Heavy-flavor mesons in a hot mesonic bath

Glòria Montaña Faiget

In collaboration with:

Àngels Ramos, Laura Tolós, Juan Torres-Rincón

Based on:

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Eur.Phys.J.A 56 (2020) 11, 294 • e-Print: 2007.15690
Phys.Rev.C 105 (2022) 2, 025203 • e-Print: 2106.01156

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UNIVERSITAT DE BARCELONA

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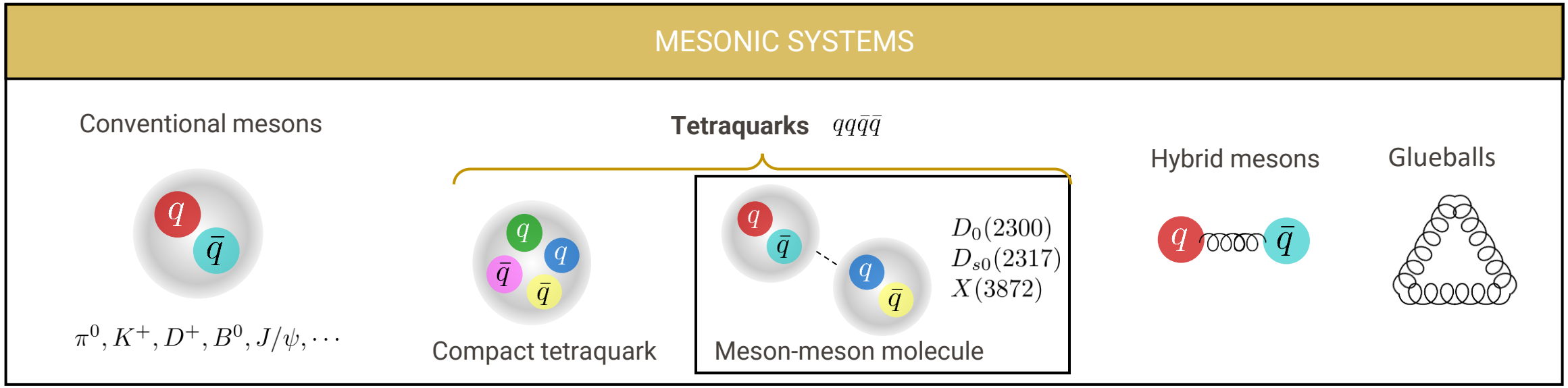
Introduction



We study **hadronic molecules** using **effective field theories** consistent with the symmetries of QCD:

- Chiral symmetry in the limit $m_u, m_d, m_s \to 0$ → **Chiral perturbation theory (χPT)**
- Heavy-quark symmetries in the limit $m_c, m_b \to \infty$
  - Heavy-quark flavor symmetry (HQFS): $\{D, \bar{B}\}$
  - Heavy-quark spin symmetry (HQSS): $\{D, D^*\}, \{\bar{B}, \bar{B}^*\}$

} Heavy-quark spin-flavor symmetry (HQSFS) $\{D, D^*, \bar{B}, \bar{B}^*\}$ ↓ **Heavy-meson effective theory (HMET)**

Interaction between open heavy-flavor mesons and Goldstone bosons

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

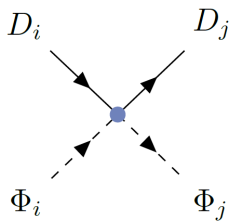
$$\mathcal{L} = \mathcal{L}_{\rm LO} + \mathcal{L}_{\rm NLO}$$

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

$$\nabla_\mu D^{(*)} = \partial_\mu D^{(*)} - D^{(*)}\Gamma^\mu$$
$$\Gamma_\mu = \tfrac{1}{2}(u^\dagger \partial_\mu u + u \partial_\mu u^\dagger)$$
$$u_\mu = \mathrm{i}\,(u^\dagger \partial_\mu u - u \partial_\mu u^\dagger)$$
$$u = \exp\left(\frac{\Phi}{\sqrt{2} f_\pi}\right)$$

$$D = \left(D^0 \; D^+ \; D_s^+\right)$$
$$D^*_\mu = \left(D^{*0} \; D^{*+} \; D_s^{*+}\right)_\mu$$

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



$$\begin{aligned}\mathcal{L}_{\rm NLO} = \mathcal{L}_{\rm NLO}^{\chi\rm PT} &- h_0 \langle D D^\dagger\rangle\langle \chi_+\rangle + h_1 \langle D \chi_+ D^\dagger\rangle + h_2 \langle D D^\dagger\rangle \langle u^\mu u_\mu\rangle + h_3 \langle D u^\mu u_\mu D^\dagger\rangle \\ &+ h_4 \langle \nabla_\mu D \nabla_\nu D^\dagger\rangle\langle u^\mu u^\nu\rangle + h_5 \langle \nabla_\mu D \{u^\mu, u^\nu\} \nabla_\nu D^\dagger\rangle \\ &+ \tilde{h}_0 \langle D^{*\mu} D^{*\dagger}_\mu\rangle\langle \chi_+\rangle - \tilde{h}_1 \langle D^{*\mu} \chi_+ D^{*\dagger}_\mu\rangle - \tilde{h}_2 \langle D^{*\mu} D^{*\dagger}_\mu\rangle\langle u^\nu u_\nu\rangle - \tilde{h}_3 \langle D^{*\mu} u^\nu u_\nu D^{*\dagger}_\mu\rangle \\ &- \tilde{h}_4 \langle \nabla_\mu D^{*\alpha} \nabla_\nu D^{*\dagger}_\alpha\rangle\langle u^\mu u^\nu\rangle - \tilde{h}_5 \langle \nabla_\mu D^{*\alpha} \{u^\mu, u^\nu\} \nabla_\nu D^{*\dagger}_\alpha\rangle\end{aligned}$$

$$\chi = \mathrm{diag}(m_\pi^2, m_\pi^2, 2m_K^2 - m_\pi^2)$$
$$\chi_+ = u^\dagger \chi u^\dagger + u \chi u$$

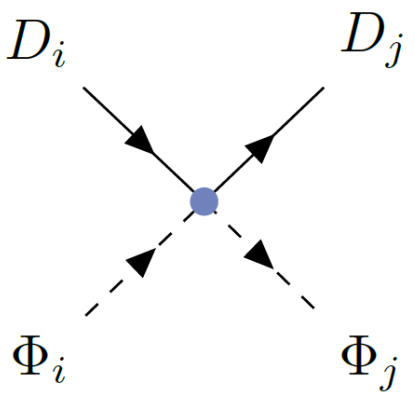
$$\boxed{\text{LECs}: \; h_{0,\ldots,5},\; \tilde{h}_{0,\ldots,5}}$$

[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)]

Interaction between open heavy-flavor mesons and Goldstone bosons

Tree-level scattering amplitude:

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



C^{ij}_k isospin coefficients

LECs fitted to lattice QCD data [Guo, Liu, Meißner, Oller and Rusetsky (2019)]

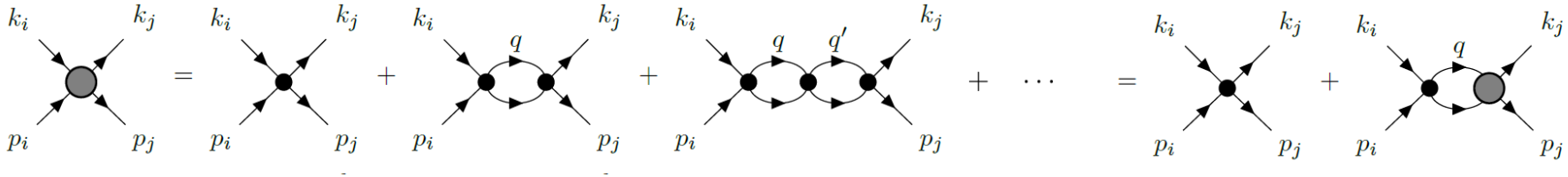
Preliminary results for $D\pi$ and DK from femtoscopy from ALICE $pp,\ \sqrt{s} = 13\,\mathrm{TeV}$ at high multiplicity (2022)

At LO in HQSFS: $h_{0,\ldots,5} = \tilde{h}_{0,\ldots,5}\ ,\quad \frac{h^B_{0,\ldots,3}}{\hat{M}_B} = \frac{h^D_{0,\ldots,3}}{\hat{M}_D}\ ,\quad h^B_{4,5}\hat{M}_B = h^D_{4,5}\hat{M}_D$

Unitarization. Dynamically generated states

On-shell Bethe-Salpeter equation in coupled channels

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



on-shell factorization

$$T = \frac{V}{1 - VG}$$

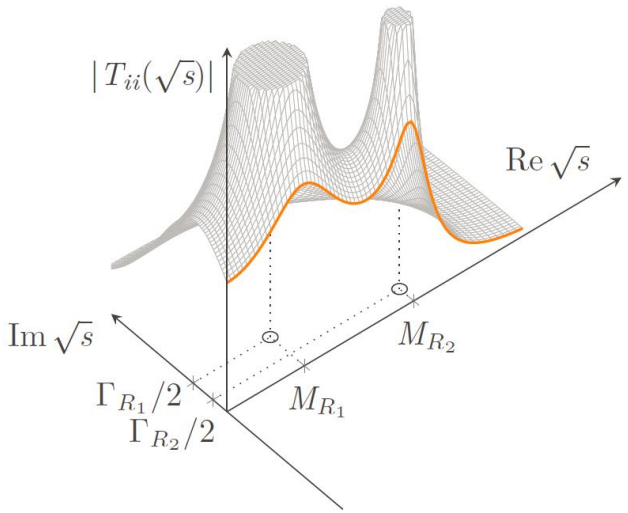
$V_{ij}(s)$: interaction potential

$G_k(s)$: two-meson propagator

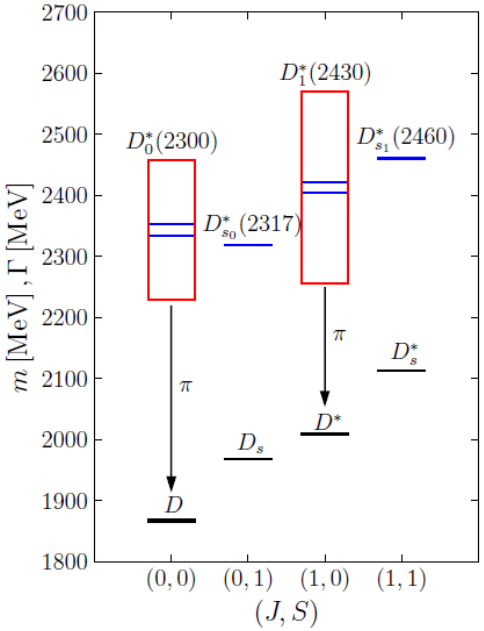
$$G_k(s) = \mathrm{i} \int \frac{d^4 q}{(2\pi)^4} \frac{1}{q^2 - m_D^2 + \mathrm{i}\,\varepsilon} \frac{1}{(p-q)^2 - m_\Phi^2 + \mathrm{i}\,\varepsilon}$$

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

- Leads to the dynamical generation of states: poles in the complex-energy plane
- Classification: **bound states** (RS-I), **resonances** (RS-II), and **virtual states** (RS-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 channels g_i
  - 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

$D_1(2430)^0$: $M = 2412 \pm 9$ MeV
$I(J^P) = \frac{1}{2}(1^+)$ $\Gamma = 314 \pm 29$ MeV

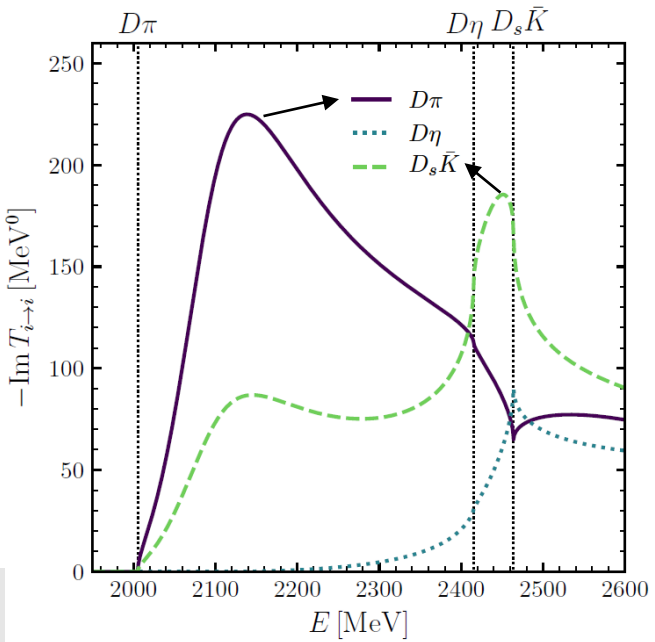
$D_{s1}(2460)^\pm$: $M = 2459.6 \pm 0.6$ MeV
$I(J^P) = 0(1^+)$ $\Gamma < 3.5$ MeV

[PDG (2020)]

(S, I)	Channels ($J^P = 0^+$)	Threshold (MeV)	Channels ($J^P = 1^+$)	Threshold (MeV)
$(-1, 0)$	$D\bar{K}$	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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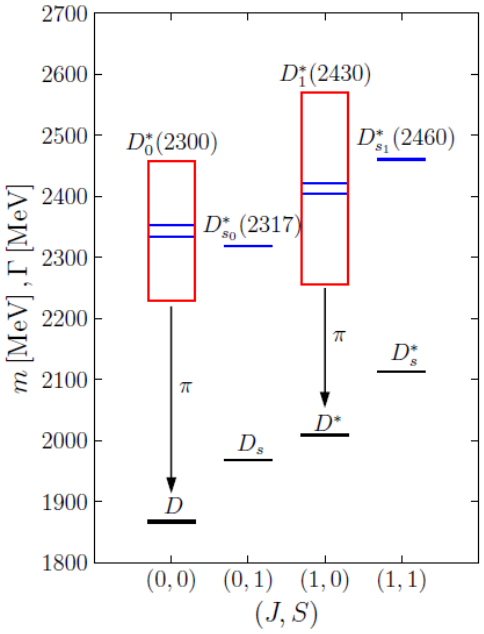

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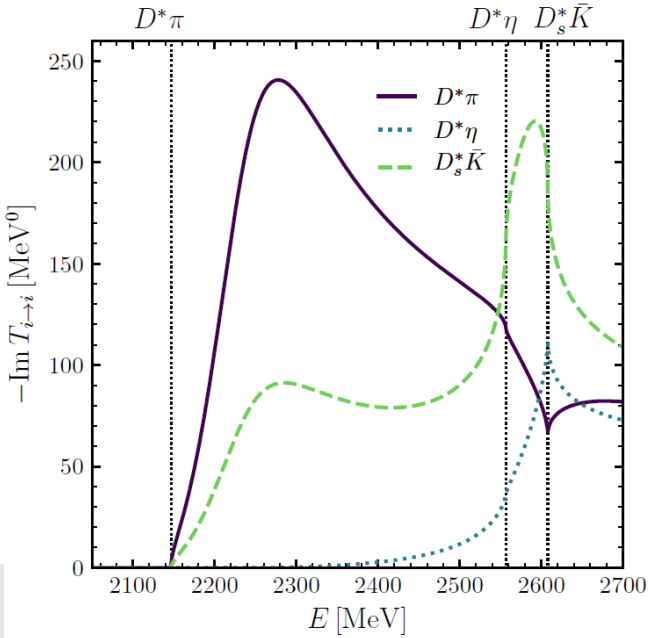
Two-pole structure	$D_1(2430)$	$(0, \frac{1}{2})$	$(-,+,+)$	2222.3	84.7	$\lvert g_{D^*\pi} \rvert = 9.5$	$\chi_{D^*\pi} = 0.45$
						$\lvert g_{D^*\eta} \rvert = 0.4$	$\chi_{D^*\eta} = 0.00$
						$\lvert g_{D_s^*\bar{K}} \rvert = 5.7$	$\chi_{D_s^*\bar{K}} = 0.02$
			$(-,-,+)$	2654.6	117.3	$\lvert g_{D^*\pi} \rvert = 6.5$	$\chi_{D^*\pi} = 0.17$
						$\lvert g_{D^*\eta} \rvert = 10.0$	$\chi_{D^*\eta} = 0.54$
						$\lvert g_{D_s^*\bar{K}} \rvert = 18.5$	$\chi_{D_s^*\bar{K}} = 0.90$
Bound state	$D_{s1}(2460)$	$(1, 0)$	$(+,+)$	2393.3	0.0	$\lvert g_{D^*K} \rvert = 14.2$	$\chi_{D^*K} = 0.45$
						$\lvert g_{D_s^*\eta} \rvert = 9.7$	$\chi_{D_s^*\eta} = 0.08$



QCD phase diagram. Finite temperature and vanishing baryon density

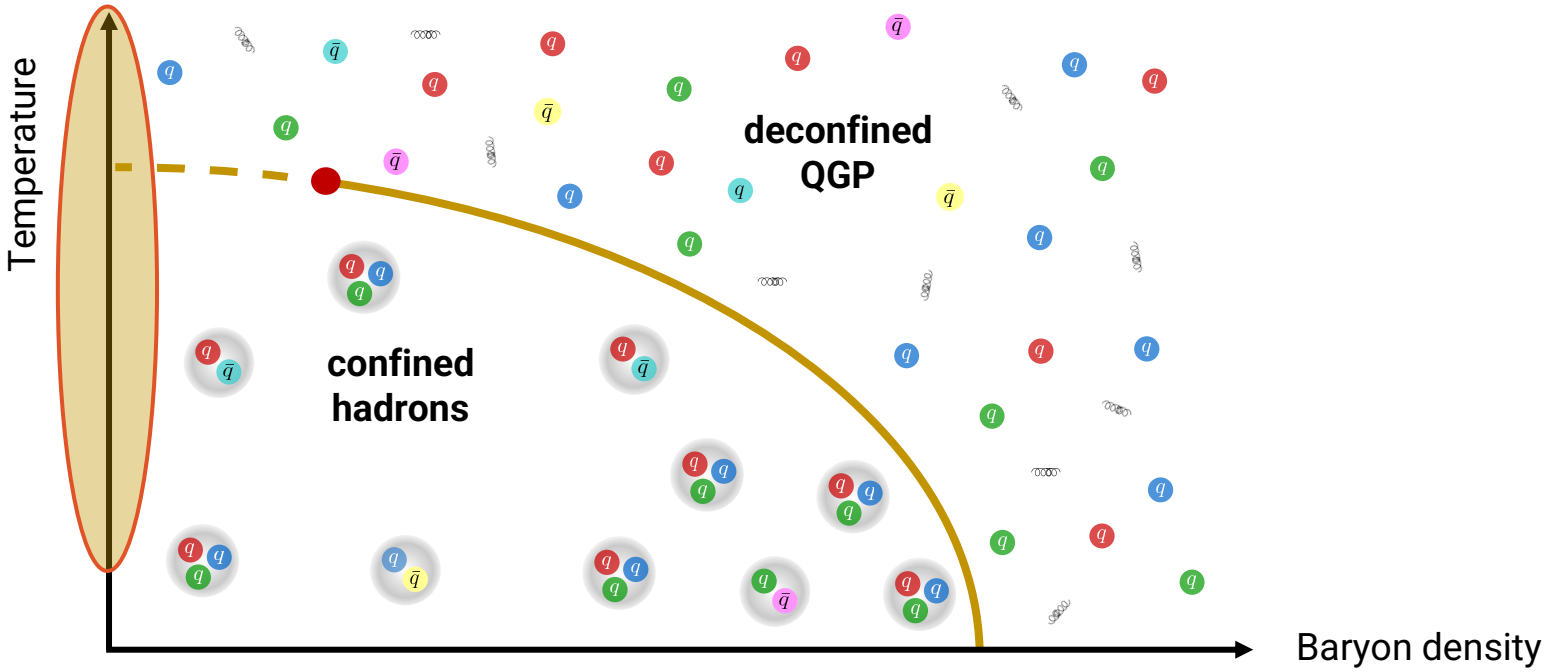
High-energy HICs

- 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

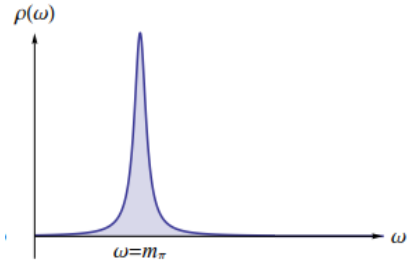
- **Heavy quarks** are created in the initial stage of the collision
- Due to its large mass and relaxation time, heavy-flavor mesons are a **powerful probe of the QGP**
- The properties of heavy mesons, i.e., masses and decay widths, are modified in hot matter
- Understanding phenomena such as quarkonia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

Mesonic bath in equilibrium at finite temperature

- Mesonic matter at **temperature** $0 < T < T_c$ and **vanishing baryon density** (matter 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 theory for open heavy-flavor mesons

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



Thermal effective theory for open heavy-flavor mesons

Imaginary time formalism

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

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

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

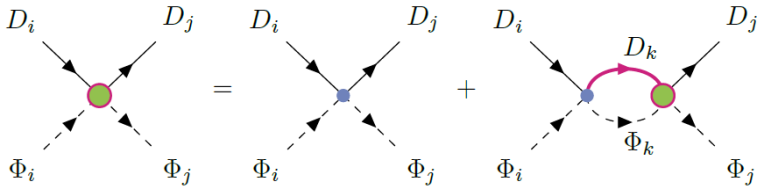
Loop function

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

Regularized with a cut-off

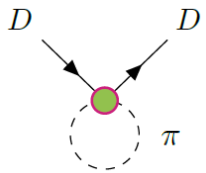
Unitarized amplitude

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



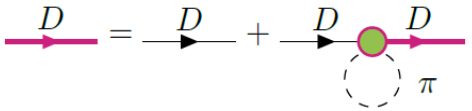
Self-energy

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



Spectral function

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

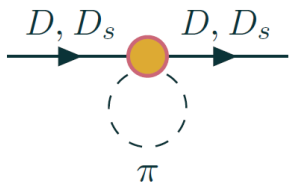


Set of coupled equations ⟶ solved self-consistently

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

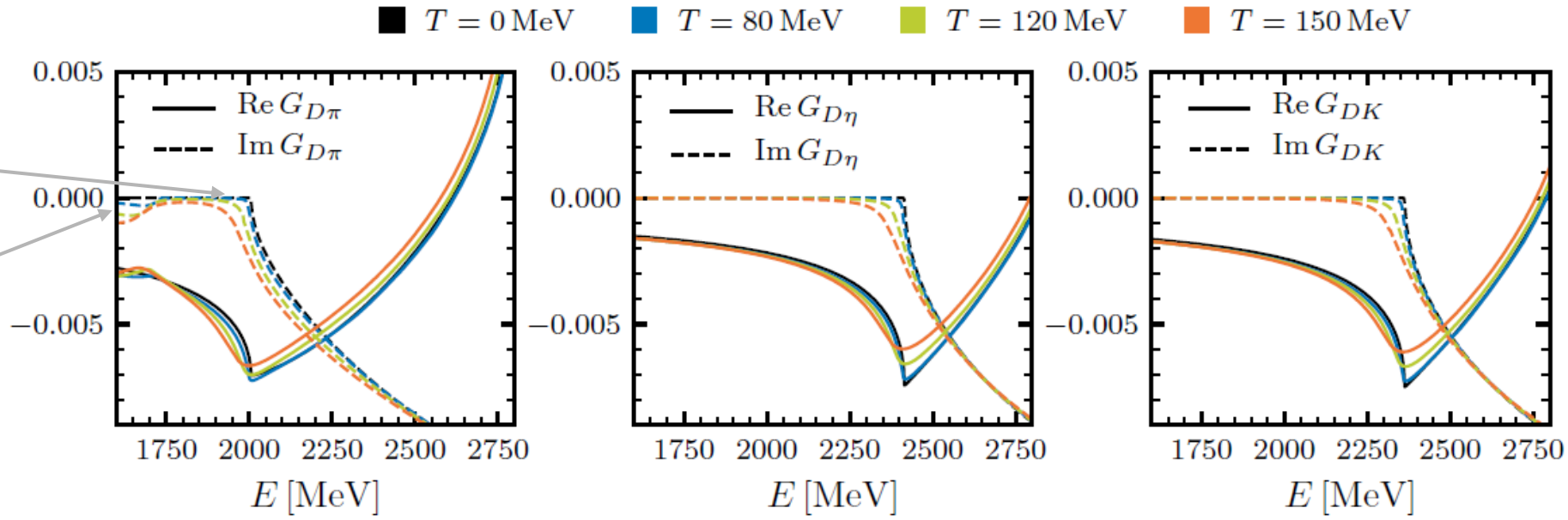


- Unitary cut

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

- Landau cut

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

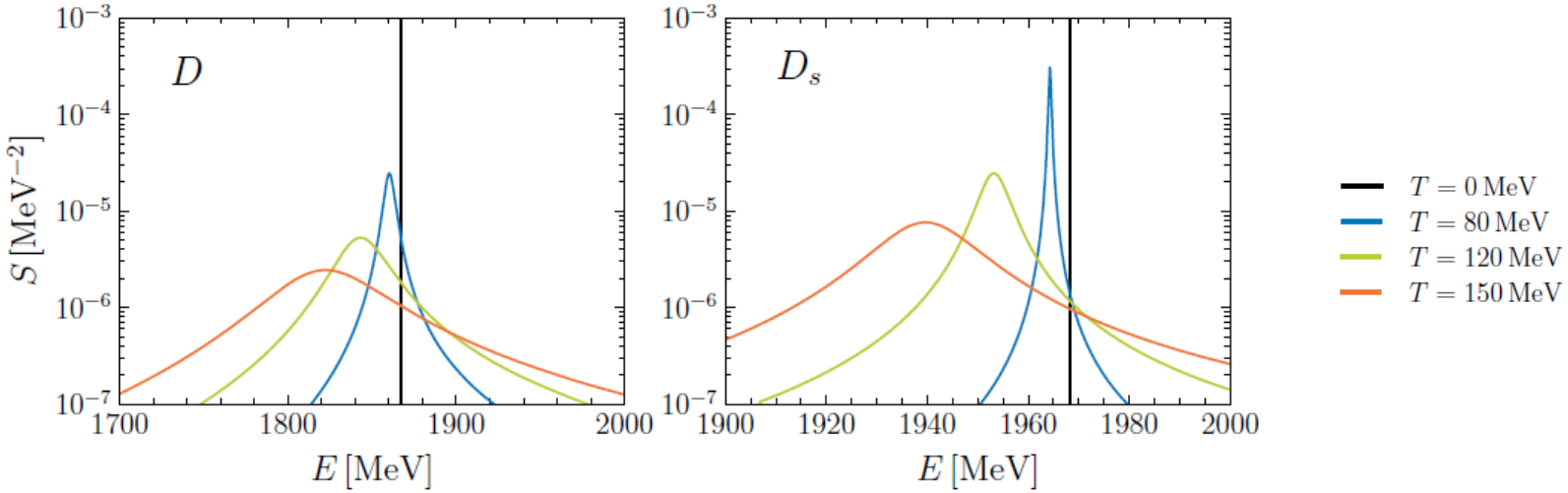


Results: spectral functions and scattering amplitudes

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

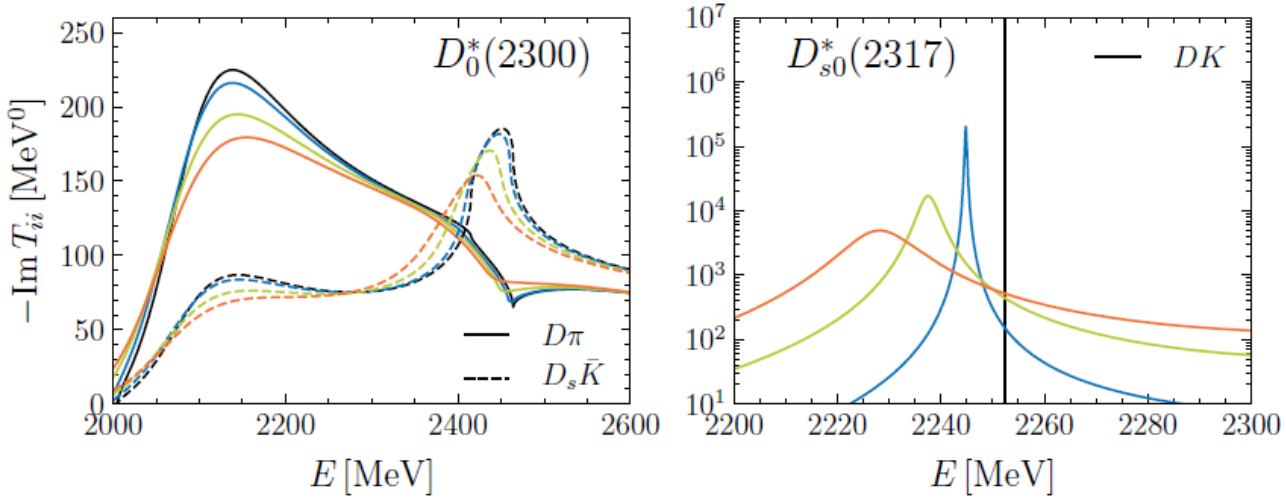
Ground states

$J^P = 0^-$



Dynamically generated states

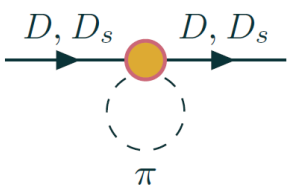
$J^P = 0^+$



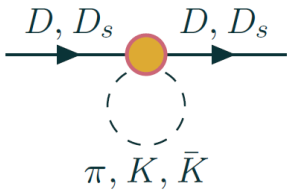
Results: thermal evolution of masses and widths

[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]

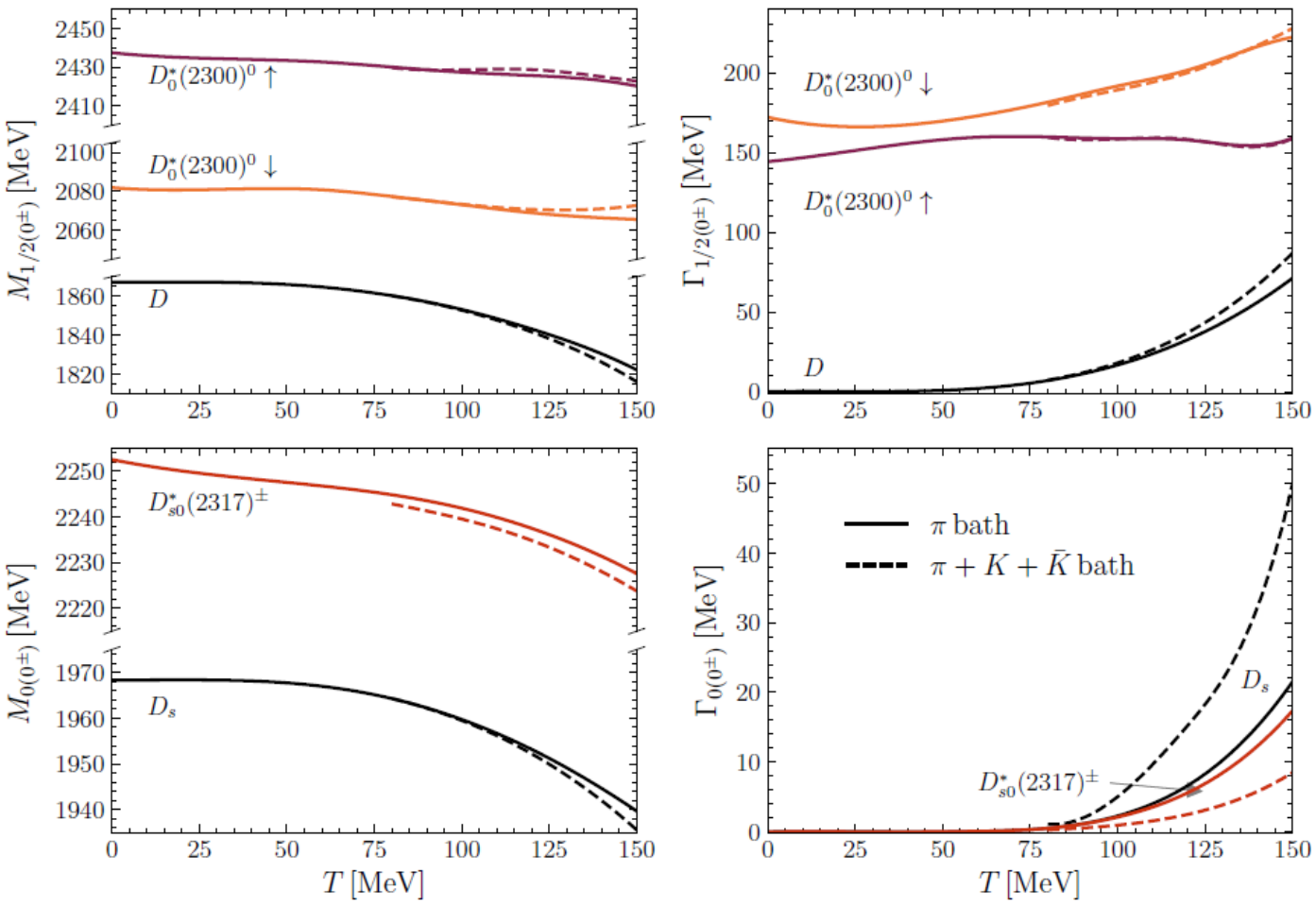
- Solid lines: pionic bath



- Dashed lines: bath of pions, kaons and antikaons



$J^P = 0^\pm$



We have also investigated the thermal modification of D^*, $\bar{B}$, $\bar{B}^*$ mesons

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)

Spectral function ⟶ Euclidean correlator

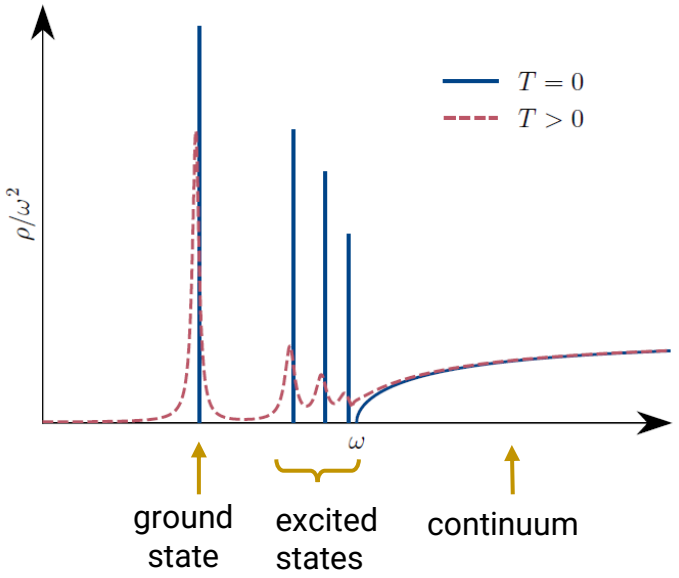
- We can obtain the ground-state spectral function (at unphysical meson masses)
  - Ground-state contribution

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

  - Continuum of scattering states [Karsch, Mustafa and Thoma (2001)] [Meyer, Ph.D. tesis (2016)]

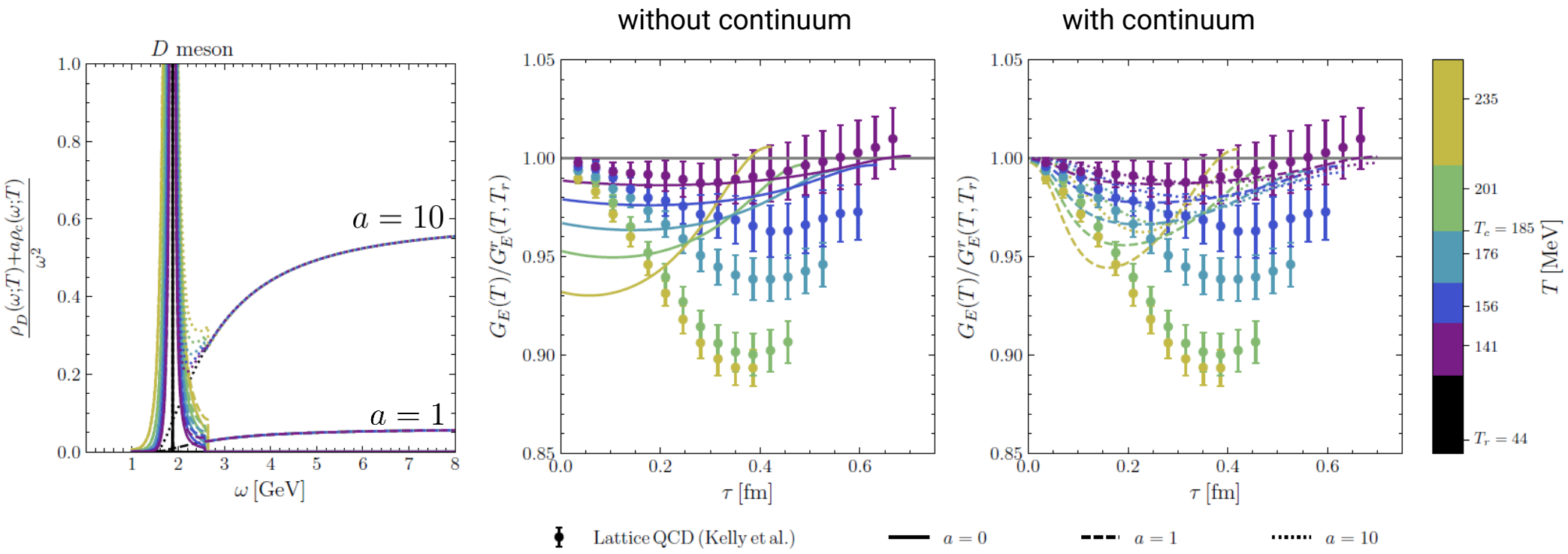
Full spectral function: $\rho(\omega;T) = \rho_{\rm gs}(\omega;T) + a\,\rho_{\rm cont}(\omega;T)$

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



Euclidean correlators: results and comparison with LQCD

[GM, O. Kaczmarek, L. Tolos, A. Ramos, Eur.Phys.J.A 56 (2020) 11]
[Kelly, Rothkopf, Skullerud (2018)]



$$T = \frac{1}{aN_\tau}$$

$$G_E^r(\tau;T,T_r) = \int_0^\infty d\omega K(\tau,\omega;T)\rho(\omega;T_r)$$

$$\frac{G_E(\tau;T)}{G_E^r(\tau;T,T_r)}$$

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

Transport coefficients of an off-shell heavy meson

Fokker-Planck equation for the Green's function

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

with $\Delta^{ij} = \delta^{ij} - k^i k^j/\vec{k}^{\,2}$

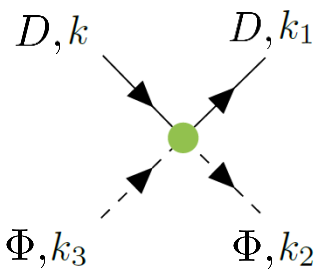
Off-shell transport coefficients

- Drag force coefficient
  - ↳ thermal average momentum transfer
- Momentum diffusion coefficients
  - ↳ average square of the momentum transfer

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

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

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



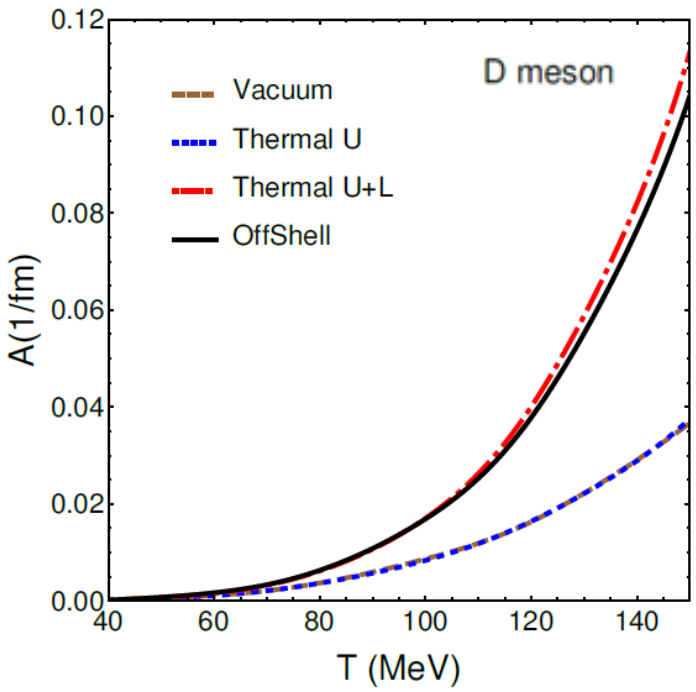
- Thermal effects in $|T|^2$ and E_k
- Landau cut contribution
- Off-shell effects

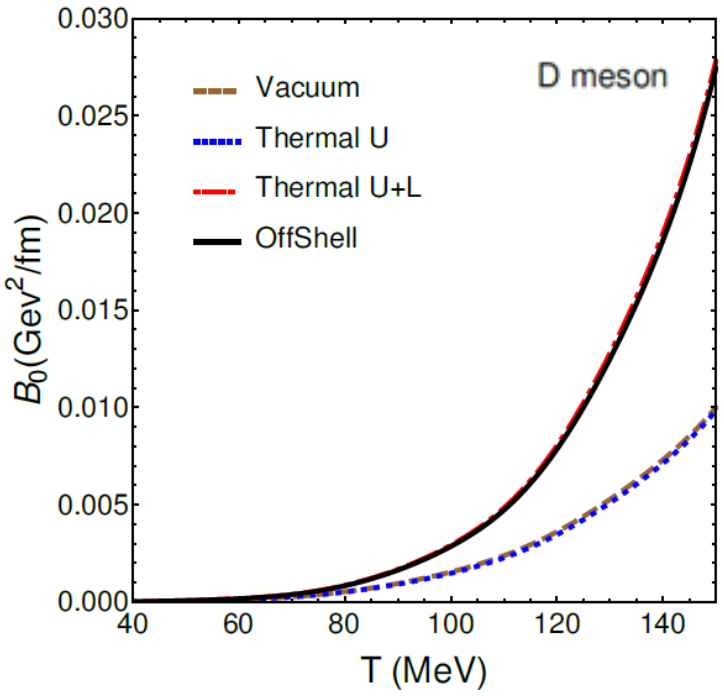
with

$$\left\langle \mathcal{F}(\vec{k},\vec{k}_1)\right\rangle = \frac{1}{2k^0}\sum_{\lambda,\lambda'=\pm}\lambda\lambda'\int_{-\infty}^{\infty}dk_1^0\int\prod_{i=1}^{3}\frac{d^3k_i}{(2\pi)^3}\frac{1}{2E_2 2E_3}\boxed{S_D(k_1^0,\vec{k}_1)}(2\pi)^4\delta^{(3)}(\vec{k}+\vec{k}_3-\vec{k}_1-\vec{k}_2)$$
$$\times\,\delta(k^0+\lambda' E_3-\lambda E_2-k_1^0)\boxed{\left|T(k^0+\lambda' E_3,\vec{k}+\vec{k}_3)\right|^2}f^{(0)}(\lambda' E_3)\tilde{f}^{(0)}(\lambda E_2)\tilde{f}^{(0)}(k_1^0)\;\;\mathcal{F}(\vec{k},\vec{k}_1)$$

Results: drag force and momentum diffusion coefficient

[J.M. Torres-Rincon, GM, A. Ramos, L. Tolos, Phys.Rev.C 105 (2022)]





Drag force A

Momentum diffusion
(longitudinal B_0 and transverse B_1)

In the static limit $\vec{k} \to 0\ , \quad B_0 = B_1$

- Increase with temperature
- **Vacuum** vs **Thermal U**: Thermal effects in the amplitudes are small
- **Thermal U** vs **Thermal U+L**: The Landau contribution is very important at finite T
- **Thermal U+L** vs **OffShell**: Off-shell effects are small
- The main contribution comes from the pions in the bath

Comparison with other approaches

[J.M. Torres-Rincon, GM, A. Ramos, L. Tolos, Phys.Rev.C 105 (2022)]

Comparison with:

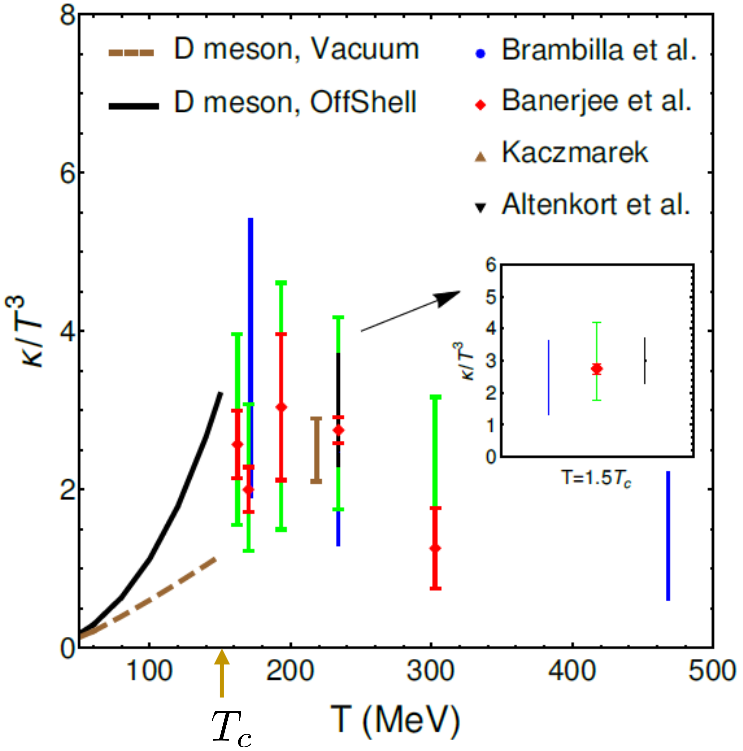
- Lattice QCD calculations

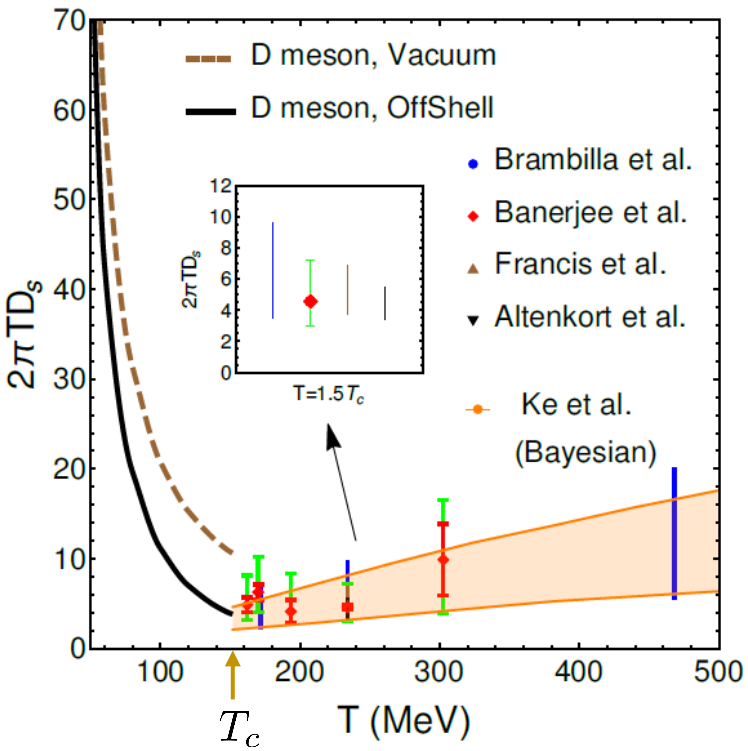
  [N. Brambilla et al. Phys. Rev. D102, 074503 (2020)]
  [I.D. Banerjee et al. Phys. Rev. D85, 014510 (2012)]
  [I.A. Francis et al. Phys. Rev. D92, 116003 (2015)]
  [I.L. Altenkort et al. Phys. Rev. D103, 014511 (2021)]

- Bayesian analysis of HICs

  [W. Ke et al. Phys. Rev. C98, 064901 (2018)]

- **Good matching at** T_c
- Important contribution of the **Landau cut** kinetic region





$$\kappa(T) = \frac{4\pi T^3}{2\pi T D_s(T)}$$

Momentum diffusion coefficient

$$\kappa(T) = 2B_0(\vec{k} \to 0; T)$$

Spatial diffusion coefficient

↳ mean squared displacement of a Brownian particle

$$2\pi T D_s(T) = \lim_{\vec{k}\to 0} \frac{2\pi T^3}{B_0(\vec{k}; T)}$$

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 on heavy mesons: moderate decrease of the masses and substantial increase of the decay widths with T.

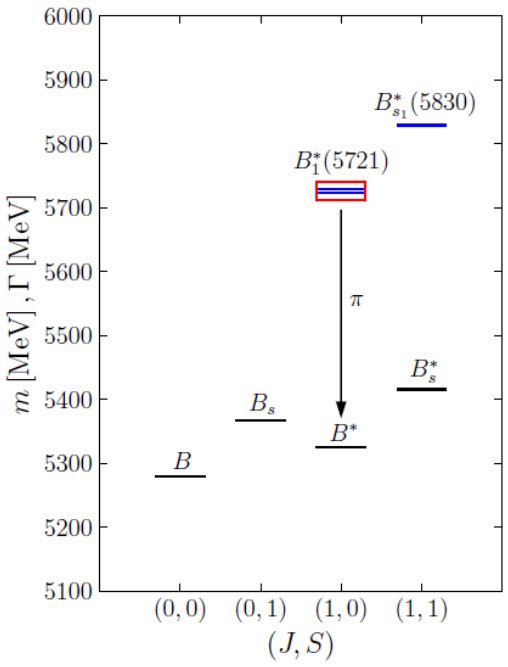
  Bath of pions provides the main contribution.
- Euclidean correlators computed from spectral functions at unphysical masses are in good agreement with lattice QCD below T_c.

  Discrepancies close to T_c possibly indicate the missing contribution of higher-excited states and the bath of kaons.
- We have computed heavy-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 analysis.

Backup slides

Results. Dynamically generated states in the bottom sector



$B_1(5721)^+$: $M = 5725.9^{+2.5}_{-2.7}$ MeV

$I(J^P) = \frac{1}{2}(1^+)$ $\Gamma = 31 \pm 6$ MeV

$B_1(5721)^0$: $M = 5726.1 \pm 1.3$ MeV

$I(J^P) = \frac{1}{2}(1^+)$ $\Gamma = 27.5 \pm 3.4$ MeV

$B_{s1}(5830)^0$: $M = 5828.70 \pm 0.20$ MeV

$I(J^P) = 0(1^+)$ $\Gamma = 0.5 \pm 0.4$ MeV

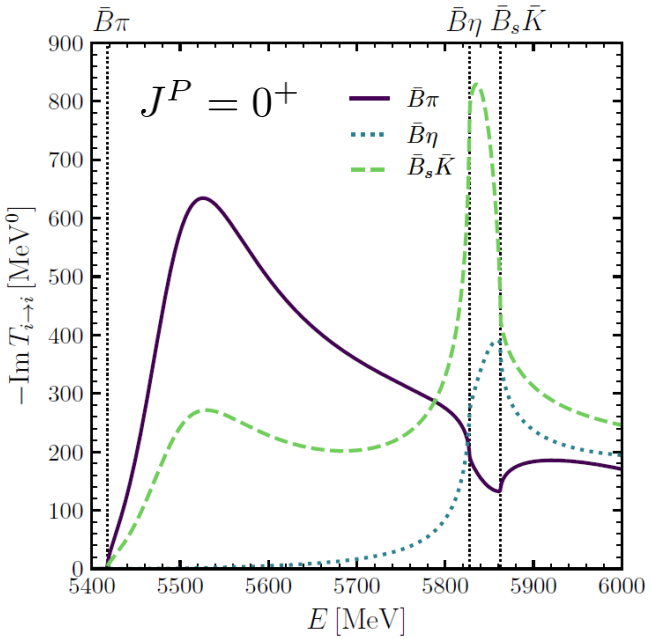
[PDG (2020)]

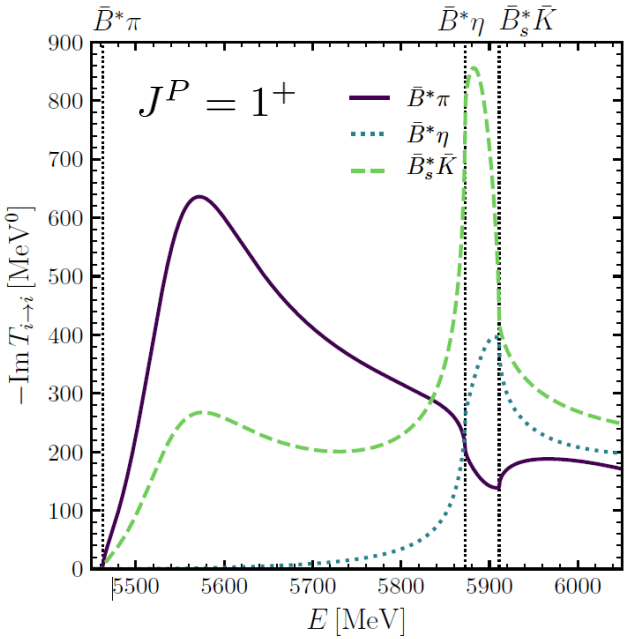
(S,I)	Channels ($J^P = 0^+$)	Threshold (MeV)	Channels ($J^P = 1^+$)	Threshold (MeV)
$(-1,0)$	$\bar{B}\bar{K}$	5775.12	$\bar{B}^*\bar{K}$	5820.29
$(-1,1)$	$\bar{B}\bar{K}$	5775.12	$\bar{B}^*\bar{K}$	5820.29
$(0,\frac{1}{2})$	$\bar{B}\pi$	5417.51	$\bar{B}^*\pi$	5462.69
	$\bar{B}\eta$	5827.34	$\bar{B}^*\eta$	5872.51
	$\bar{B}_s\bar{K}$	5862.53	$\bar{B}_s^*\bar{K}$	5911.04
$(0,\frac{3}{2})$	$\bar{B}\pi$	5417.51	$\bar{B}^*\pi$	5462.29
$(1,0)$	$\bar{B}K$	5775.12	$\bar{B}^*K$	5820.29
	$\bar{B}_s\eta$	5914.75	$\bar{B}_s^*\eta$	5963.26
$(1,1)$	$\bar{B}_s\pi$	5504.93	$\bar{B}_s^*\pi$	5553.44
	$\bar{B}K$	5775.12	$\bar{B}^*K$	5820.29
$(2,\frac{1}{2})$	$\bar{B}_sK$	5862.53	$\bar{B}_s^*K$	5911.04

LECs $\frac{h_i^B}{\hat{M}_B} = \frac{h_i^D}{\hat{M}_D}$, $i = \{0,1,2,3\}$

$h_i^B \hat{M}_B = h_i^D \hat{M}_D$, $i = \{4,5\}$

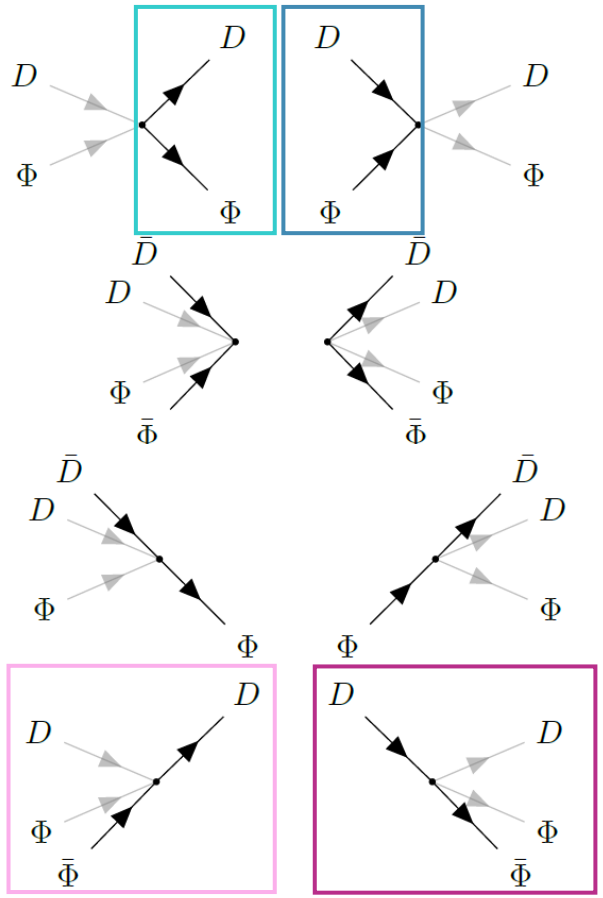
- Two-pole structure for $(S,I) = (0,\frac{1}{2})$
- Bound state for $(S,I) = (1,0)$





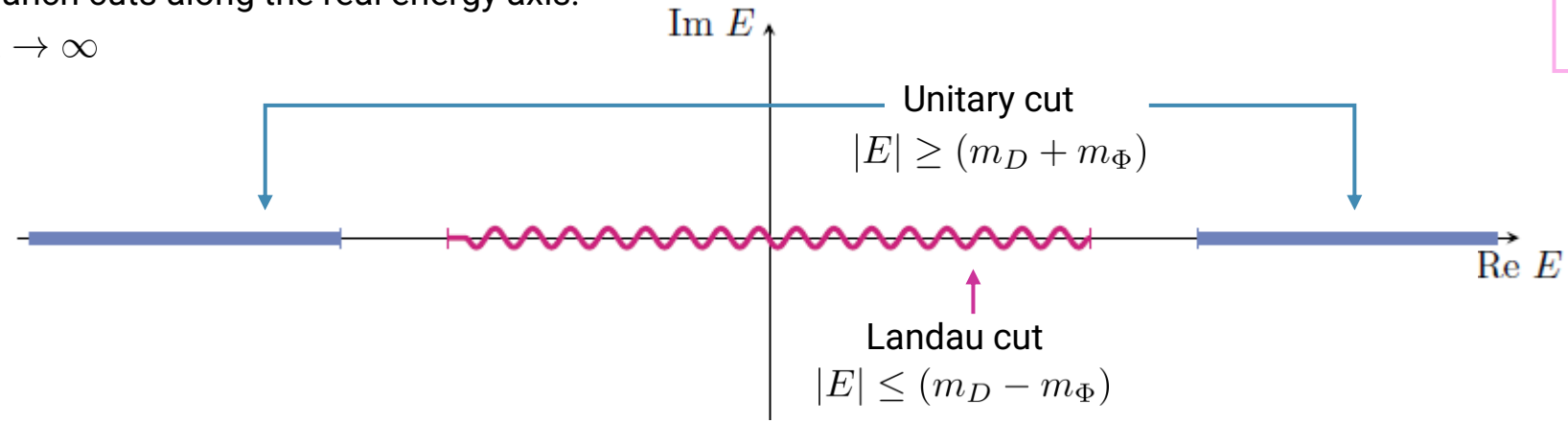
Physical interpretation and cuts of the thermal propagator

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



Branch cuts along the real energy axis:

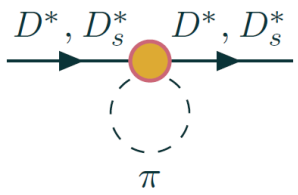
$\Lambda \to \infty$



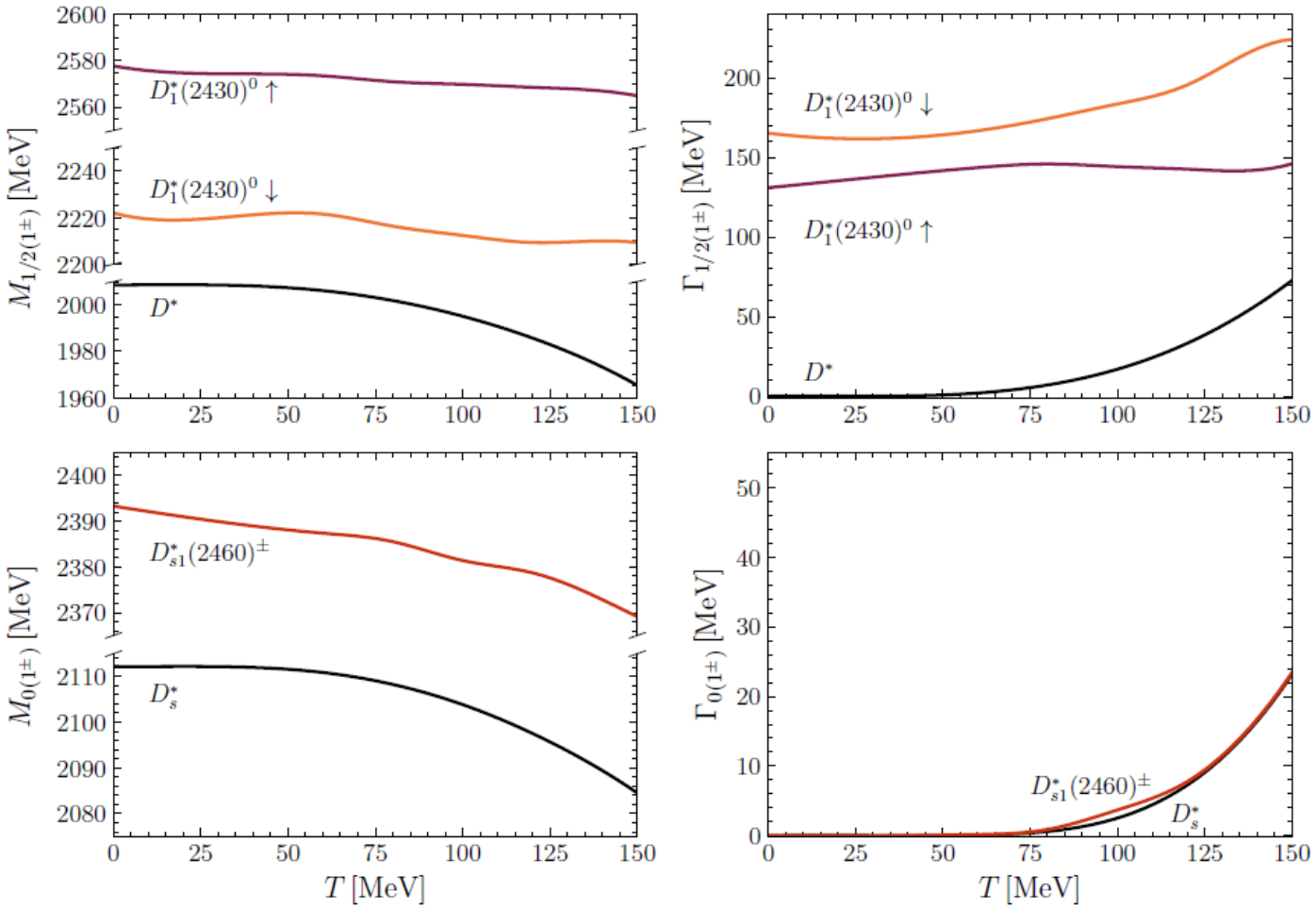
Results: thermal evolution of masses and widths (charmed vector mesons)

[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

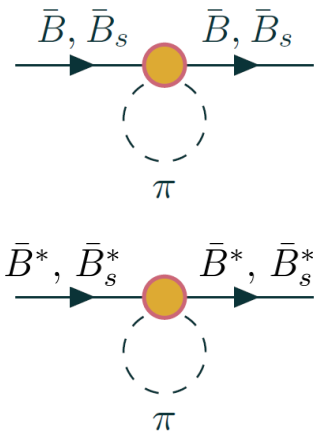


$$J^P = 1^\pm$$

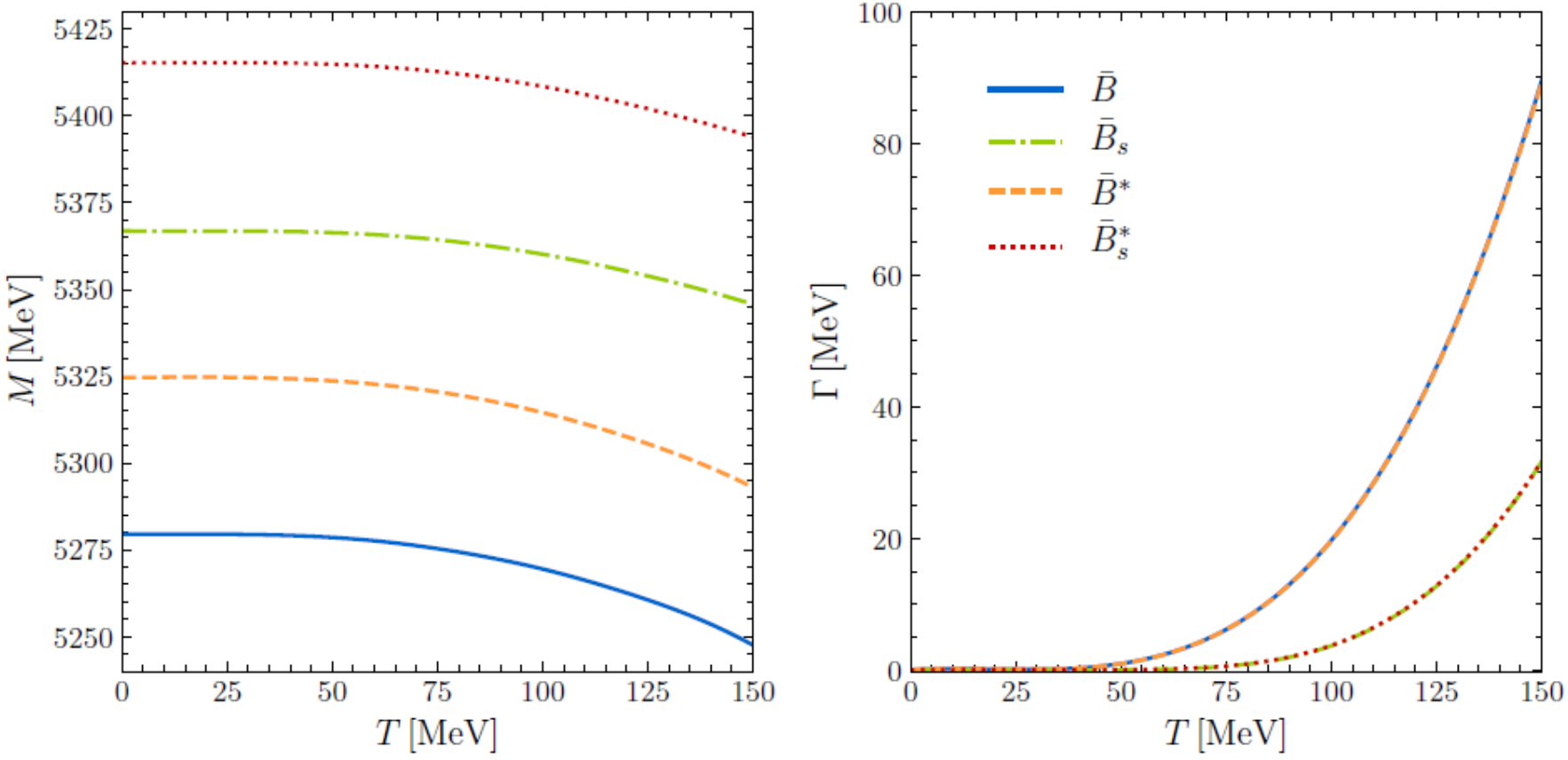


Results: thermal evolution of masses and widths (bottomed mesons)

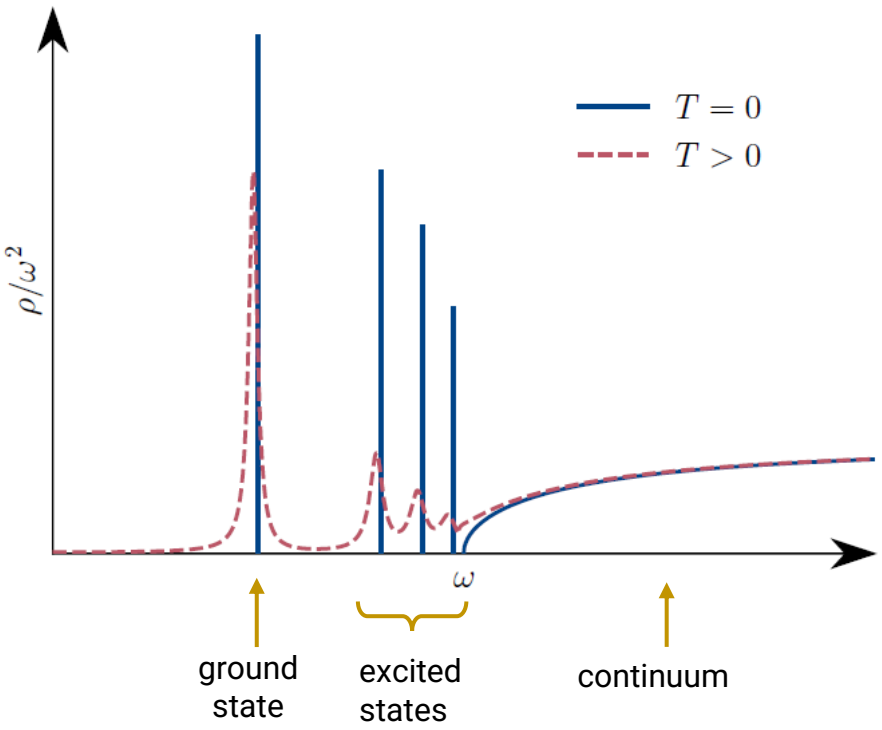
- Pionic bath



$J^P = 0^\pm, 1^\pm$



Euclidean correlators from effective field theories



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 $\rho_{\mathrm{gs}}(\omega; T) \propto S_D(\omega; T)$
- Continuum of scattering states

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

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

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

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

Results: Spectral functions at unphysical meson masses

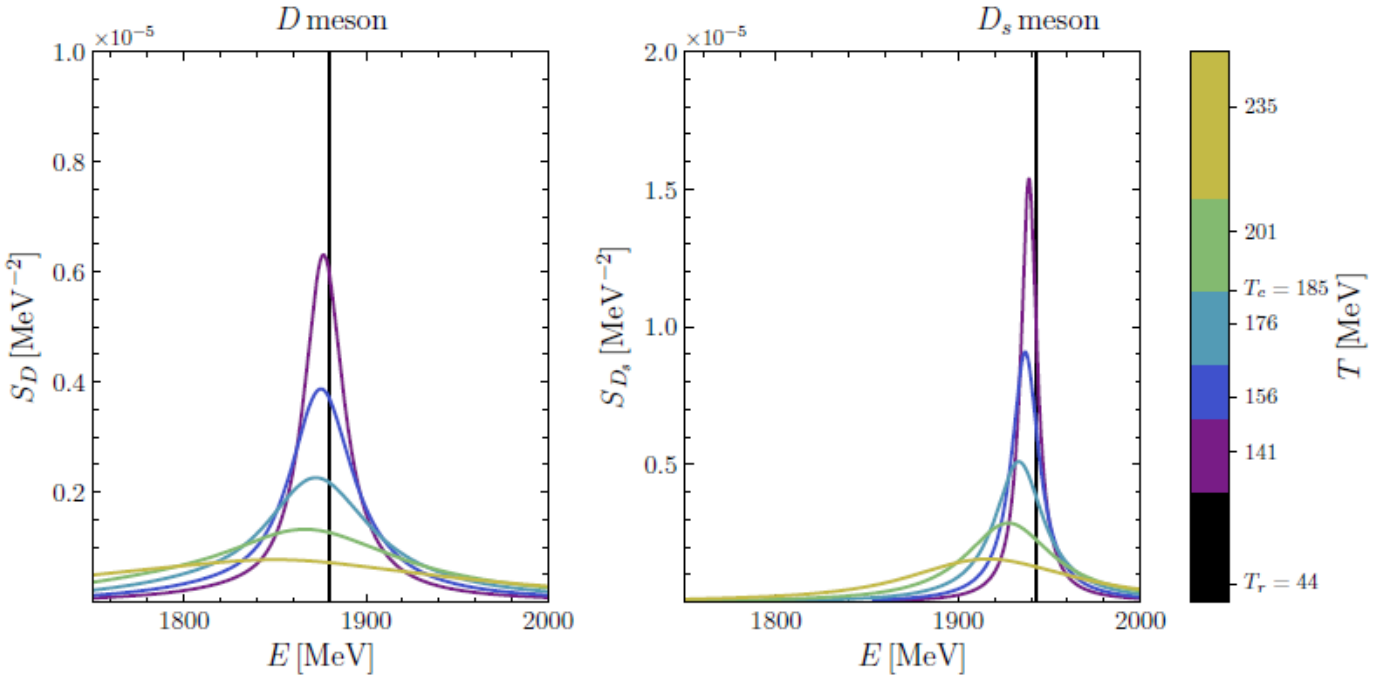
[GM, O. Kaczmarek, L. Tolos, A. Ramos, Eur.Phys.J.A 56 (2020) 11]

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

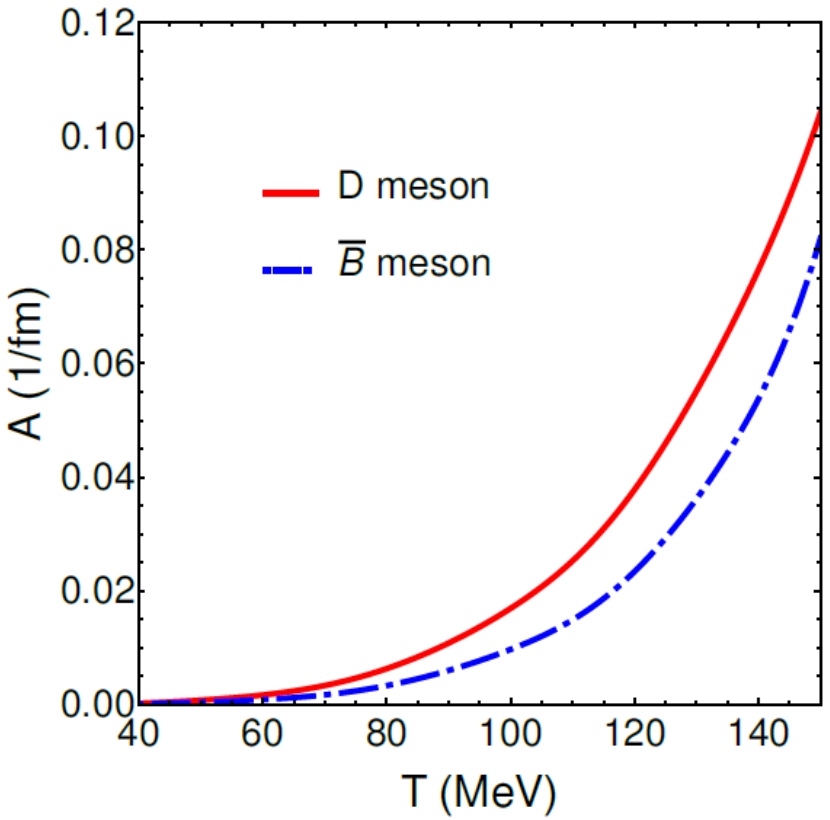
[Kelly, Rothkopf, Skullerud (2018)]

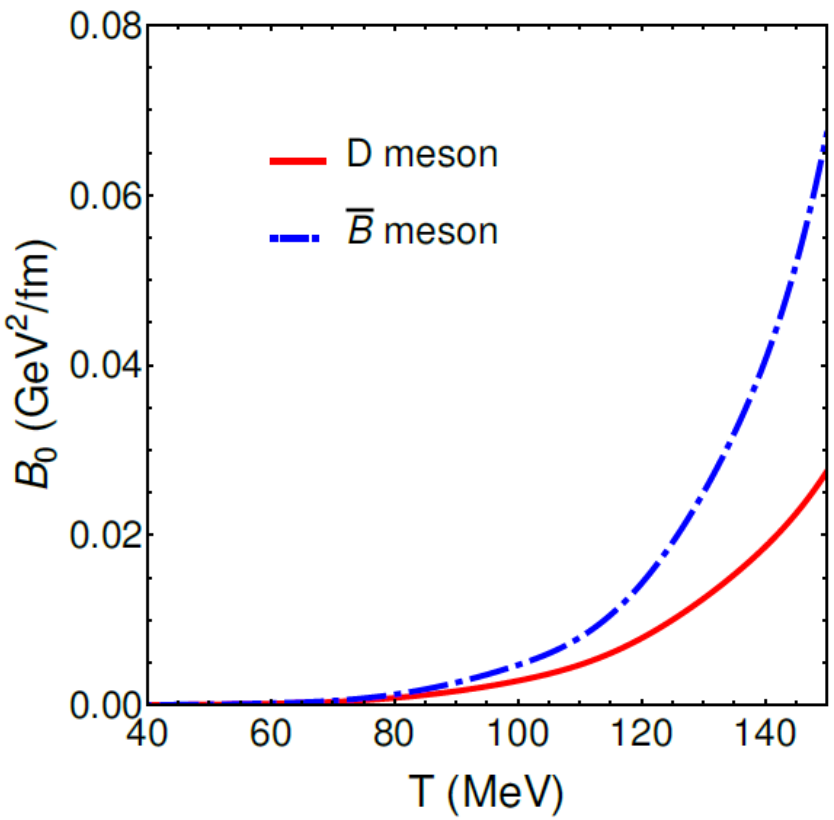
Ground-state spectral functions using unphysical meson masses:



$$T = \frac{1}{aN_\tau}$$

Results: drag force and momentum diffusion coefficient. CHARM vs BOTTOM





Comparison with other approaches. CHARM vs BOTTOM

Comparison with:

- Bayesian analysis of HICs [W. Ke et al. Phys. Rev. C98, 064901 (2018)]
- Quasiparticle model [S.K. Das, J.M. Torres-Rincon, L. Tolos (2018)]