Heavy-flavor exotica: Properties of heavy mesons at finite temperature from hadronic EFTs

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Based on:
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Exotic hadrons and hadronic molecules

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<th>MESONIC SYSTEMS</th>
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<td>Conventional mesons</td>
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<td><img src="image1" alt="Conventional meson" /></td>
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<td><img src="image3" alt="Compact tetraquark" /></td>
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<td><img src="image5" alt="Meson-meson molecule" /></td>
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**Hadronic molecules** are deuteron-like quasi-bound states of two hadrons
- Dynamically generated via multiple scattering of their hadronic components
- Located near threshold
- Studied using **effective hadronic theories**: hadronic degrees of freedom
**Heavy meson sector**

- **2003**: discovery of the first **heavy exotica** candidates (with at least one heavy quark, c or b)

- Confirmed and extensively studied in electron-positron and proton-(anti)proton colliders (Belle, Babar, BESIII, CLEO, CDF, C0, LHCb…)

- Their internal structure is still unknown (compact tetraquark, molecule, admixture?)

- **2021**: first evidence for X(3872) production in Pb-Pb collisions by the CMS collaboration

- Future femtoscopy measurements

New opportunities to probe the nature of exotic states
Theoretical tools to study QCD matter at high temperatures:

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

Motivation
Thermal EFT for heavy mesons
Open heavy-flavor mesons
Transport coefficients
X(3872) & X(4014)
Summary

High-energy HICs
- LHC@CERN
- RHIC@BNL

- Heavy quarks are created in the initial stage of the collision
- Due to the large mass and relaxation time, heavy-flavor mesons are a powerful probe of the QGP
- The properties of heavy mesons (masses and decay widths) are modified in hot matter
Hot mesonic matter

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High-energy HICs

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Our approach:

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Mesonic matter at temperature $0 < T < T_c$ and vanishing baryon density → mostly pions (thermal equilibrium)

Heavy mesons behave as Brownian particles scattering off the light mesons

New processes are available: production and absorption of thermal mesons
### Thermal effective field theory for heavy mesons (I)

Interaction between open heavy-flavor mesons and Goldstone bosons given by **heavy-meson effective theory (HMET)** (in vacuum)

- Chiral symmetry in the limit $m_u, m_d, m_s \rightarrow 0$
- Heavy-quark symmetries in the limit $m_c, m_b \rightarrow \infty$
  - Heavy-quark spin-flavor symmetry (HQSFS):
    \[
    \{c \uparrow, c \downarrow, b \uparrow, b \downarrow\} \quad \{D, D^*, \bar{B}, \bar{B}^*\}
    \]

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Motivation

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  ◦ Heavy-quark spin-flavor symmetry (HQSFS):
    \( \{ c \uparrow, c \downarrow, b \uparrow, b \downarrow \} \quad \{ D, D^*, \bar{B}, \bar{B}^* \} \)

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

Tree-level scattering amplitude:

\[
V^{ij}(s, t, u) = \frac{1}{f^2} \left[ \frac{C_{LO}^{ij}}{4} (s - u) - 4 C_0^{ij} h_0 + 2 C_1^{ij} p_1 
- 2 C_2^{ij} \left[ 2 h_2 (p_2 \cdot p_4) + h_4 ((p_1 \cdot p_2) (p_3 \cdot p_4) + (p_1 \cdot p_4) (p_2 \cdot p_3)) \right] 
+ 2 C_3^{ij} \left[ h_3 (p_2 \cdot p_4) + h_5 ((p_1 \cdot p_2) (p_3 \cdot p_4) + (p_1 \cdot p_4) (p_2 \cdot p_3)) \right] \right]
\]

At LO in HQSFS:

\[
h^B_0,3 \hat{M}_B^{-1} = h^D_0,3 \hat{M}_D^{-1}, \quad h^B_{4,5} \hat{M}_B = h^D_{4,5} \hat{M}_D
\]

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

[ALI-PREL-513658]

LECs fitted to lattice QCD data

Isospin coefficients

Thermal effective field theory for heavy mesons (II)

Unitarization: on-shell Bethe-Salpeter equation in coupled channels

\[ T = \frac{V}{1 - VG} \]

Two-meson propagator or loop function

\[ G_k(s) = i \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_D^2 + i\varepsilon} \frac{1}{(p - q)^2 - m_F^2 + i\varepsilon} \]

regularized with a momentum cut-off
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**Imaginary time formalism**

- Sum over Matsubara frequencies \( q^0 \rightarrow i\omega_n = i \frac{2n\pi}{\beta} \) (bosons),
- 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
Thermal effective field theory for heavy mesons (III)

\[ G_D(\omega, \vec{q}; T) = \frac{1}{(2\pi)^3} \int d^3 q \int d\omega \int d\omega' \frac{S_D(\omega, \vec{q}; T)S(\omega', \vec{p} - \vec{q}; T)}{E - \omega - \omega' + i\epsilon} \left(1 + f(\omega, T) + f(\omega', T)\right) \]

\[ T_{ij} = V_{ij} + V_{ik} G_k T_{kj} \]

\[ \Pi_D(\omega, \vec{q}; T) = \frac{1}{\pi} \int \frac{d^3 q'}{(2\pi)^3} \int dE \frac{\omega - \omega\Phi}{\omega^2 - (\omega\Phi - E)^2 + \text{sgn}(\omega) i\epsilon} \left[f(E, T) - f(\omega\Phi, T)\right] \text{Im} T_D(\omega, \vec{p}; T) \]

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

Set of coupled equations solved self-consistently
Thermal loop function

Pionic bath

\[ D, D_s \rightarrow D, D_s \rightarrow \pi \]

\[ \text{Re } G_{D\pi}, \text{Im } G_{D\pi} \]

\[ T = 150 \text{ MeV}, T = 120 \text{ MeV}, T = 80 \text{ MeV}, T = 0 \text{ MeV} \]

Thermal loop function

Pionic bath

\[ \text{Unitary cut} \quad |E| \geq (m_D + m_\Phi) \]

Thermal loop function

Motivation

Thermal EFT for heavy mesons

Open heavy-flavor mesons

Transport coefficients

X(3872) & X(4014)

Summary

**Pionic bath**

\[ D, D_s \quad \text{and} \quad D, D_s \]

\[ \pi \]

**Landau cut**

\[ |E| \leq (m_D - m_\Phi) \]

**Re \( G_{D\pi} \)**

**Im \( G_{D\pi} \)**

\[ T = 150 \text{ MeV} \]

\[ T = 120 \text{ MeV} \]

\[ T = 80 \text{ MeV} \]

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**Unitary cut**

\[ |E| \geq (m_D + m_\Phi) \]

Open heavy-flavor mesons

Ground-state spectral functions:

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

$$J^P = 0^-$$
Open heavy-flavor mesons

Ground-state spectral functions:

\[ S_D(\omega, q^2; T) = -\frac{1}{\pi} \text{Im} \left( \frac{1}{\omega^2 - q^2 - m_D^2 - \Pi_D(\omega, q^2; T)} \right) \]

\[ J^P = 0^- \]

In vacuum \((T = 0)\)

- \(D_0^*(2300)\) : Two-pole structure
- \(D_{s0}^*(2317)\) : Bound state

Dynamically generated states:

\[ J^P = 0^+ \]

We have also investigated the thermal modification of the \(1^\pm\) and bottom counterparts

Thermal masses and widths

The thermal properties can be directly obtained from the spectral functions

Our results:
- reduction of the in-medium mass
- thermal widening with increasing temperature

Also, reduction of the mass of the $D$ and $D_s$ with increasing temperature from lattice-QCD data
Transport coefficients of off-shell heavy mesons

Fokker-Planck equation (from Kadanoff-Baym approach)

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

Green's function

$$i G_D^\lept(t, k) = 2\pi S_D(t, k_0, \vec{k}) f_D(t, k_0)$$

Off-shell transport coefficients

- Drag force coefficient:
  $$\hat{A}(k^0_0, \vec{k}_1; T) \equiv \left\langle 1 - \frac{\vec{k} \cdot \vec{k}_1}{k^2} \right\rangle$$

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

with

$$\left\langle \mathcal{F}(\vec{k}, \vec{k}_1) \right\rangle = \frac{1}{2k_0^0} \sum_{\lambda, \lambda'} \lambda \lambda' \int_{-\infty}^{\infty} dk_1^0 \int \prod_{i=1}^3 \frac{d^3 k_i}{(2\pi)^3} \frac{1}{2E_2 2E_3} S_D(k_1^0, \vec{k}_1)(2\pi)^4 \delta^{(3)}(\vec{k} + \vec{k}_3 - \vec{k}_1 - \vec{k}_2)$$

$$\times \delta(k^0 + \lambda E_3 - \lambda E_2 - k^0_1) \left| T(k^0_0 + \lambda E_3, \vec{k} + \vec{k}_3) \right|^2 f(0)(\lambda E_3) f(0)(\lambda E_2) f(0)(k^0_1) \mathcal{F}(\vec{k}, \vec{k}_1)$$

- Thermal effects in $|T|^2$ and $E_k$
- Landau cut contribution
- Off-shell effects
Drag force and momentum diffusion coefficients

- 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 temperature
- Thermal U+L vs OffShell: Off-shell effects are small
- The main contribution comes from the pions in the bath

\[ \lim_{\vec{k} \to 0} B_0 = B_1 \]
Spatial diffusion coefficient

\[ 2\pi TD_s(T) = \lim_{k \to 0} \frac{2\pi T^3}{B_0(k; T)} \]

Comparison with:
- Lattice QCD calculations
  - [N. Brambilla et al. Phys. Rev. D102, 074503 (2020)]
- Bayesian analysis of HICs
Spatial diffusion coefficient

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Comparison with:
- Quasiparticle model
**X(3872) and X(4014)**

- **Motivation**
  - **Thermal EFT for heavy mesons**
  - **Open heavy-flavor mesons**
  - **Transport coefficients**

- **Summary**

- **X(3872)**
  - 2003: $X(3872)$, a.k.a. $\chi_{c1}(3872)$, discovered by Belle
  - 2013: quantum numbers determined by LHCb: $J^{PC} = 1^{++}$
  - Its internal structure remains under debate
  - Its prompt production in HICs provides an alternative probe to its internal structure

- **X(4014)**

- [PRL 110 (2013) 222001]
- [PRL 91 (2003) 262001]
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Summary

- [PRL 128 (2022) 3, 032001]
- [Esposito et al. (2021)]
- [Braaten et al. (2021)]

A different model for calculating breakup cross section

[arXiv:2211.02491]
X(3872) and X(4014)

- 2003: $X(3872)$, a.k.a. $\chi_{c1}(3872)$, discovered by Belle
  - Predicted as the partner of the $[\text{PRD 105 (2022) 11, 112011}]$
  - [Nieves, Pavon Valderrama (2012)]
  - [Guo, Hidalgo-Duque, Nieves, Pavon Valderrama (2013)]

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- 2021: $X(4014)$, observed by the Belle collaboration
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- **2021**: $X(4014)$, observed by the Belle collaboration
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**Notes**:
- Investigate these states as heavy meson molecules within the local hidden-gauge symmetry approach
- Analyze the in-medium modification

**Summary**

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The local hidden-gauge symmetry approach

The interaction is mediated by the exchange of vector mesons
Extended to SU(4), broken by physical masses (exchange of charm is suppressed)

\[ \mathcal{L}_{III} = -\frac{1}{4} \langle V_{\mu\nu} V^{\mu\nu} \rangle + \frac{1}{2} m_V^2 \left\langle \left( V_{\mu} - \frac{i}{g} \Gamma_{\mu} \right)^2 \right\rangle \]

- We obtain the interaction kernel and solve the Bethe-Salpeter equation with G regularized with a cut-off
- The cut-off is fixed in vacuum to reproduce the experimental masses
- At finite temperature, G is dressed with the spectral functions of the $D/D_s$ and $D^*/D_s^*$ mesons
Thermal modification of the $X(3872)$ and $X(4014)$

The masses decrease with increasing temperature

- drop of the thresholds

Non-zero decay widths at finite

- widening of open heavy-flavor ground-states

Summary and conclusions

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

2. Thermal effects on open heavy-flavor mesons: moderate decrease of the masses and substantial increase of the decay widths with increasing temperature
   Similar findings from recent lattice QCD calculations

3. We have computed heavy-meson transport coefficients in the hadronic phase 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.

4. We dynamically generate the \(X(3872)\) as a \(D\bar{D}^* + \text{c.c.}\) molecule within the hidden gauge approach and identified the \(X(4014)\) as its \(J^{PC} = 2^{++}\) partner.
   We have studied the finite-temperature modification of the properties of the \(X(3872)\) and the \(X(4014)\):
   - The masses decrease with temperature (related to the drop of the thresholds \(D^{(*)}\bar{D}^*\))
   - Non-zero decay widths at finite temperature (related to the widening of \(D/\bar{D}^*\) states)