCD calculations and Bayesian analyses.

Thermal effects on open heavy-flavor mesons

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

Second Strong2020 online Workshop
14-16 September 2021

STRONG 2020

UNIVERSITAT DE BARCELONA

ICCUB

EXCELENCIA MARÍA DE MAEZTU

GOBIERNO DE ESPAÑA

MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

Backup slides

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	$D_s^*\eta$		$(+,+)$	$2393.3 - i0.0$	$\lvert g_{D^*K}\rvert = 14.2$, $\lvert g_{D_s^*\eta}\rvert = 9.7$
		(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)	$B_1^*(5721)^+ \,:\, 31 \pm 6$ $B_1^*(5721)^0 \,:\, 27.5 \pm 3.4$	0.5 ± 0.4

J^P	(S, I)	Coupled channels			RS	Poles (MeV)	Couplings (GeV)
0^+	$(0, \frac{1}{2})$	$\bar{B}\pi$	$\bar{B}\eta$	$\bar{B}_s\bar{K}$	$(-,+,+)$	$5483.1 - i71.8$	$\lvert g_{\bar{B}\pi}\rvert = 22.4$, $\lvert g_{\bar{B}\eta}\rvert = 0.8$, $\lvert g_{\bar{B}_s\bar{K}}\rvert = 14.4$
		(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)	$(-,-,+)$	$5893.3 - i65.0$	$\lvert g_{\bar{B}^*\pi}\rvert = 10.7$, $\lvert g_{\bar{B}^*\eta}\rvert = 18.0$, $\lvert g_{\bar{B}_s^*\bar{K}}\rvert = 32.1$
	$(1, 0)$	$\bar{B}^*K$	$\bar{B}_s^*\eta$		$(+,+)$	$5686.0 - i0.0$	$\lvert g_{\bar{B}^*K}\rvert = 14.2$, $\lvert g_{\bar{B}_s^*\eta}\rvert = 9.7$
		(5820.29)	(5963.26)				

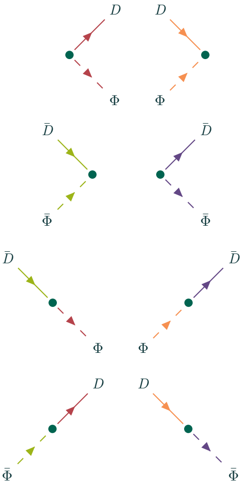
PHYSICAL INTERPRETATION OF THE THERMAL BATH

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

$$+ \frac{\overset{\text{bath} + \bar{D}\bar{\Phi} \to \text{bath}}{f(\omega_D, T) f(\omega_\Phi, T)} - \overset{\text{bath} \to \text{bath} + \bar{D}\bar{\Phi}}{[1 + f(\omega_D, T)][1 + f(\omega_\Phi, T)]}}{E + \omega_D + \omega_\Phi + i\varepsilon}$$

$$+ \frac{\overset{\text{bath} + \bar{D} \to \text{bath} + \Phi}{f(\omega_D, T)\,[1 + f(\omega_\Phi, T)]} - \overset{\text{bath} + \Phi \to \text{bath} + \bar{D}}{f(\omega_\Phi, T)\,[1 + f(\omega_D, T)]}}{E + \omega_D - \omega_\Phi + i\varepsilon}$$

$$+ \frac{\overset{\text{bath} + \bar{\Phi} \to \text{bath} + D}{f(\omega_\Phi, T)\,[1 + f(\omega_D, T)]} - \overset{\text{bath} + D \to \text{bath} + \bar{\Phi}}{f(\omega_D, T)\,[1 + f(\omega_\Phi, T)]}}{E - \omega_D + \omega_\Phi + i\varepsilon} \Bigg\}$$



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

PHYSICAL INTERPRETATION OF THE THERMAL BATH

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

First branch cut
($T=0$ unitary cut):

$$E \geq (m_D + m_\Phi)$$

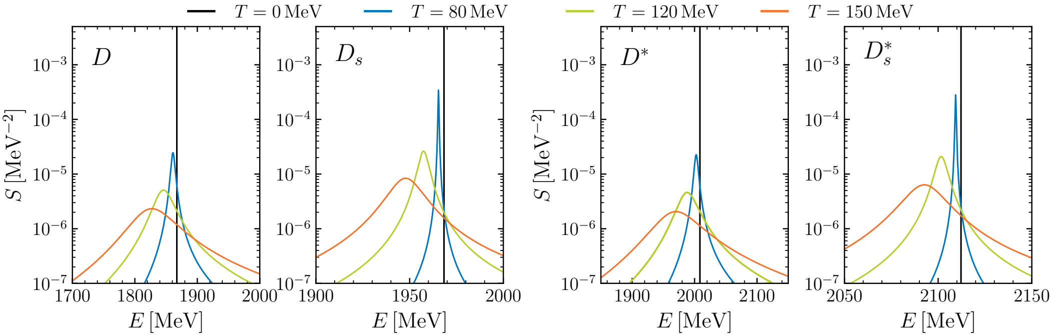
Additional branch cut
(Landau cut):

$$E \leq (m_D - m_\Phi)$$

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

SPECTRAL FUNCTIONS

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



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

Widening and mass shift to lower energies of the ground-state heavy mesons with increasing T.

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:

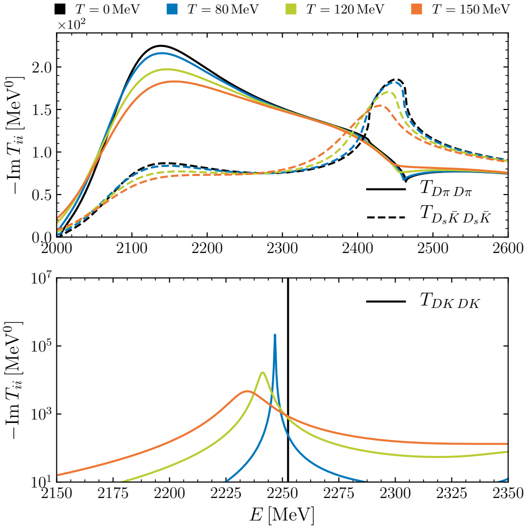
$M_R = 2300 \pm 19$ MeV, $\Gamma_R = 274 \pm 40$ MeV

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