Thermal masses of *D* mesons and hidden-charm exotics

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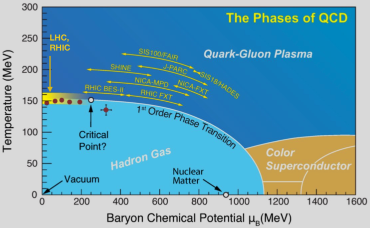
Hadron Spectroscopy and Structure
Genova, Italy, 7 June 2023

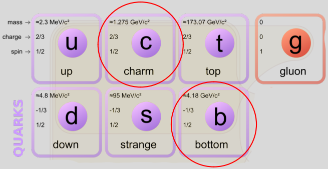
Introduction: Heavy flavor

(A. Bazavov *et al.*, 1904.09951)



- Infer QCD properties at high temperatures through final state of RHICs
- Find clean and solid observables to connect detections to early stages
- **Hard Probes:** Jets, hard electromagnetic emission, heavy flavor (quarkonia, open-heavy flavor hadrons...)

Heavy quarks: formed at the initial stage of the collision (short formation time) and difficult to equilibrate along their evolution (large relaxation time)



Interactions in a thermal medium?

Transport coefficients?

Introduction: Thermal propagation

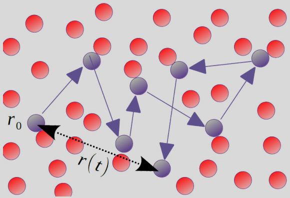
- Heavy mesons (D, D_s, D^*...) at $T < 150$ MeV$/k_B$
- Interacting with an equilibrated light-meson gas ($\Phi = \{\pi, K, \bar{K}, \eta\}$)
- **Heavy-hadron mass is the dominant scale**

$$M_D \gg m_\Phi, T, \Lambda_{QCD}$$

- Picture: Brownian particle in a thermal bath
  B. Svetitsky, Phys. Rev. D37, 484 (1988)
- Transport properties: (Heavy-flavor) diffusion coefficient, $\boldsymbol{D_s}$.

Mean square displacement

$$\langle [r(t) - r_0]^2 \rangle = 6\boldsymbol{D_s(T)}t$$



Effective field theory

Effective Lagrangian based on **chiral** and **heavy-quark spin-flavor** symmetries.

see talk by Li-Sheng Geng

- **Chiral expansion** up to NLO
  : also explicitly broken due to light-meson masses $(\pi, K, \bar{K}, \eta)$.
- **Heavy-quark mass expansion** up to LO
  : broken by heavy meson masses (D, D_s, D^*, D_s^*).

E.E. Kolomeitsev and M.F.M. Lutz *Phys.Lett. B582 (2004) 39*, J. Hofmann and M.F.M. Lutz *Nucl.Phys. A733 (2004) 142*, F.K.Guo, C.Hanhart. S. Krewald, U.G. Meissner *Phys.Lett. B666 (2008) 251*, L.S. Geng, N. Kaiser, J. Martin-Camalich and W. Weise *Phys.Rev.D82,05422 (2010)*, L.M. Abreu, D. Cabrera, F.J. Llanes-Estrada and JMT-R. *Annals Phys. 326 (2011) 2737...*

$$\mathcal{L}_{\mathbf{LO}} = Tr[\nabla^\mu D \nabla_\mu D^\dagger] - m_D^2 Tr[DD^\dagger] - Tr[\nabla^\mu D^{*\nu} \nabla_\mu D_\nu^{*\dagger}] + m_{D^*}^2 Tr[D^{*\mu} D_\mu^{*\dagger}]$$

$$+igTr\left[\left(D^{*\mu} u_\mu D^\dagger - D u^\mu D_\mu^{*\dagger}\right)\right] + \frac{g}{2m_D} Tr\left[\left(D_\mu^* u_\alpha \nabla_\beta D_\nu^{*\dagger} - \nabla_\beta D_\mu^* u_\alpha D_\nu^{*\dagger}\right) \epsilon^{\mu\nu\alpha\beta}\right]$$

$$D = (D^0, D^+, D_s^+)$$

$$\nabla^\mu = \partial^\mu - \tfrac{1}{2}(u^\dagger \partial^\mu u + u \partial^\mu u^\dagger)$$

$$u^\mu = i(u^\dagger \partial^\mu u - u \partial^\mu u^\dagger)$$

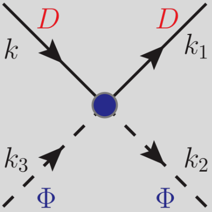
$$u = \exp\left[\frac{i}{\sqrt{2}F}\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix}\right]$$

Perturbative potential

Perturbative amplitude

$$
\begin{aligned}
V(s,t,u) &= \frac{C_0}{4f_\pi^2}(s-u) + \frac{2C_1}{f_\pi^2}h_1 + \frac{2C_2}{f_\pi^2}h_3(k_2\cdot k_3) \\
&+ \frac{2C_3}{f_\pi^2}h_5[(k\cdot k_3)(k_1\cdot k_2)+(k\cdot k_2)(k_1\cdot k_3)]
\end{aligned}
$$

f_π: pion decay constant
Isospin coefficients: fixed by symmetry
Low-energy constants: fixed by experiment
or by underlying theory
Z.-H. Guo *et al.* Eur. Phys. J.C79, 1, 13 (2019)



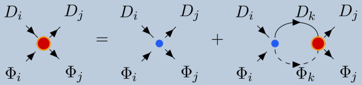
Elastic processes:
$D\pi$, DK, $D\bar{K}$, $D\eta$
$D_s\pi$, D_sK, $D_s\bar{K}$, $D_s\eta$ and their inelastic channels.

Unitarization

We impose **exact unitarity** to the scattering matrix amplitudes

Bethe-Salpeter equation

$$T(s) = V(s) + \int VGT \;\; (s)$$



"On-shell factorization" approximation

J.A.Oller, E. Oset, NPA620 (1997) 438; L. Roca, E. Oset, J. Singh, PRD72 (2005) 014002

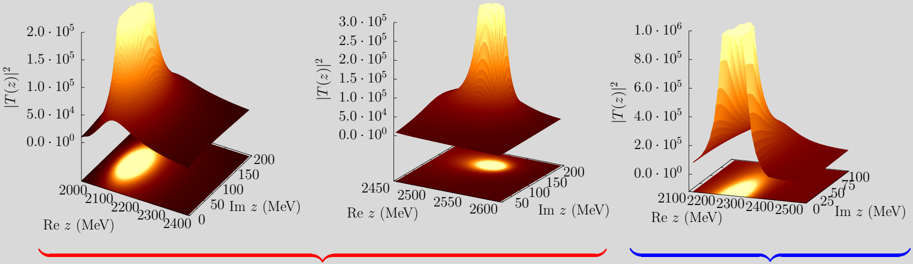
Scattering (T-matrix) amplitude

$$T(s) = \frac{V(s)}{1 - G(s)V(s)} \; ; \qquad G(s) = i \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_D^2 + i\epsilon} \frac{1}{(p-k)^2 - m_\Phi^2 + i\epsilon}$$

Interpretation of poles

Resonances and Bound states are poles in the complex energy plane

$$m_R = \mathrm{Re}\ z_R\ , \qquad \Gamma_R = 2\mathrm{Im}\ z_R \qquad\qquad (z = \sqrt{s} \in \mathbb{C})$$



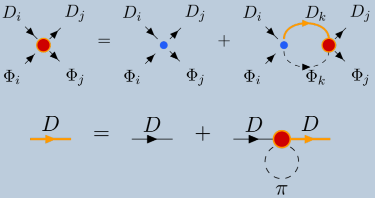
$D_0^*(2300)$ $\qquad$ $D_{s0}^*(2317)$

Double pole structure of $D_0^*(2300)$ (also $D_1^*(2430)$ in $J = 1$)

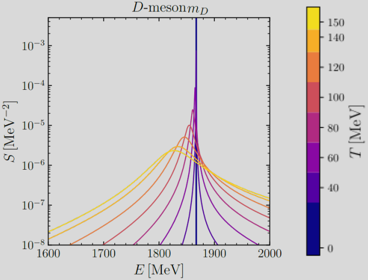
M. Albadalejo *et al.* Phys.Lett.B 767 (2017) 465 ; Z.-H. Guo *et al.* Eur.Phys.J.C79 (2019)13;
U. Meissner, Symmetry 12 (2020) 6, 981 talk by M. Albadalejo

Self-consistency at finite temperature

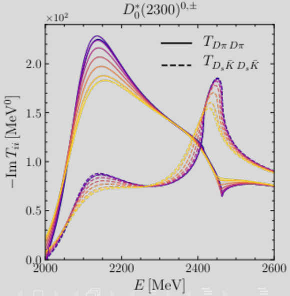
T-matrix equation in Imaginary Time Formalism



Spectral function



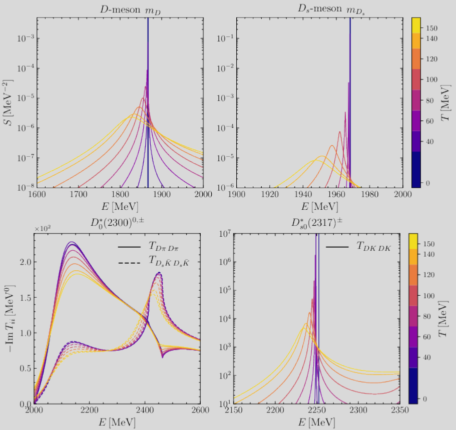
T-matrix elements



G. Montaña, À. Ramos, L. Tolos, JMT-R, PLB 806 (2020) 135464

G. Montaña, À. Ramos, L. Tolos, JMT-R, PRD 102 (2020) 9, 096020

Spectral functions

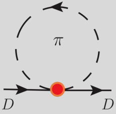


$$S_D(E,\boldsymbol{q}) = -\frac{1}{\pi}\mathrm{Im}\left(\frac{1}{E^2-\boldsymbol{q}^2-m^2-\Pi_D(E,\boldsymbol{q})}\right)$$

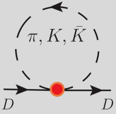
$$-\mathrm{Im}\, T_{ii}(E,\boldsymbol{q}) = -\mathrm{Im}\left(\frac{V(E,\boldsymbol{q})}{1-G(E,\boldsymbol{q})V(E,\boldsymbol{q})}\right)$$

G. Montaña *et al.* (JMT-R), Phys.Lett.B 806 (2020) 135464, Phys.Rev.D 102 (2020) 9, 096020

Ground and bound states acquire a thermal width at finite temperature solid line:



dashed line:



G. Montaña *et al.* (JMT-R),
Phys.Lett.B 806 (2020) 135464,
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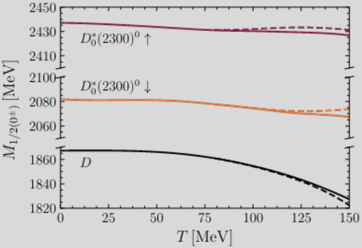
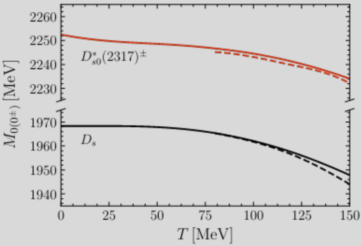
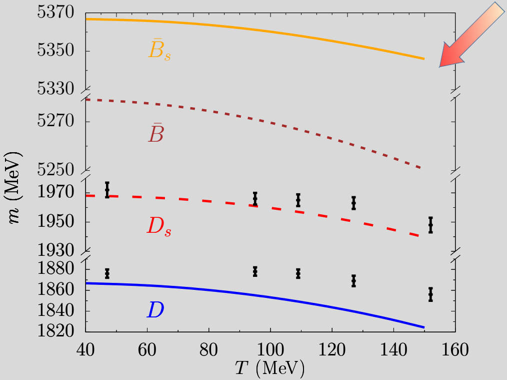




No evidence of chiral partner degeneracy due to chiral symmetry restoration (JMT-R, Symmetry 13 (2021) 1400)

G. Montaña *et al.* (JMT-R),
Phys.Lett.B 806 (2020) 135464,
Phys.Rev.D 102 (2020) 9, 096020

B-meson results to be published,
see G. Montaña's PhD thesis
2207.10752 [hep-ph]



see also talk by Liping He

Lattice-QCD data:
G. Aarts *et al.*, 2209.14681
$m_\pi = 239(1)$ MeV

Fokker-Planck equation

Many-body EFT in real time formalism: **Kadanoff-Baym** approach

- L. Kadanoff, G. Baym, “Quantum statistical mechanics” (1962)
- P. Danielewicz, Annals Phys. 152, 239 (1984)
- W. Botermans and R. Malfliet, Phys. Rept. 198, 115 (1990)
- J.-P. Blaizot and E. Iancu, Nucl. Phys. B557, 183 (1999)
- J. Rammer ”Quantum field theory of non-equilibrium states” (2007)
- W. Cassing, Eur. Phys. J.168, 3 (2009)

Fokker-Planck equation

Many-body EFT in real time formalism: **Kadanoff-Baym** approach

Off-shell Fokker-Planck equation

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

where $\Delta^{ij} = \delta^{ij} - k^i k^j / \boldsymbol{k}^2$

JMT-R, G. Montaña, À. Ramos, L. Tolos, Phys.Rev.C 105, 025203 (2022)

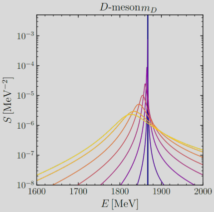
$$\text{Wigner function: } iG_D^<(t,k) = 2\pi S_D(t,k^0,\boldsymbol{k}) f_D(t,k^0)$$

Off-shell Transport Coefficients

$$\begin{cases} \hat{A}(k^0,\mathbf{k};T) \equiv \left\langle 1 - \frac{\boldsymbol{k}\cdot\boldsymbol{k}_1}{\boldsymbol{k}^2}\right\rangle & \text{drag force} \\ \hat{B}_0(k^0,\mathbf{k};T) \equiv \frac{1}{4}\left\langle \boldsymbol{k}_1^2 - \frac{(\boldsymbol{k}\cdot\boldsymbol{k}_1)^2}{\boldsymbol{k}^2}\right\rangle & \text{transverse diffusion coeff.} \\ \hat{B}_1(k^0,\mathbf{k};T) \equiv \frac{1}{2}\left\langle \frac{[\boldsymbol{k}\cdot(\boldsymbol{k}-\boldsymbol{k}_1)]^2}{\boldsymbol{k}^2}\right\rangle & \text{longitudinal diffusion coeff.} \end{cases}$$

Off-shell and thermal effects

Spectral function

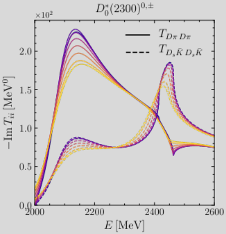


Energy-momentum conservation

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

$$\times \, \delta(k^0 + \lambda' E_3 - \lambda E_2 - k_1^0) |T(k^0 + \lambda' E_3, \boldsymbol{k} + \boldsymbol{k}_3)|^2 f^{(0)}(\lambda' E_3) \tilde{f}^{(0)}(\lambda E_2) f^{(0)}(k_1^0) \, \mathcal{F}(\boldsymbol{k}, \boldsymbol{k}_1)$$

Interaction

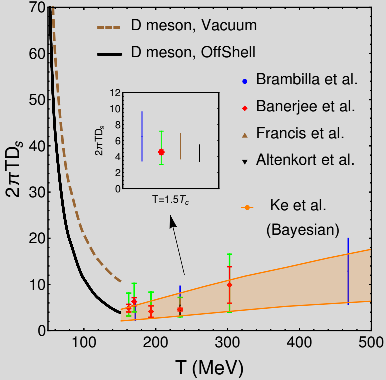


Equilibrium distribution functions

Spatial diffusion coefficient

Spatial diffusion coefficient

$$2\pi T \boldsymbol{D_s}(T) = \frac{2\pi T^3}{B_0(k^0 = E_k, \boldsymbol{k} \to 0; T)}$$



JMT-R, G. Montaña, À. Ramos, L. Tolos, Phys.Rev.C 105, 025203 (2022)

Lattice-QCD calculations

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

Bayesian study of RHICs

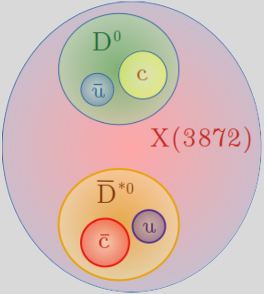
- W. Ke *et al.* Phys. Rev. C98, 064901 (2018)

Exotic hadrons as molecular states

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

$X(3872)$ $\quad I^G(J^{PC}) = 0^+(1^{++})$

$X(3872)/X(4014)$ taken as s-wave bound state of $D^{(*)}$ and $\bar{D}^*$.



Alternative scenarios (tetraquark, admixture..):

F.K.Guo *et al.* Rev.Mod.Phys.90 (2018) 015004
N.Brambilla *et al.* Phys.Rep.873 (2020) 1
Y.R.Liu *et al.* Prog.Part.Nucl.Phys.107 (2019) 237)

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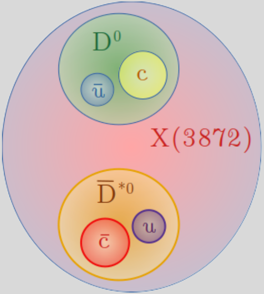

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Y.R.Liu *et al.* Prog.Part.Nucl.Phys.107 (2019) 237)

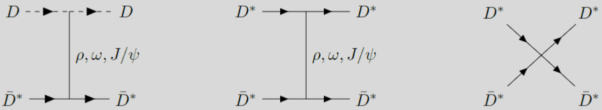
Local hidden-gauge Lagrangian

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

V_μ: SU(4) vector fields
Γ_μ: connection incorporating SU(4) pseudosc. fields

Talk by R. Molina

Generation of $X(3872)$ and $X(4014)$

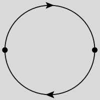


Talk by R. Molina

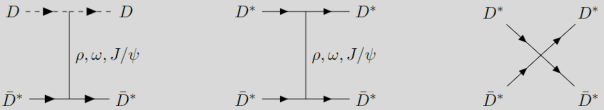
R. Molina, E. Oset PRD80(2009)114013, R. Molina, T.Branz and E. Oset, PRD82 (2010) 014010; R. Molina *et al.* PRD80 (2009) 014025

$\mathcal{T}$-matrix equation

$\mathcal{T} = V + VG\mathcal{T}$ for $J^{PC} = 1^{++}$ and $J^{PC} = 2^{++}$

$G(\sqrt{s}) =$ 

Generation of $X(3872)$ and $X(4014)$



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R. Molina, E. Oset PRD80(2009)114013, R. Molina, T.Branz and E. Oset, PRD82 (2010) 014010; R. Molina *et al.* PRD80 (2009) 014025

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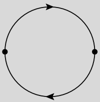
$G(\sqrt{s}) =$ 

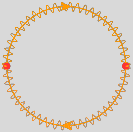
	Λ (MeV)	State	Nearest threshold (MeV)	$\sqrt{z_p}$ (MeV)	Couplings (GeV)	
$J = 1$	567	$X(3872)$	$m_D + m_{\bar{D}^*} = 3875.80$	$3871.65 + i\,0.00$	$\lvert g_{D\bar{D}^*}\rvert = 9.23$	$\lvert g_{D_s\bar{D}_s^*}\rvert = 3.98$
$J = 2$	510	$X(4014)$	$m_{D^*} + m_{\bar{D}^*} = 4017.11$	$4014.31 + i\,0.00$	$\lvert g_{D^*\bar{D}^*}\rvert = 8.56$	$\lvert g_{D_s^*\bar{D}_s^*}\rvert = 3.69$

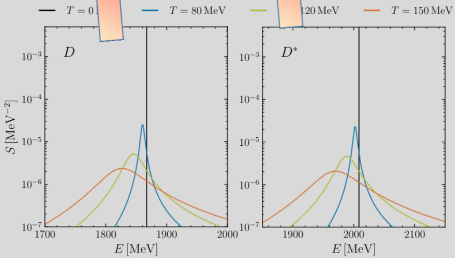
G. Montaña, À. Ramos, L. Tolos and JMT-R, Phys. Rev. D 107, 054014 (2023)

$\mathcal{T}$-matrix equation at finite temperature

$$\mathcal{T} = V + VG\mathcal{T}$$

$$G(E,\vec{P};T) = \int \frac{d^3q}{(2\pi)^3} \int d\omega \int d\omega' \, \frac{S_1(\omega,\vec{q};T) S_2(\omega',\vec{P}-\vec{q};T)}{E-\omega-\omega'+i\varepsilon} \left[1 + f(\omega,T) + f(\omega',T)\right]$$

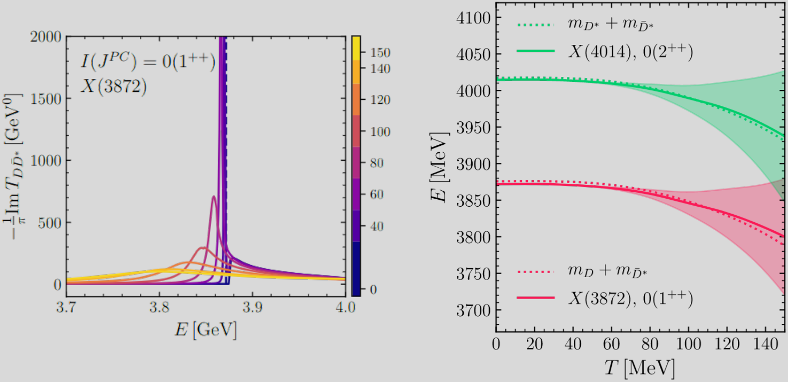




D-meson medium effects included in the thermal loop function

Thermal masses of $X(3872)$ and $X(4014)$

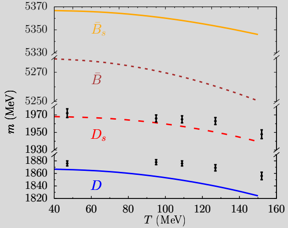
G. Montaña, À. Ramos, L. Tolos and JMT-R, Phys. Rev. D 107, 054014 (2023)

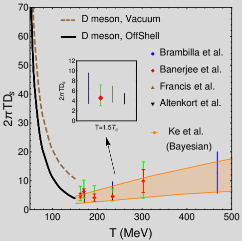


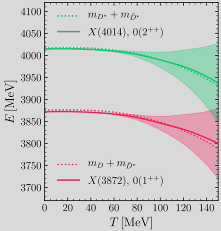
Xs melt down with temperature. Mott temperature around $T = 110$ MeV.
Modified thermal production at freeze-out in RHICs?

Summary

- D-meson **EFT** extended to **finite temperature** in a self-consistent approach. Mass reduction and thermal broadening of ground states.
- Heavy-meson **kinetic theory** studied via the Kadanoff-Baym equations. We derived an **off-shell Fokker-Planck** equation.
- $X(3872)$ and $X(4014)$ generated as **bound states** of $D^{(*)}$ and $\bar{D}^*$ mesons at $T = 0$.
- At $T \neq 0$ these states present a **thermal width** which increases moderately for $T > 110$ MeV. Their **thermal mass** is also reduced.







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Deutsche Forschungsgemeinschaft

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Hadron Spectroscopy and Structure
Genova, Italy, 7 June 2023

HADRON 2023