Open heavy flavor in a hot bath

Gloria Montaña, Olaf Kaczmarek,
Angels Ramos, **Laura Tolós** and Juan Torres-Rincón

FIAS Frankfurt Institute for Advanced Studies

Institute of Space Sciences
CSIC IEEC
Consejo Superior de Investigaciones Científicas

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EMMI The ExtreMe Matter Institute - EMMI
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University of Stavanger

OUTLINE

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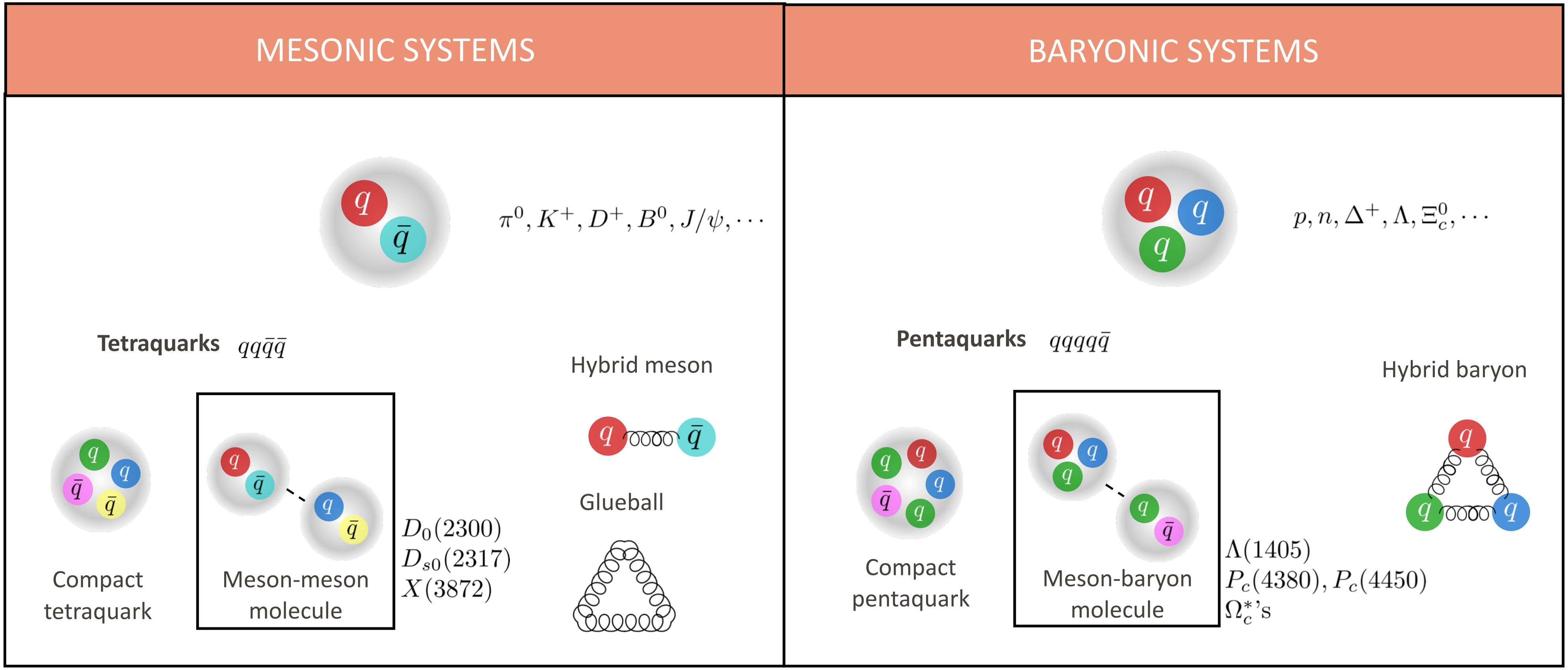
2 Heavy mesons in a hot medium

3 Open-charm Euclidean correlators

4 Conclusions

presentation based on G. Montaña PhD defense

1 Exotic heavy mesons with unitarized effective theories

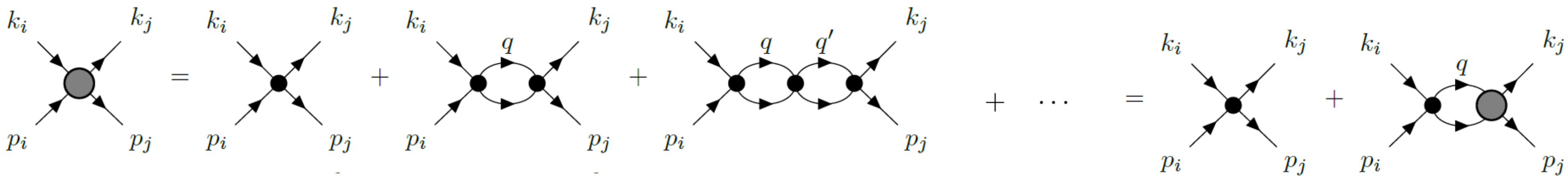


There are many (excited) hadrons that do not accommodate in the qqq or $q\bar{q}$ picture.

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

Interaction between open heavy-flavor mesons and Goldstone bosons and unitarization via Bethe-Salpeter equation

On-shell Bethe-Salpeter equation in coupled channels

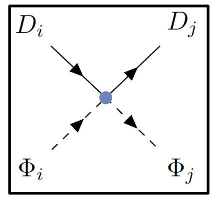


$$T_{ij} = V_{ij} + V_{ik} G_k T_{kj} \quad \longrightarrow \quad T = \frac{V}{1 - VG}$$

on-shell factorization

$V_{ij}(s)$: interaction potential

$G_k(s)$: two-meson propagator



$V_{ij}(s)$ from Lagrangian at NLO in the chiral expansion and LO in the heavy-quark expansion

[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)]

$$G_k(s) = \mathrm{i} \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_D^2 + \mathrm{i}\,\varepsilon} \frac{1}{(p-q)^2 - m_\Phi^2 + \mathrm{i}\,\varepsilon}$$

regularized with a momentum cut-off $|\vec{q}\,| \leq \Lambda$

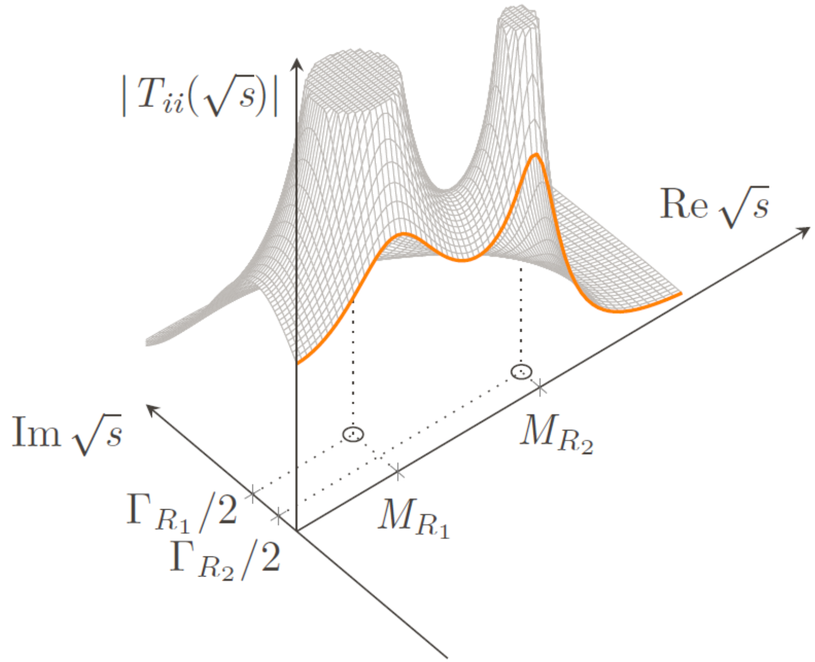
Unitarization and Analytical Continuation

- leads to the dynamical generation of states
- cuts along the real-energy axis and poles in the complex-energy plane
- classification of the poles depending on their location in the Riemann surface:

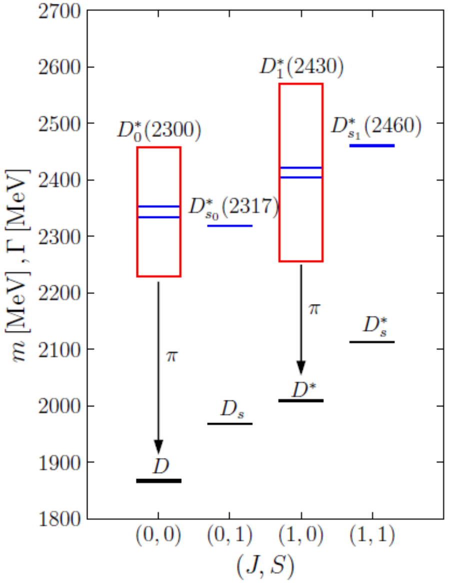
bound states ($\mathrm{RS\text{-}I}$), **resonances** ($\mathrm{RS\text{-}II}$), and **virtual states** ($\mathrm{RS\text{-}II}$)

Properties of the dynamically generated states:

- Mass $M_R = \mathrm{Re}\sqrt{s_p}$
- Width $\Gamma_R = 2\mathrm{Im}\sqrt{s_p}$
- Coupling constants to the different g_i channels (from the residue around the pole)
- Compositeness $\chi_i = \left| g_i \frac{\partial G_i(s_p)}{\partial s} \right|$



Results: Dynamically generated states in the charm sector



$D_0^*(2300)$: $M = 2343 \pm 10$ MeV
$I(J^P) = \frac{1}{2}(0^+)$ $\Gamma = 229 \pm 16$ MeV

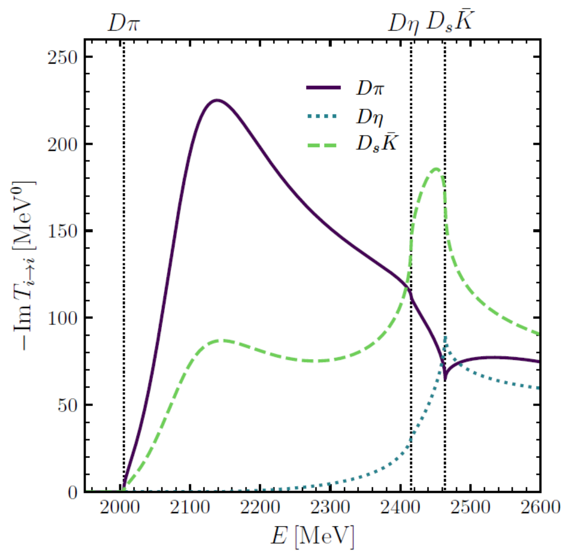
$D_{s0}^*(2317)^{\pm}$: $M = 2317.8 \pm 0.5$ MeV
$I(J^P) = 0(0^+)$ $\Gamma < 3.8$ MeV

[PDG (2020)]

(S,I)	Channels ($J^P = 0^+$)	Threshold (MeV)	Channels ($J^P = 1^+$)	Threshold (MeV)
$(-1,0)$	$D\bar{K}$	2364.88	$D^*\bar{K}$	2504.20
$(-1,1)$	$D\bar{K}$	2364.88	$D^*\bar{K}$	2504.20
$(0,\frac{1}{2})$	$D\pi$	2005.28	$D^*\pi$	2146.59
	$D\eta$	2415.10	$D^*\eta$	2556.42
	$D_s\bar{K}$	2463.98	$D_s^*\bar{K}$	2607.84
$(0,\frac{3}{2})$	$D\pi$	2005.28	$D^*\pi$	2146.59
$(1,0)$	DK	2364.88	D^*K	2504.20
	$D_s\eta$	2516.20	$D_s^*\eta$	2660.06
$(1,1)$	$D_s\pi$	2106.38	$D_s^*\pi$	2250.24
	DK	2364.88	D^*K	2504.20
$(2,\frac{1}{2})$	D_sK	2463.98	D_s^*K	2607.84

Poles of the unitarized scattering amplitude:

		(S,I)	RS	M_R (MeV)	$\Gamma_R/2$ (MeV)	$\lvert g_i\rvert$ (GeV)	χ_i
Two-pole structure	$D_0^*(2300)$	$(0,\frac{1}{2})$	$(-,+,+)$	2081.9	86.0	$\lvert g_{D\pi}\rvert = 8.9$	$\chi_{D\pi} = 0.45$
						$\lvert g_{D\eta}\rvert = 0.4$	$\chi_{D\eta} = 0.00$
						$\lvert g_{D_s\bar{K}}\rvert = 5.4$	$\chi_{D_s\bar{K}} = 0.02$
			$(-,-,+)$	2529.3	145.4	$\lvert g_{D\pi}\rvert = 6.7$	$\chi_{D\pi} = 0.20$
						$\lvert g_{D\eta}\rvert = 9.9$	$\chi_{D\eta} = 0.55$
						$\lvert g_{D_s\bar{K}}\rvert = 19.4$	$\chi_{D_s\bar{K}} = 0.95$
Bound state	$D_{s0}^*(2317)$	$(1,0)$	$(+,+)$	2252.5	0.0	$\lvert g_{DK}\rvert = 13.3$	$\chi_{DK} = 0.44$
						$\lvert g_{D_s\eta}\rvert = 9.2$	$\chi_{D_s\eta} = 0.08$



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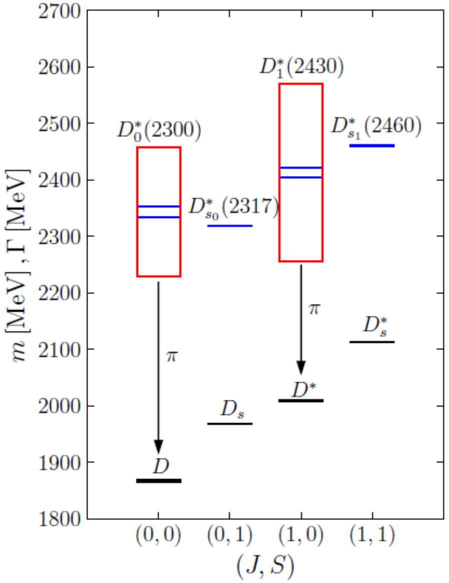

$D_1(2430)^0$: $M = 2412 \pm 9$ MeV

$I(J^P) = \frac{1}{2}(1^+)$ $\Gamma = 314 \pm 29$ MeV

$D_{s1}(2460)^\pm$: $M = 2459.6 \pm 0.6$ MeV

$I(J^P) = 0(1^+)$ $\Gamma < 3.5$ MeV

[PDG (2020)]

(S, I)	Channels ($J^P = 0^+$)	Threshold (MeV)	Channels ($J^P = 1^+$)	Threshold (MeV)
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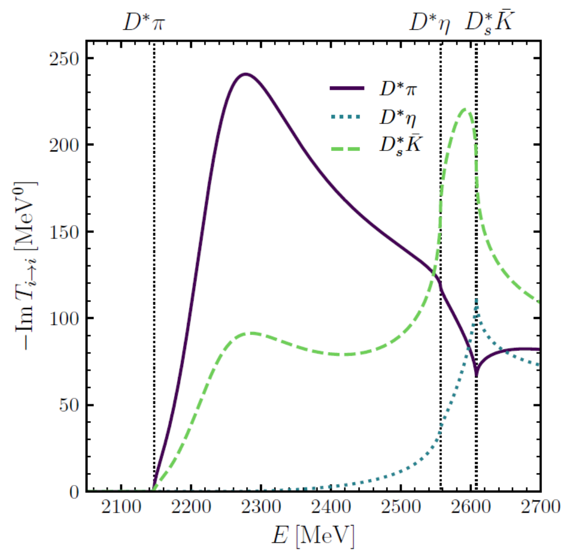
Poles of the unitarized scattering amplitude:

		(S, I)	RS	M_R (MeV)	$\Gamma_R/2$ (MeV)	$\|g_i\|$ (GeV)	χ_i
Two-pole structure	$D_1(2430)$	$(0, \frac{1}{2})$	$(-, +, +)$	2222.3	84.7	$\|g_{D^*\pi}\| = 9.5$	$\chi_{D^*\pi} = 0.45$
						$\|g_{D^*\eta}\| = 0.4$	$\chi_{D^*\eta} = 0.00$
						$\|g_{D_s^*\bar{K}}\| = 5.7$	$\chi_{D_s^*\bar{K}} = 0.02$
			$(-, -, +)$	2654.6	117.3	$\|g_{D^*\pi}\| = 6.5$	$\chi_{D^*\pi} = 0.17$
						$\|g_{D^*\eta}\| = 10.0$	$\chi_{D^*\eta} = 0.54$
						$\|g_{D_s^*\bar{K}}\| = 18.5$	$\chi_{D_s^*\bar{K}} = 0.90$
Bounc state	$D_{s1}(2460)$	$(1, 0)$	$(+, +)$	2393.3	0.0	$\|g_{D^*K}\| = 14.2$	$\chi_{D^*K} = 0.45$
						$\|g_{D_s^*\eta}\| = 9.7$	$\chi_{D_s^*\eta} = 0.08$



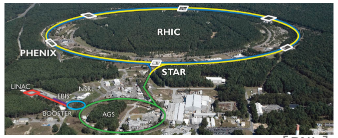
2 Heavy mesons in a hot medium

High-energy HICs

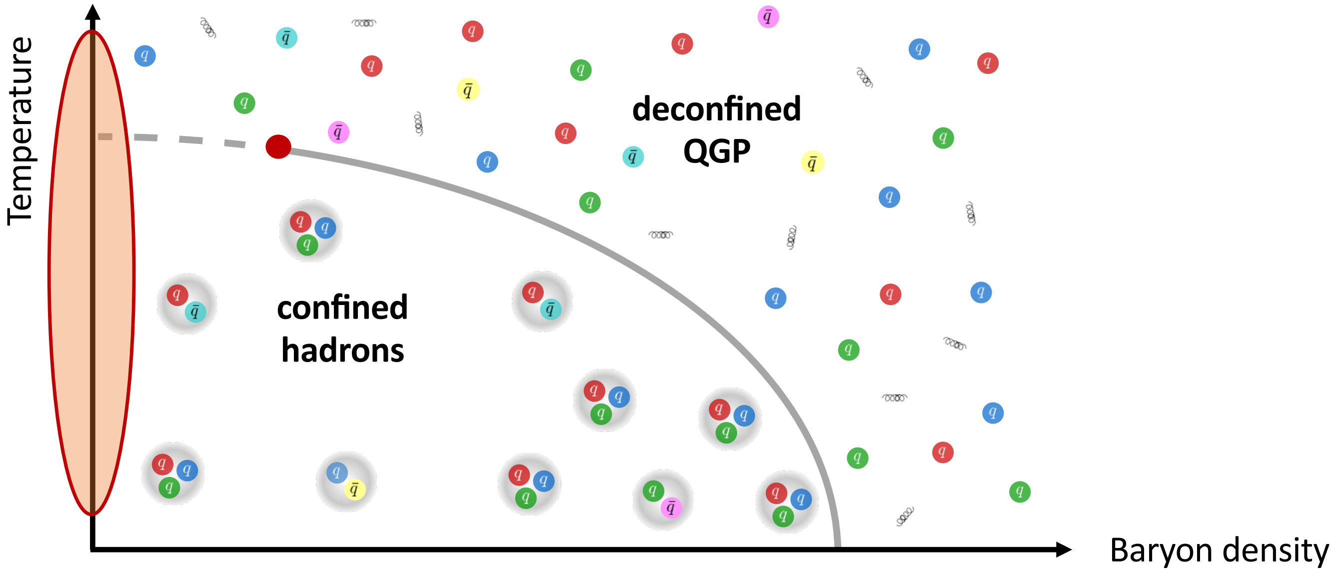
- LHC@CERN

[CERN]

- RHIC@BNL



[BNL]



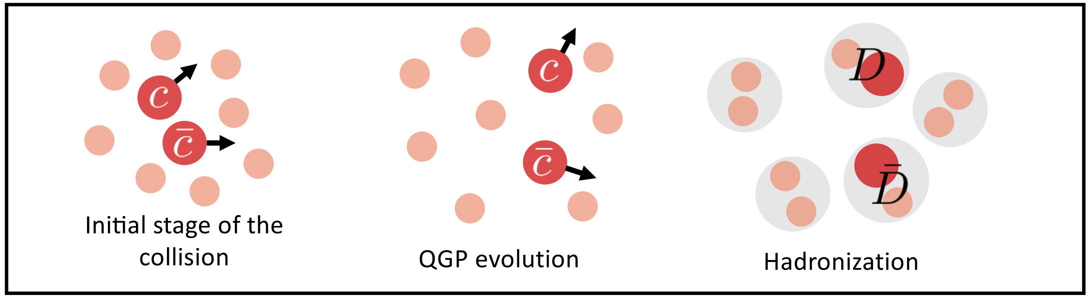
Theoretical tools to study QCD matter at high temperatures

- Perturbative theories (very high temperatures)
- Lattice QCD
- **Non-perturbative effective hadronic theories** (below transition temperature T_c)

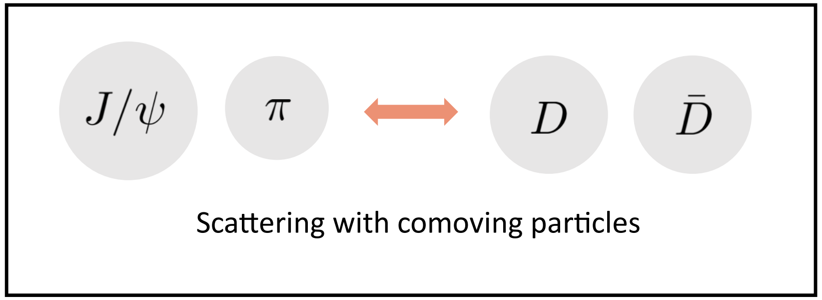
Heavy flavor

- **Heavy quarks** (mostly charm) are created in the initial stage of the collision
- Due to its large mass and relaxation time, heavy-flavor mesons are a **powerful probe of the QGP**
- The properties of heavy mesons, i.e., masses and widths, are modified in hot matter
- Understanding phenomena such as quarkonia suppression:

color screening



comover scattering

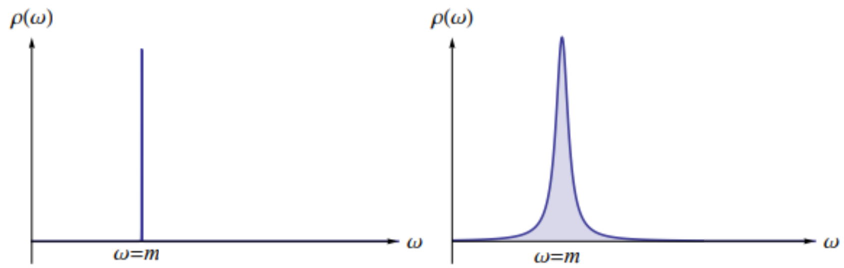


Mesonic bath in equilibrium at finite temperature

- Mesonic matter at **temperature** $0 < T < T_c$ and **vanishing baryon density** (produced in RHIC & LHC)
- Pions are the most abundant (lightest particles)
- Heavy mesons behave as Brownian particles scattering off the light mesons
- New processes are available: **production** and **absorption** of thermal mesons

Thermal effective hadronic theory

- Thermal scattering amplitudes → temperature evolution of the dynamically generated states
- Thermal spectral functions → temperature evolution of the ground states



The spectral function tells the probability that a particle with a certain momentum has a specific energy

It encodes information about the properties of the particle, i.e., its mass and decay width (or lifetime)

Thermal effective theory for open heavy-flavor mesons

Imaginary time formalism

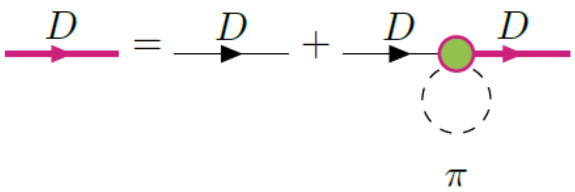
- Sum over Matsubara frequencies $\quad q^0 \to \mathrm{i}\,\omega_n = \mathrm{i}\,\dfrac{2n\pi}{\beta}$ (bosons), $\quad \displaystyle\int \frac{d^4q}{(2\pi)^4} \to \frac{1}{\beta}\sum_n \int \frac{d^3q}{(2\pi)^3}$

  ↳ Thermal production and absorption processes by weighted combinations of Bose-Einstein distribution functions $\quad f(\omega, T) = \frac{1}{e^{\omega/T}-1}$

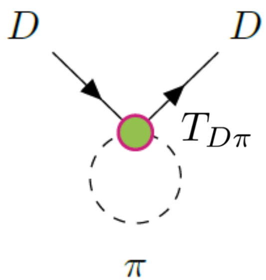
Dressing of the mesons in the loop functions with their spectral functions

- Self-energy corrections to the heavy meson propagator
- Pion mass slightly varies below T_c → Approximation: only the heavy meson is dressed

Dressed propagator



D-meson self-energy



Thermal effective theory for open heavy-flavor mesons: self-consistency

Loop function

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

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

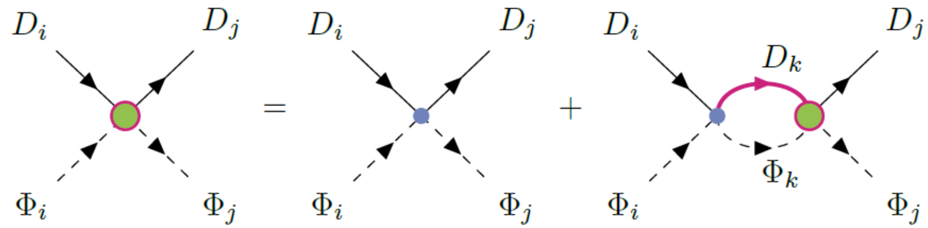
Bose-Einstein distribution function $f(\omega,T)=\frac{1}{e^{\omega/T}-1}$

Regularized with a cut-off Λ

Unitarized amplitude

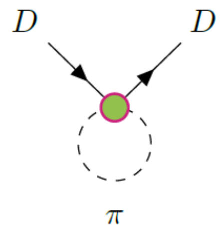
$$T_{ij}=V_{ij}+V_{ik}G_kT_{kj}$$

Bethe-Salpeter equation



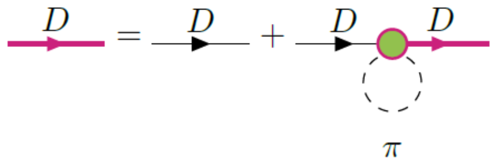
Self-energy

$$\Pi_D(\omega,\vec{q};T)=\frac{1}{\pi}\int\frac{d^3q'}{(2\pi)^3}\int dE\,\frac{\omega-\omega_\Phi}{\omega_\Phi}\,\frac{f(E,T)-f(\omega_\Phi,T)}{\omega^2-(\omega_\Phi-E)^2+\mathrm{sgn}(\omega)\,\mathrm{i}\,\varepsilon}\,\mathrm{Im}\,T_{D\Phi}(E,\vec{p};T)$$



Spectral function

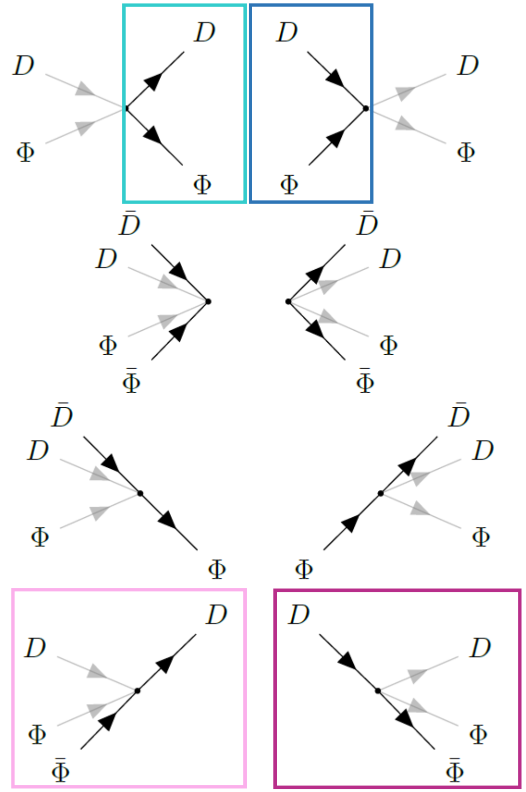
$$S_D(\omega,\vec{q};T)=-\frac{1}{\pi}\mathrm{Im}\,\mathcal{D}_D(\omega,\vec{q};T)=-\frac{1}{\pi}\,\mathrm{Im}\left(\frac{1}{\omega^2-\vec{q}^{\,2}-m_D^2-\Pi_D(\omega,\vec{q};T)}\right)$$



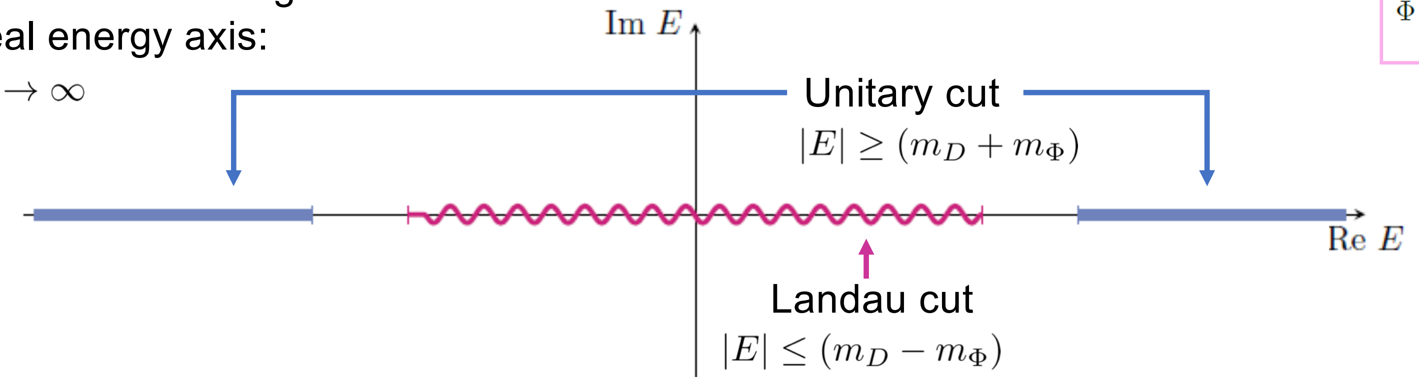
Set of coupled equations → solved self-consistently

Physical interpretation and cuts of the thermal propagator

$$\mathrm{Im}\, G_{D\Phi}(E,\vec{p};T) = -\pi \int \frac{d^3q}{(2\pi)^3}\frac{1}{4\omega_D\omega_\Phi}$$
$$\times \Big\{ [(1+f_D)(1+f_\Phi) - f_D f_\Phi]\,\delta(E-\omega_D-\omega_\Phi)$$
$$+ [f_{\bar{D}} f_{\bar{\Phi}} - (1+f_{\bar{D}})(1+f_{\bar{\Phi}})]\,\delta(E+\omega_D+\omega_\Phi)$$
$$+ [f_{\bar{D}}(1+f_\Phi) - (1+f_{\bar{D}})f_\Phi]\,\delta(E+\omega_D-\omega_\Phi)$$
$$+ [(1+f_D)f_{\bar{\Phi}} - f_D(1+f_{\bar{\Phi}})]\,\delta(E-\omega_D+\omega_\Phi)\Big\}$$



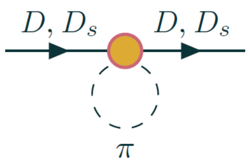
Branch cuts along the real energy axis:
$\Lambda \to \infty$



Results: Thermal loop functions

[GM, A. Ramos, L. Tolos, J.M. Torres-Rincon, *Phys. Lett. B 806* (2020) 135464]
[GM, A. Ramos, L. Tolos, J.M. Torres-Rincon, *Phys. Rev. D 102* (2020) 9, 096020]

Pionic bath

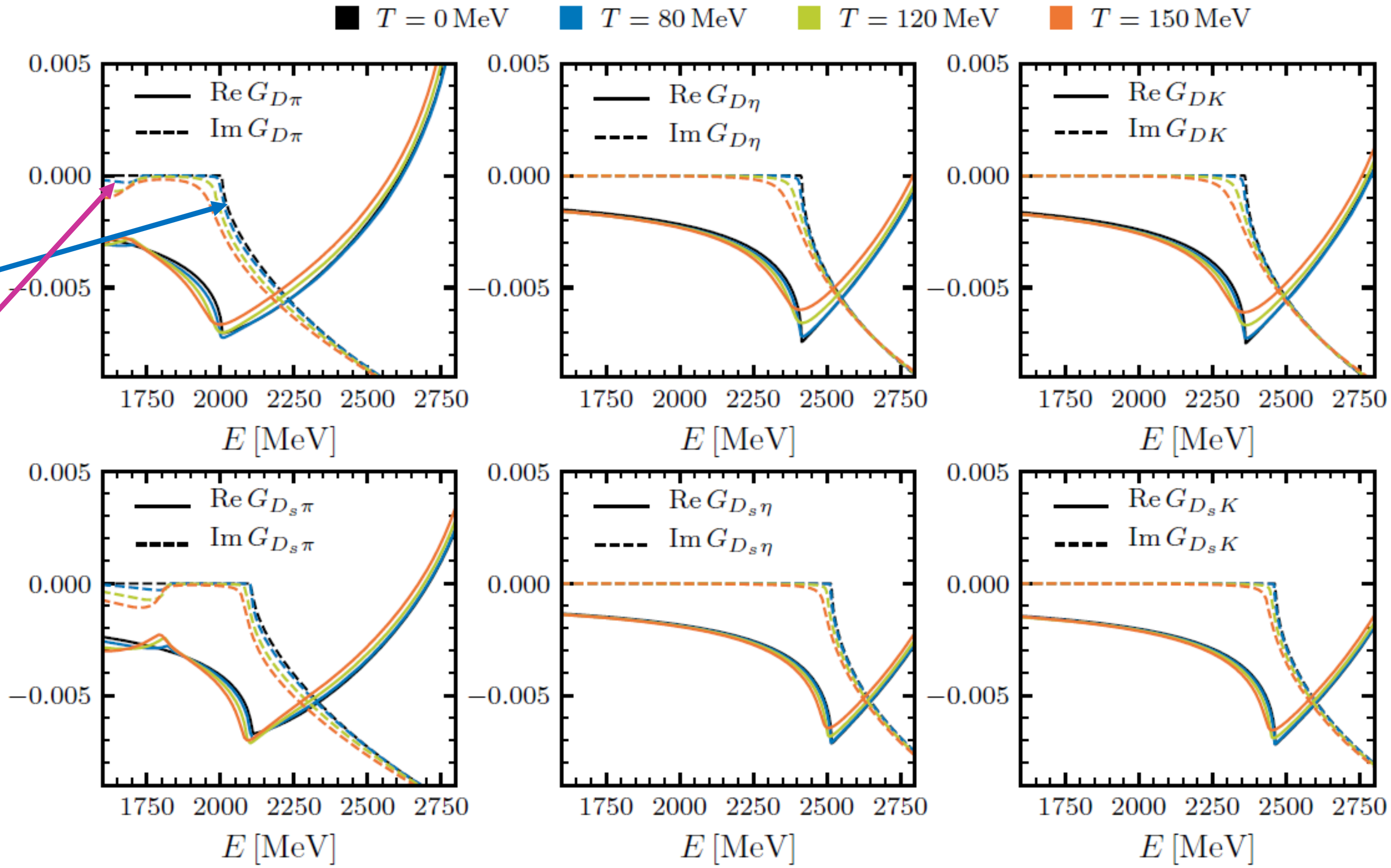


- Unitary cut

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

- Landau cut

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



Results: Spectral functions and scattering amplitudes

[GM, A. Ramos, L. Tolos, J.M. Torres-Rincon, *Phys. Lett. B 806* (2020) 135464]
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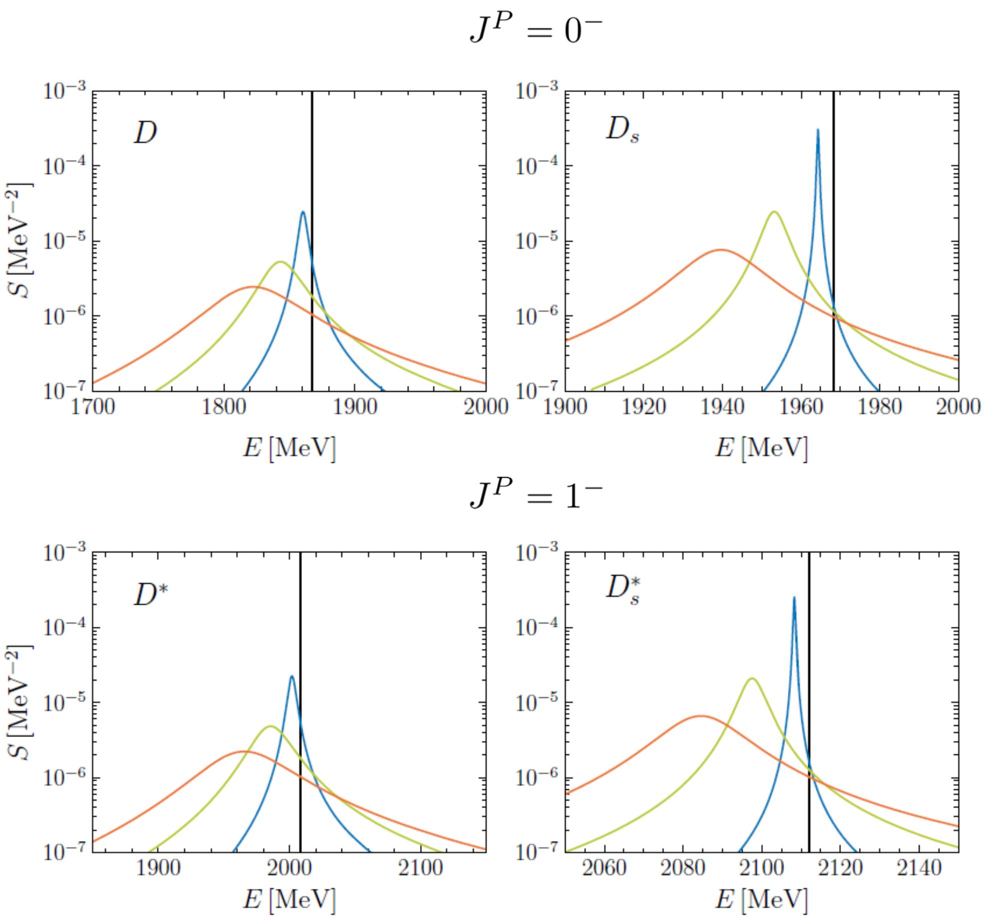
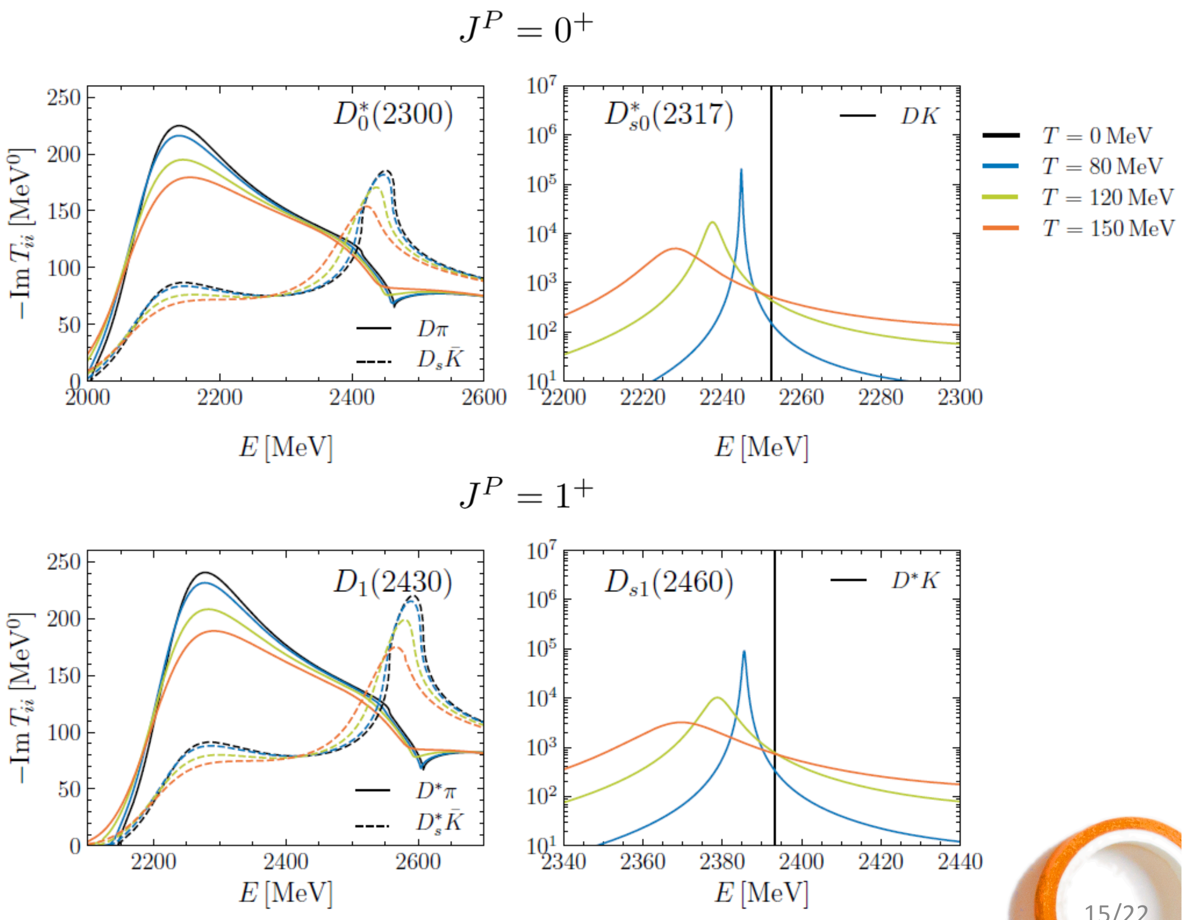
Ground states



Dynamically generated states



Results: Thermal evolution of masses and widths

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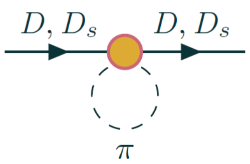
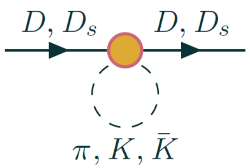
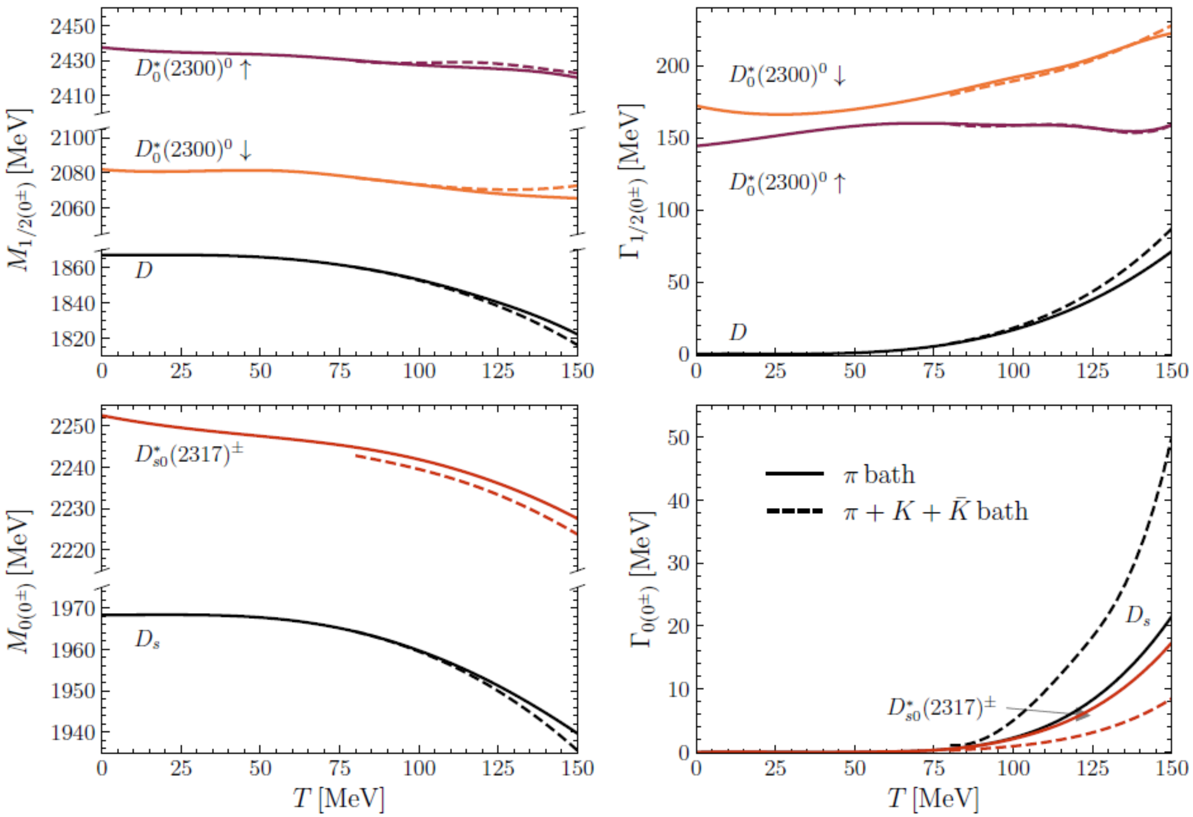
- Solid lines: pionic bath



- Dashed lines: bath of pions, kaons and antikaons



$J^P = 0^\pm$



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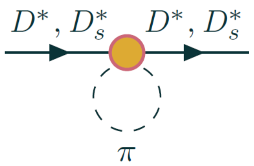
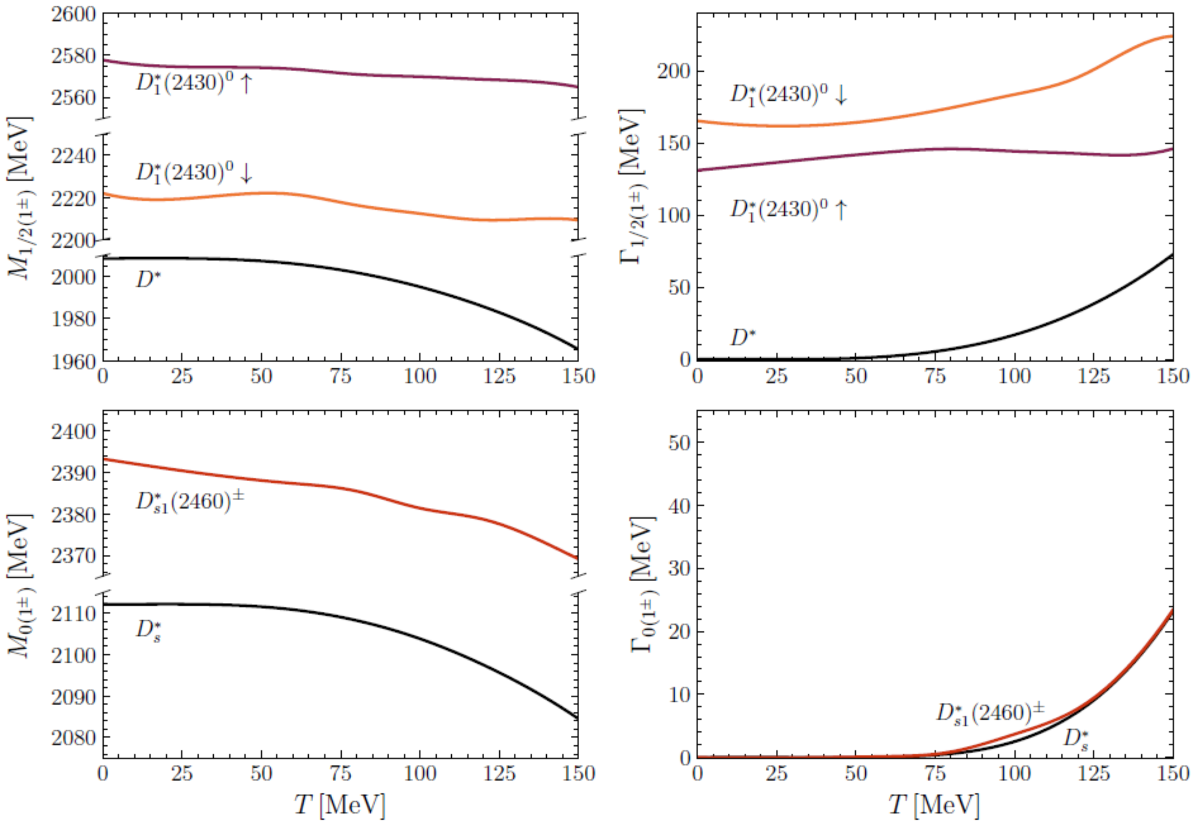
- Pionic bath

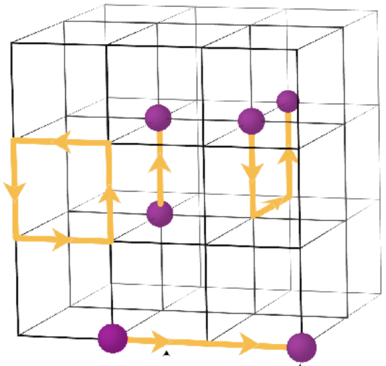


$J^P = 1^\pm$



3 Open-charm Euclidean correlators

- Euclidean correlators are directly accessible in lattice QCD simulations



- Meson **spectral functions** are related to meson temporal Euclidean correlators

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

Spectral function $\rho(\omega;T)$

$$K(\tau,\omega;T) = \frac{\cosh\left[\omega\left(\tau - \frac{1}{2T}\right)\right]}{\sinh\left(\frac{\omega}{2T}\right)}$$

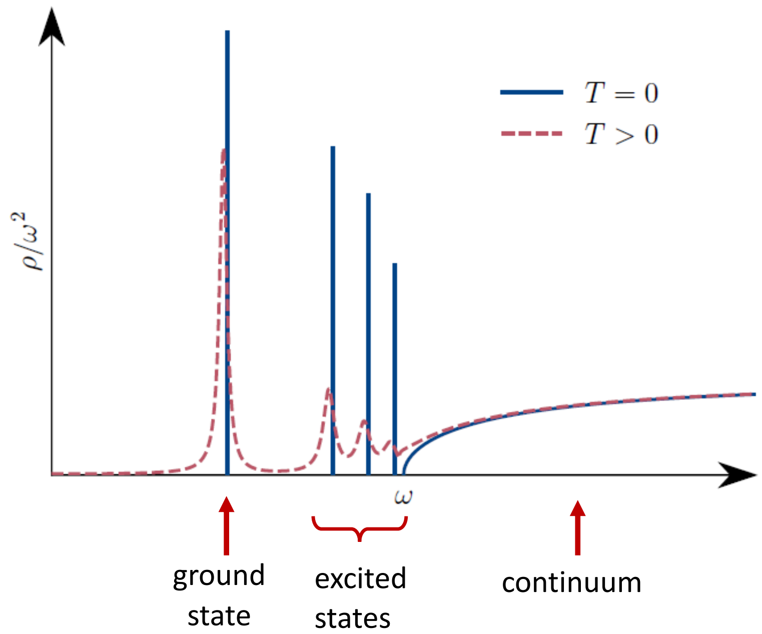
Euclidean correlator → Spectral function (ill-posed)

- Bayesian methods (MEM)
- Fitting *Ansätze*

Spectral function → Euclidean correlator

- Reconstructed correlator $G_E^r(\tau;T,T_r) = \int_0^\infty d\omega K(\tau,\omega;T)\rho(\omega;T_r)$ → $\dfrac{G_E(\tau;T)}{G_E^r(\tau;T,T_r)}$

Euclidean correlators from the effective field theory



We can obtain the ground-state spectral function at unphysically large meson masses (used in the lattice)

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

- Ground-state contribution $\rho_{\rm gs}(\omega; T) \propto S_D(\omega; T)$
- Continuum of scattering states

[Karsch, Mustafa and Thoma (2001)]
[Meyer, Ph.D. tesis (2016)]

$$\rho_{\rm cont}(\omega; T) = \frac{N_c}{32\pi} \sqrt{\left(\frac{m_1^2 - m_2^2}{\omega^2} + 1\right)^2 - \frac{4m_2^2}{\omega^2}}\ \omega^2$$
$$\times \left[(a_M - b_M) + 2b_M \frac{m_1^2 + m_2^2}{\omega^2} - 4c_M \frac{m_1 m_2}{\omega^2} - (a_M + b_M)\left(\frac{m_1^2 - m_2^2}{\omega^2}\right)^2\right]$$
$$\times \left[n(-\omega_0, T) - n(\omega - \omega_0, T)\right]\ \theta\left(\omega - (m_1 + m_2)\right)$$

Full spectral function: $\rho(\omega; T) = \rho_{\rm gs}(\omega; T) + a\, \rho_{\rm cont}(\omega; T)$

with a weight parameter $a = \{0, 1, 10\}$

Results: Spectral functions at unphysical meson masses

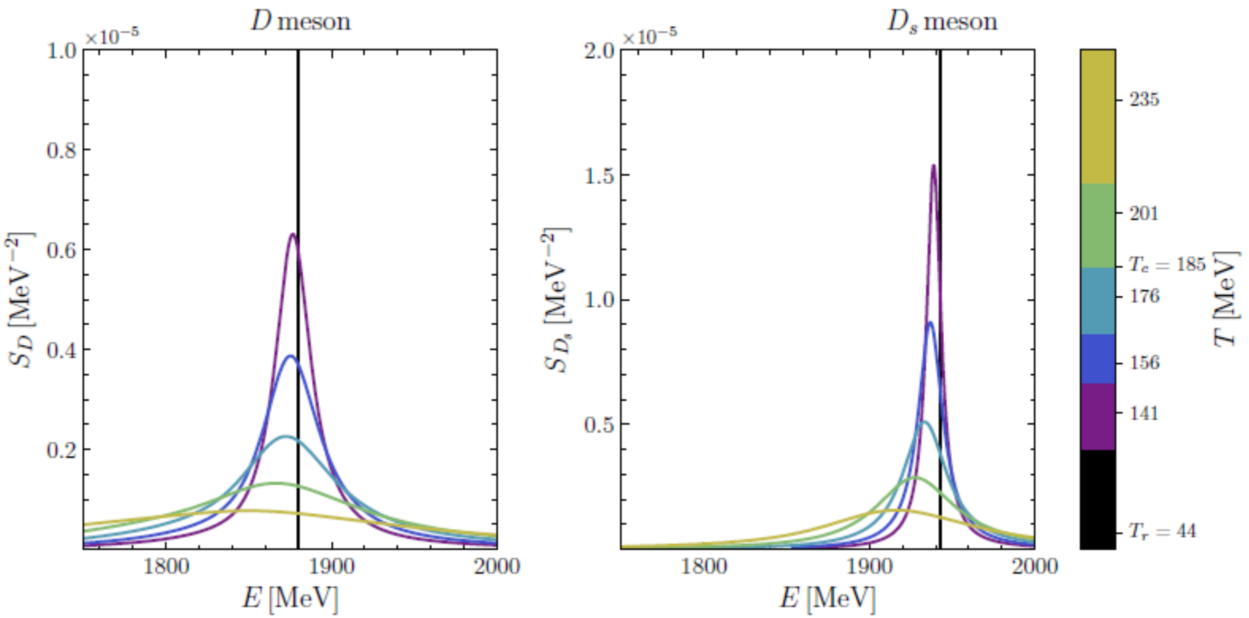
[GM, O. Kaczmarek, L. Tolos, A. Ramos, Eur.Phys.J.A 56 (2020) 11]

Lattice setup in *Kelly et al.* :

	m_π (MeV)	m_K (MeV)	m_η (MeV)	m_D (MeV)	m_{D_s} (MeV)
Lattice	384	546	589	1880	1943
Physical	138	496	548	1867	1968

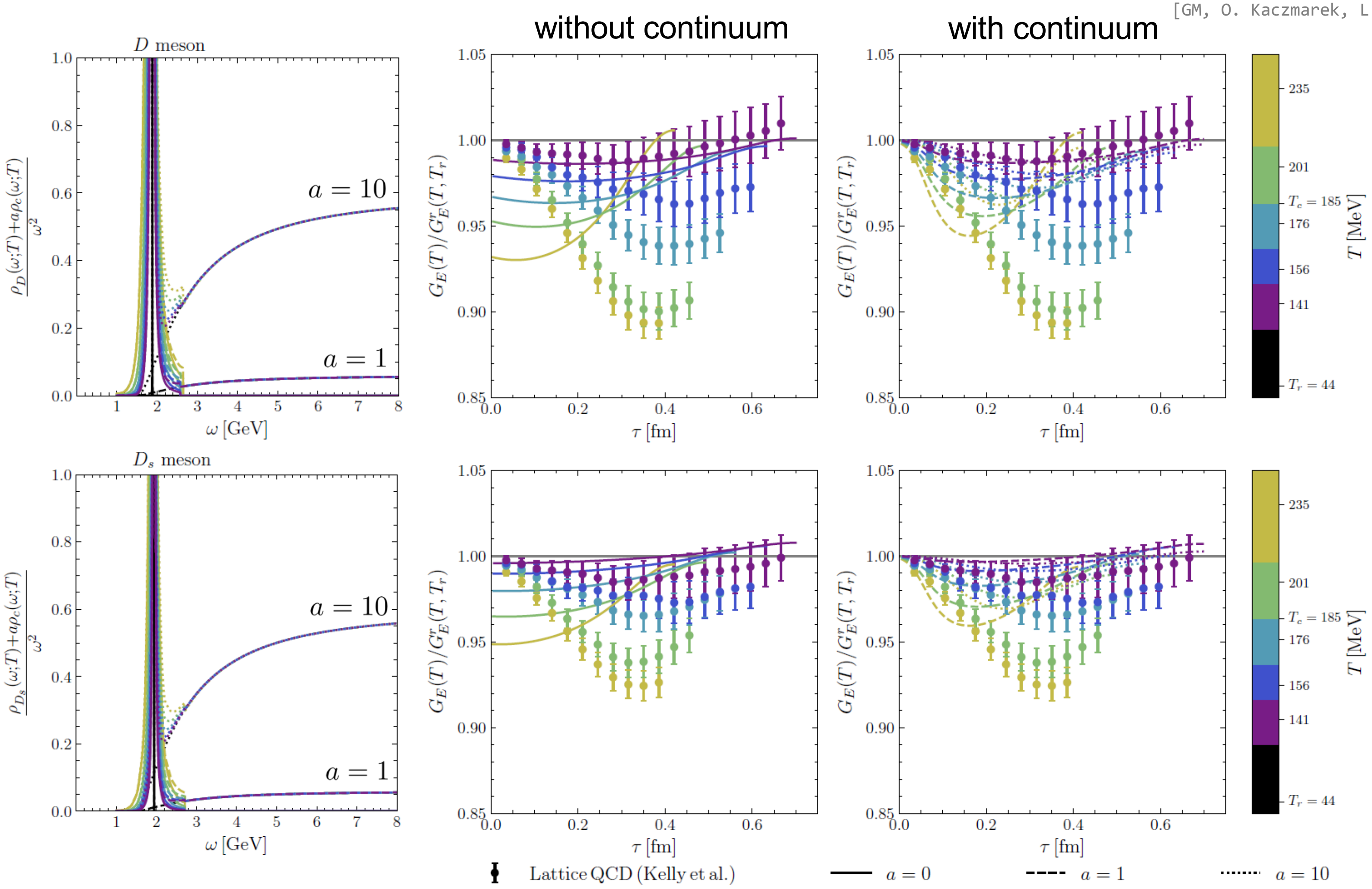
[Kelly, Rothkopf, Skullerud (2018)]

Ground-state spectral functions using unphysical meson masses:



Results: Euclidean correlators and comparison with lattice QCD

[GM, O. Kaczmarek, L. Tolos, A. Ramos, Eur.Phys.J.A 56 (2020) 11]



- The continuum improves the behavior at small Euclidean times
- **Agreement at the lowest temperature** $(0.76\,T_c)$
- Deviation at larger T : excited states? Kaonic bath?
- Above T_c the EFT breaks down

4 Conclusions

- **Effective field theories** allow to describe the dynamics of heavy mesons in the non-perturbative regime.

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

  Thermal effects: heavy-meson **masses decrease moderately** while the **decay widths increase substantially** with increasing temperatures. **Pions** provide the main contribution (most abundant mesons in the bath).

- **Euclidean correlators** computed from spectral functions at unphysical meson masses are in agreement with lattice QCD results below the QCD transition temperature.

  Discrepancies close to T_c possibly indicate the missing contribution of higher-excited states and the kaons of the bath.

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