Charm meson and charm-meson molecule in an expanding hadron gas

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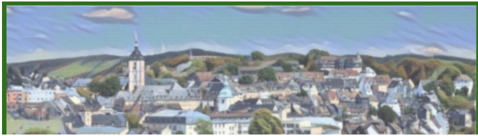
Based on arXiv:2209.04972, 2303.08072, 2307.07470



11th International Workshop on Charm Physics (CHARM 2023)

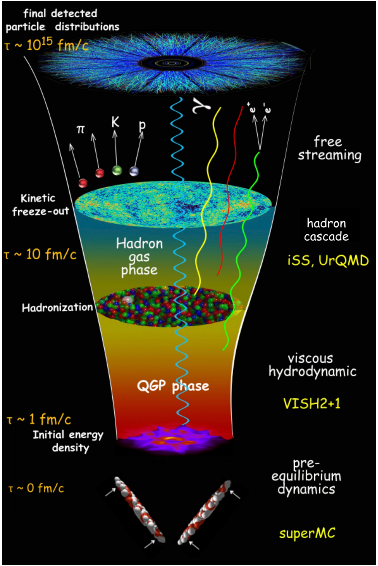
Outline

Expanding hadron gas from heavy-ion collisions

The standard model of heavy-ion collisions is a multi-stage model:

- **S1** Initial Collision
- **S2** Thermalization
- **S3** Hadronization
- **S4** Kinetic freeze-out

State-of-the-art models consist of complex numerical simulations for each stage



Credit: Paul Sorensen and Chun Shen

Expanding hadron gas from heavy-ion collisions: kinetic freeze-out

Near kinetic freeze-out, the most abundant hadrons in the hadron gas are pions. The abundance of kaons is smaller by about a factor of 5 and other hadrons are even less abundant.
The hadron gas can be approximated by a pion gas.

- temperature fixed at $T = T_F$ (≈ 115 MeV for Pb-Pb collisions at LHC)
- volume continues to expand with proper time τ.
- pion number density decreases in inverse proportion to the volume:

$$\mathfrak{n}_\pi(\tau) = [V(\tau_F)/V(\tau)]\mathfrak{n}_\pi(\tau_F)$$

- pion momentum distributions are frozen and given by Bose-Einstein distributions with temperature T_F:

$$\mathfrak{f}_\pi(\boldsymbol{q}) = \frac{\mathfrak{n}_\pi(\tau)}{\mathfrak{n}_\pi(\tau_F)} \frac{1}{e^{\sqrt{\boldsymbol{q}^2+m_\pi^2}/T_F} - 1}$$

Thermal mass shifts and widths: Charm mesons

In a pion gas, charm meson and pion properties are modified by the interactions with the pion gas.

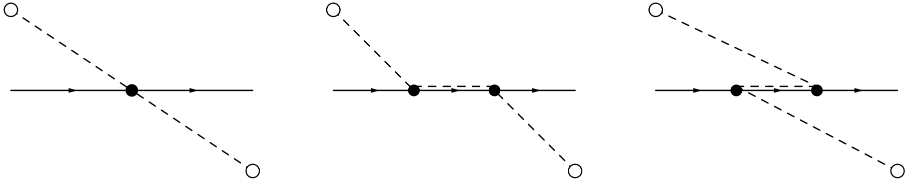
D self-energy diagrams in HHχEFT at leading order

□ zero-temperature part (taken into account in parameters of the EFT)
■ thermal part from the coherent forward scattering of an on-shell pion
□ thermal part from the coherent forward scattering of an on-shell charm meson (suppressed by the charm-meson thermal distribution)

Thermal mass shifts and widths: Charm mesons

Thermal self-energies in a pion gas arise primarily from **coherent pion forward scattering**.

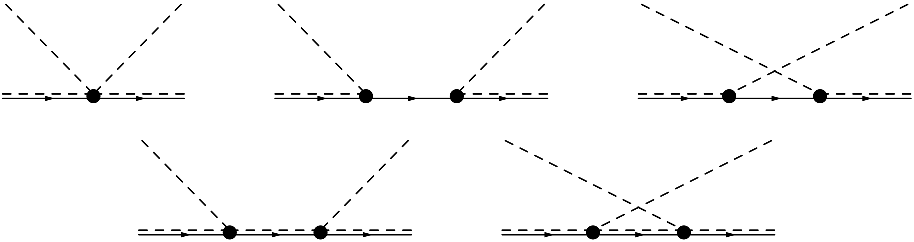
D self-energy diagrams from coherent pion forward scattering in HHχEFT at LO



Thermal mass shifts and widths: Charm mesons

Thermal self-energies in a pion gas arise primarily from **coherent pion forward scattering**.

D^* self-energy diagrams from coherent pion forward scattering in HHχEFT at LO

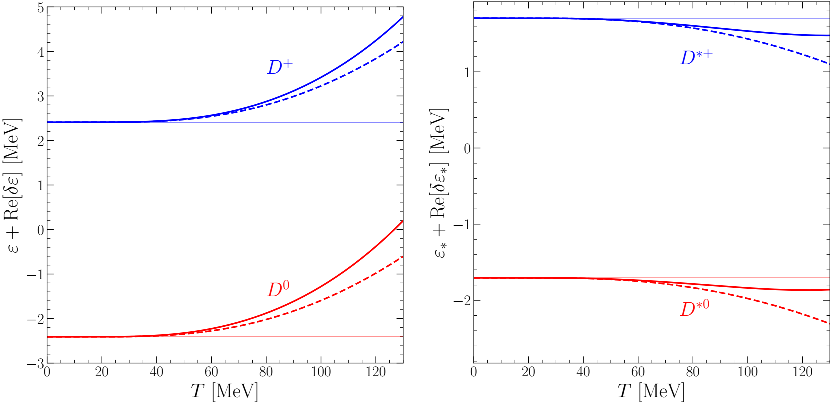


Real part of self energy $\Pi(p=0)$ determines the mass shift of $D^{(*)}$
Imaginary part of $\Pi(p=0)$ determines the thermal width of $D^{(*)}$ at rest

Thermal mass shifts and widths: Charm mesons

Real rest energies as functions of the temperature T

Real rest energy at T = real rest energy at $T = 0$ + thermal mass shift

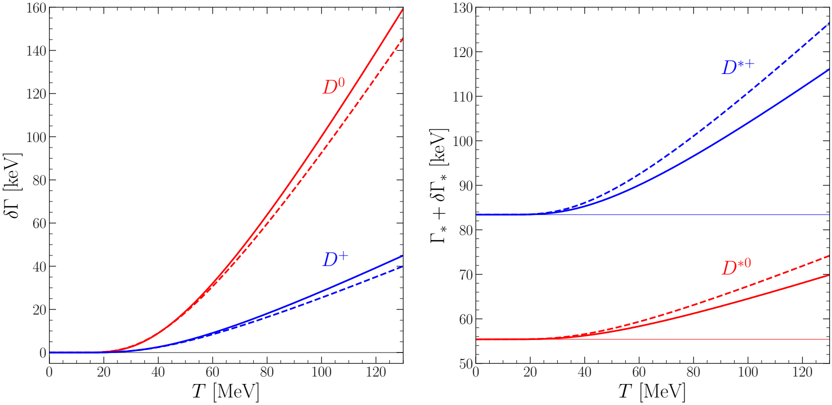


Dashed line: LO in heavy meson expansion ($m_\pi \ll M_D$)
Solid line: NLO in heavy meson expansion

Thermal mass shifts and widths: Charm mesons

Widths as functions of the temperature T

width at T = width at $T = 0$ + thermal width



Dashed line: LO in heavy meson expansion
Solid line: NLO in heavy meson expansion

Thermal mass shifts and widths: Comparison with previous work

$\delta M - i\delta\Gamma$ for charm mesons in MeV.

T [MeV]	FMFK[1]		MRTT[2]	
	D	D^*	D	D^*
100	$-7-8i$	$-6-12i$	$-13-17i$	$-12-17i$
	CMR[3]		this work	
	D	D^*	D	D^*
100	$0-15i$	$0-10i$	$1.07-0.064i$	$-0.15-0.015i$

There are orders-of-magnitude discrepancies. Possible reasons:

- higher-order terms in the chiral expansions are much larger than the leading-order terms in our work (even at $T = 100$ MeV)
- models used in previous works may give too large results at low temperatures.

[1] Fuchs *et al.*, PRC **73**, 035204 (2006). [2] Montana *et al.*, PLB **806**, 135464 (2020), PRD **102**, 096020 (2020)
[3] Cleven *et al.*, PRC **96**, 045201 (2017)

Thermal mass shifts and widths: Comparison with previous work

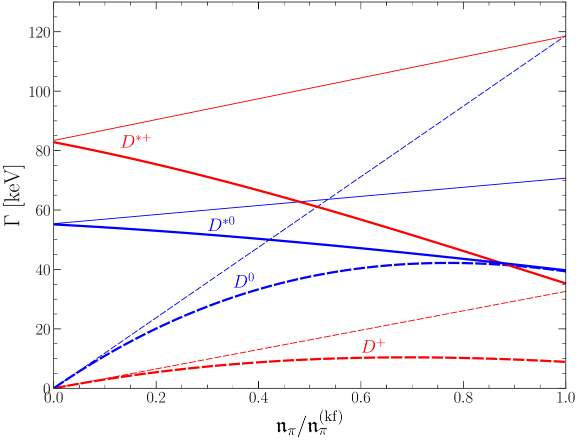
- Lattice QCD[1] calculations of charm meson masses:
  At $T = 47, 95, 109, 127$ MeV, the thermal mass shifts of D and D^* were consistent with 0 within the error (± 6 MeV).
  At $T =$152 MeV, $\delta m_D = -20 \pm 7$ MeV, $\delta m_{D^*} = -43 \pm 10$ MeV.
- FMFK[2]:
  At $T = 150$ MeV, $\delta m_{D^{(*)}} \approx -15$ MeV
- MRTT[3]:
  At $T = 150$ MeV, $\delta m_{D^{(*)}} \approx -40$ MeV

lattice QCD is beginning to provide useful results for the thermal shifts in charm-meson masses

[1] Aarts *et al.*, arXiv:2209.14681
[2] Fuchs *et al.*, PRC **73**, 035204 (2006)
[3] Montana *et al.*, PLB **806**, 135464 (2020), PRD **102**, 096020 (2020)

Thermal mass shifts and widths: Charm mesons

Thermal widths VS pion number density



thicker (thinner) lines: widths with mass shift (not) taken into account

Loosely bound charm-meson molecule: Overview

Experimental discoveries:

- $X(3872)$: discovered by Belle in 2003
  - ⋆ $E_B = M_{DD^*} - M_X < 0.22$ MeV
  - ⋆ $J^{PC} = 1^{++}$

  $\Longrightarrow$ S-wave loosely bound molecule: $\frac{1}{\sqrt{2}}(D^{*0}\bar{D}^0 + \bar{D}^{*0}D^0)$
  Other components with smaller probabilities: $\chi_{c1}(2P)$, compact tetraquark, $\cdots$

- $T_{cc}^+(3875)$: discovered by LHCb in 2021
  - ⋆ $E_B = M_{DD^*} - M_X = 0.36 \pm 0.04$ MeV
  - ⋆ $J^{PC} = 1^{++}$

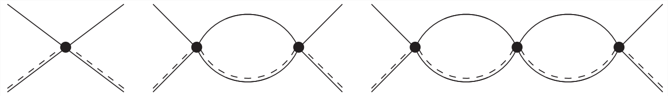
  $\Longrightarrow$ S-wave loosely bound molecule: $D^{*+}D^0$
  Other components with smaller probabilities: $D^{*0}D^+$, compact tetraquark, $\cdots$

Simplest effective field theory (EFT) for a loosely bound charm-meson molecule: zero-range EFT (ZREFT).

Loosely bound charm-meson molecule: Overview

amplitude for the propagation of D and D^* between contact interactions

in vacuum:



$$= \frac{i(2\pi/\mu)}{\frac{2\pi/\mu}{C_0} - \Lambda + S_0(E_{\rm cm})} = \frac{i\,(2\pi/\mu)}{-\gamma_X + S_0(E_{\rm cm})}$$

If the binding momentum $\gamma_X > 0$, it has a pole at $E_{\rm cm} = E_X = -\gamma_X^2/(2\mu)$

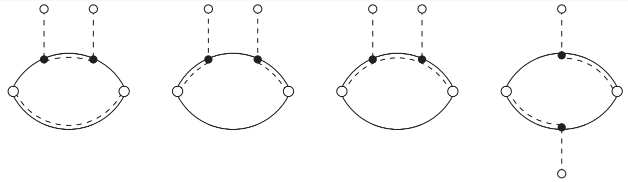
in a hadron gas:

$$\frac{i\,(2\pi/\mu)}{\frac{2\pi/\mu}{C_1} - \Lambda + S_0(E_{\rm cm}) + \Sigma(E_{\rm cm}, P)} \to \frac{i\,(2\pi/\mu)\,Z_X}{-(\gamma_X + \delta\gamma_X) + S_1(E_{\rm cm}, P) + \ldots}$$

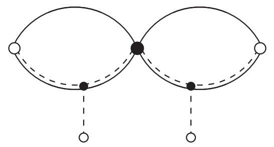
$$S_0(E_{\rm cm}) = \sqrt{-2\mu\big[E_{\rm cm} - (\varepsilon_* + \varepsilon) + i\epsilon\big]}, \quad S_1(E_{\rm cm}) = \sqrt{-2\mu\big[E_{\rm cm} + i\epsilon + \ldots\big]}$$

Loosely bound charm-meson molecule: Self-energy

One-loop diagrams for $\Sigma(E_{\rm cm}, P)$ from coherent pion forward scattering

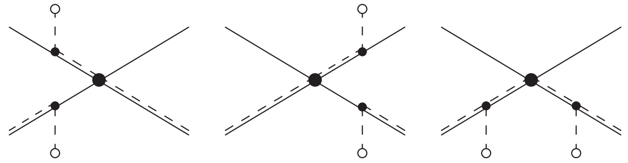


Two-loop diagram for $\Sigma(E_{\rm cm}, P)$ from coherent pion forward scattering



Loosely bound charm-meson molecule: Self energy

Contact vertex corrections: δC



complete amplitude in a pion gas:

$$\frac{i\,(2\pi/\mu)}{\frac{2\pi/\mu}{C_1} - \Lambda + S_0(E_{\rm cm}) + \Sigma(E_{\rm cm}, P)} = \frac{i\,(2\pi/\mu)\,Z_X}{-(\gamma_X + \delta\gamma_X) + S_1(E_{\rm cm}, P) + \ldots}$$

$$S_1(E_{\rm cm}, P) = \sqrt{-2\mu\Big[E_{\rm cm} - (\varepsilon_* + \varepsilon) - (\delta\varepsilon_* + \delta\varepsilon) - \zeta_X P^2/(2M_X) + i\epsilon\Big]}$$

Loosely bound charm-meson molecule: Thermal mass shifts and widths

Pole energy of molecule with zero 3-momentum at NLO:

$$E_X = (\varepsilon_{*a} - i\,\Gamma_{*a}/2) + \varepsilon_b + (\delta\varepsilon_{*a} + \delta\varepsilon_b) - (\gamma_X + \delta\gamma_X)^2/(2\mu).$$

$\delta\varepsilon_{*a}, \delta\varepsilon_b$: thermal energy shift for charm mesons
$\delta\gamma_X$: correction to the binding momentum

$X(3872)$ pole energy from LHCb: $(0.025 - 0.140i)$ MeV
$X(3872)$ pole energy in a pion gas at $T = 115$ MeV: $(1.64 - 0.21i)$ MeV

$T_{cc}^{+}(3875)$ pole energy from LHCb: $(-0.36 - 0.024i)$ MeV
$T_{cc}^{+}(3875)$ pole energy in a pion gas at $T = 115$ MeV: (1.20 - 0.10 i) MeV

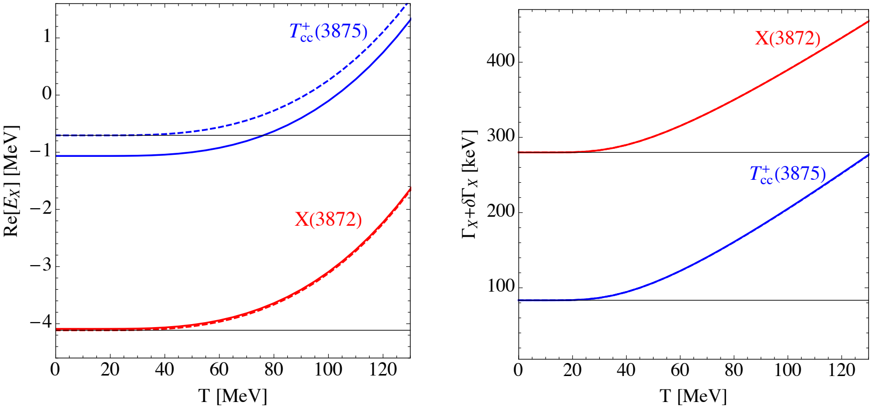
Thermal contribution from correction to the binding momentum is negligible compared to those from charm meson constituents

LHCb, JHEP **08**, 123 (2020)
LHCb, Nature Commun. **13**, 3351(2022)

Loosely bound charm-meson molecule: Thermal mass shifts and widths

Pole energy of molecule with zero 3-momentum at NLO:

$$E_X = (\varepsilon_{*a} - i\,\Gamma_{*a}/2) + \varepsilon_b + (\delta\varepsilon_{*a} + \delta\varepsilon_b) - (\gamma_X + \delta\gamma_X)^2/(2\mu).$$



Dashed lines: charm-meson thresholds

Loosely bound charm-meson molecule: Comparison with previous work

Thermal mass shifts and widths for $X(3872)$ at $T = 100$ MeV

	$M_X - M_{DD^*}^{T=0}$	δM_{DD^*}	$\delta\Gamma_X$	$M_X - M_{DD^*}$ at $T = 0$
CMR[1] [MeV]	$+3$	0	30	-2.5
MRTT[2] [MeV]	-30	-27	30	-4
This work	0.97	1.00	0.11	0.025

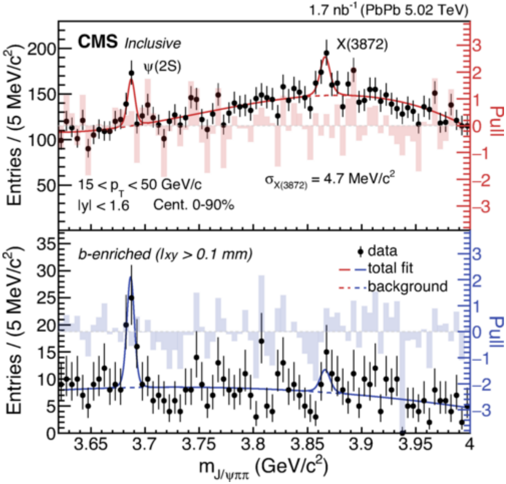
There are orders-of-magnitude discrepancies. Possible reasons:

- higher-order terms in the chiral expansions are much larger than the leading-order terms in our work (even at $T = 100$ MeV)
- models used in previous works may give too large results at low temperatures.

[1]Cleven *et al.*, PLB **799**, 135050 (2019): the $D^* D$ threshold was somehow held constant at its $T = 0$ value
[2]Montana *et al.*, arXiv:2211.01896

Prompt production of X(3872) in PbPb collisions

CMS, Phys. Rev. Lett. **128**, 032001 (2022)



prompt X-to-ψ' ratio ~ 1, order of magnitude larger than in pp collisions

Summary

(a) We calculated the thermal mass shifts and widths of $D^{(*)}$ mesons to NLO in the heavy-meson expansion

(b) Thermal corrections to a loosely bound charm-meson molecule in a pion gas come primarily from the complex thermal energy shift of the charm-meson constituents.

(c) It is encouraging to observe loosely bound charm-meson molecules in the hadron gas from the heavy-ion collisions.

Thank you for your attention.