Chiral symmetry restoration with three chiral partners

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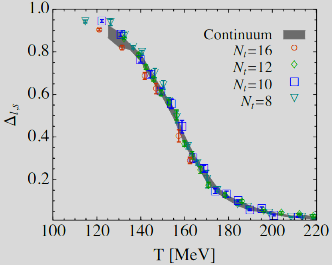
(Goethe University Frankfurt)

XXXIII International (ONLINE) Workshop on High Energy Physics
Logunov Institute for High Energy Physics (Protvino, Russia)
Nov. 12, 2021

Outline

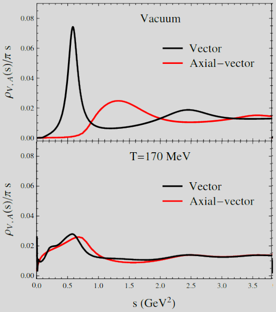
- Introduction: Thermal restoration of chiral symmetry
- **Two chiral partners:** Nambu–Jona-Lasinio model
- **Three chiral companions:** Covariant chiral EFT
- Conclusions

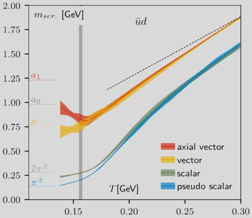
Borsanyi *et al.*, JHEP (2010) 1009:073



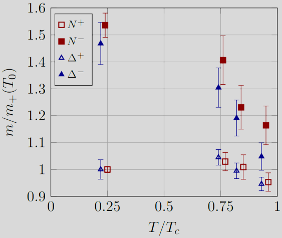
$$\Delta_{l,s} = \frac{\langle\bar{\psi}_l\psi_l\rangle(T) - m_l/m_s\langle\bar{\psi}_s\psi_s\rangle(T)}{\langle\bar{\psi}_l\psi_l\rangle(0) - m_l/m_s\langle\bar{\psi}_s\psi_s\rangle(0)}$$

Hohler, Rapp, PLB 731 (2014) 103





Bazavov *et al.*,
PRD 100 (2019) 094510



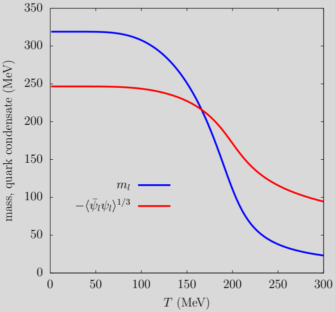
Aarts *et al.*, JHEP 06 (2017) 034

Nambu–Jona-Lasinio model

Effective Lagrangian

$$\mathcal{L}_{NJL} = \sum_{l=u,d} \bar{\psi}_l (i\not{D} - m_{0l})\psi_l$$
$$+ \mathcal{G} \sum_a \sum_{ijkl} \left[(\bar{\psi}_i \, i\gamma_5 \tau^a_{ij} \psi_j) \, (\bar{\psi}_k \, i\gamma_5 \tau^a_{kl} \psi_l) + (\bar{\psi}_i \mathbb{I} \tau^a_{ij} \psi_j) \, (\bar{\psi}_k \mathbb{I} \tau^a_{kl} \psi_l) \right]$$

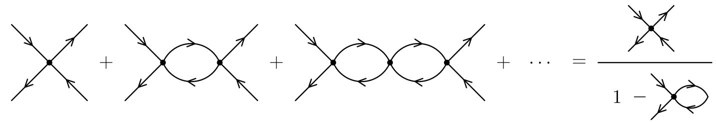
- Incorporates spontaneous chiral symmetry breaking and thermal restoration
- Local interaction with coupling $\mathcal{G}$
- Vertices in the scalar ($\mathbb{I}$) and pseudoscalar ($i\gamma_5$) channels
- No mesons as fundamental degrees of freedom!



$\bar{q}q$ scattering

$\mathcal{G}$ is used in a Bethe-Salpeter approach

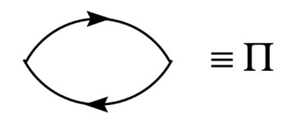
$$\mathcal{T}(p) = \mathcal{G} + \mathcal{G}\,\Pi(p)\,\mathcal{T}(p)$$



Scattering amplitude

$$\mathcal{T}(p) = \frac{\mathcal{G}}{1 - \mathcal{G}\,\Pi(p)}$$

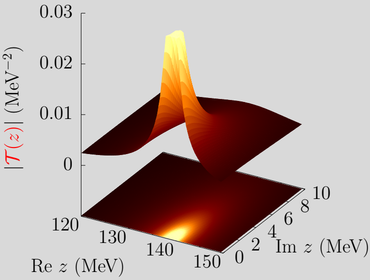
Polarization function at finite temperature T



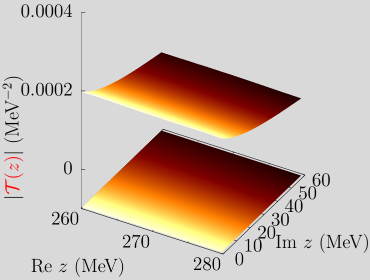
Generated mesons

$J^\pi = 0^-$

$T = 25$ MeV, 1st RS



$T = 250$ MeV, 1st RS



Parameter set: Blaschke *et al.* Annals Phys. 348 (2014) 228

- Usual extraction of meson masses based on quasiparticle approximation, or neglecting imaginary part of resonance
- However...no pole in 1st Riemann Surface above Mott temperature!

Generated mesons

$$J^\pi = 0^-$$

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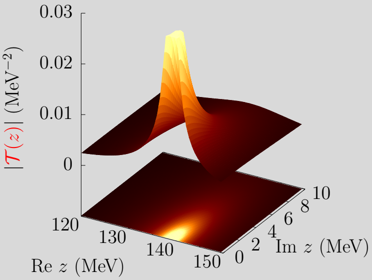
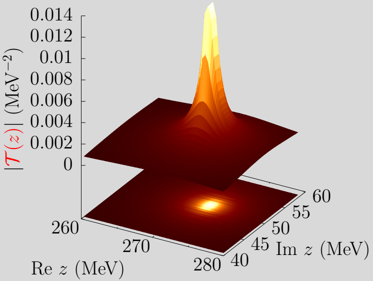


$T = 250$ MeV, 2nd RS

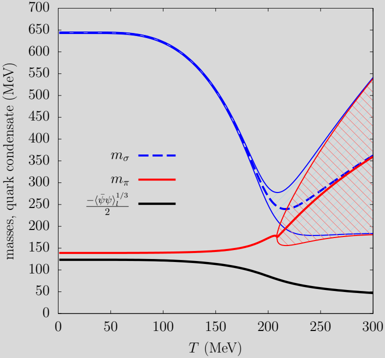


Parameter set: Blaschke *et al.* Annals Phys. 348 (2014) 228

Analytic continuation above Mott temperature

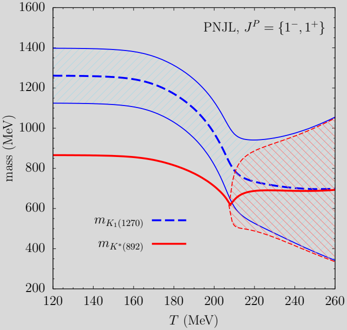
$$\Pi^{II}(z, \mathbf{p}, T) = \Pi^{I}(z, \mathbf{p}, T) - 2i\, \mathrm{Im}\Pi^{I}(z, \mathbf{p}; T) \qquad \mathrm{Re}\, z > 2m_q(T)$$

Chiral partners and symmetry restoration



← Masses and decay widths become degenerate at $T > T_c$

Another example:
$SU_f(3)$ Polyakov–NJL model →
JT-R, Symmetry 2021, 13(8), 1400



Nature of chiral companions

Different models formulated with chiral partners of different nature:
(JT-R, Symmetry 2021, 13(8), 1400)

$J^\pi = 0^+$ / $J^\pi = 0^-$	Fundamental d.o.f.	Dynamical d.o.f.
Fundamental d.o.f.	**Linear σ model** -Coleman, Jackiw, Politzer, PRD (1974), 10, 2491 -Bochkarev, Kapusta, PRD (1996), 54, 4066 -Dobado, Llanes-Estrada, JT-R, PRD (2009), 80, 114015 **Quark-meson model** -Jungnickel, Wetterich, PRD (1996) 53, 5142 -Scavenius *et al.*, PRC (2001) 64,045202 -Tripolt *et al.*, PRD (2014) 89, 034010	**Chiral perturbation theory** -Schenk, PRD (1993), 47, 5138 -Toublan, PRD (1997) 56, 5629 -Dobado *et al.*, PRC (2002), 66, 055201 -Gomez-Nicola *et al.* AIP Conf. Proc. 2003, 660, 156
Dynamical d.o.f.	**-**	**(Polyakov-)NJL model** -Vogl, Weise, Prog. Part. Nucl. Phys. (1991) 27, 195 -Klevansky, Rev. Mod. Phys. (1992) 64, 649 -Ratti, Thaler, Weise, PRD (2006), 73, 014019 -JT-R, Sintes, Aichelin, PRC (2015) 91, 065206

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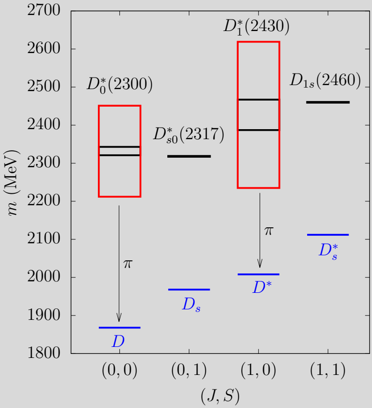
More possibilities?

D-meson spectrum



Zyla *et al.* (Particle Data Group),
Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Chiral partners

$$D \leftrightarrow D_0^*(2300)$$
$$D_s \leftrightarrow D_{s0}^*(2317)$$

(Bardeen, Eichten, Hill,
PRD 68 (2003) 054024)

- Heavy-quark spin symmetry between $J = 0 \leftrightarrow J = 1$
- Heavy-quark flavor symmetry between $D \leftrightarrow \bar{B}$

Temperature dependence?

Covariant Chiral EFT

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

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

Kolomeitsev, Lutz, PLB582 (2004) 39

Hofmann, Lutz, Nucl.Phys. A733 (2004) 142

Guo *et al.*, PLB641 (2006) 278

Lutz, Soyeur, Nucl.Phys. A813 (2008) 14

Guo, Hanhart, Krewald, Meißner, PLB666 (2008) 251

Guo, Hanhart, Meißner, EPJA40 (2009) 171

Geng, Kaiser, Martin-Camalich, Weise PRD82 (2010) 05422

Abreu, Cabrera, Llanes-Estrada, JT-R, Annals Phys. 326 (2011) 2737

Perturbative potential

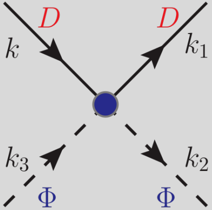
Tree-level amplitudes at LO

Perturbative amplitudes

▸ full tree level

$$V(k, k_3, k_1, k_2) = \frac{C_0}{4 f_\pi^2} [(k + k_3)^2 - (k - k_2)^2]$$

f_π: pion decay constant
C_0: isospin coefficients



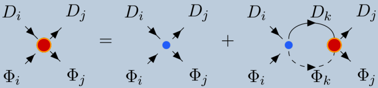
All elastic and inelastic channels calculated:
$D\pi, DK, D\bar{K}, D\eta$
$D_s\pi, D_sK, D_s\bar{K}, D_s\eta$

Unitarization

Impose **exact unitarity**, lost upon truncation of the EFT

Bethe-Salpeter equation

$$\mathcal{T}(s) = V(s) + \int V G_2 \, \mathcal{T} \; (s)$$



On-shell factorization method

Oller, Oset, NPA620 (1997) 438; Roca, Oset, Singh, PRD72 (2005) 014002

Unitarized scattering amplitude

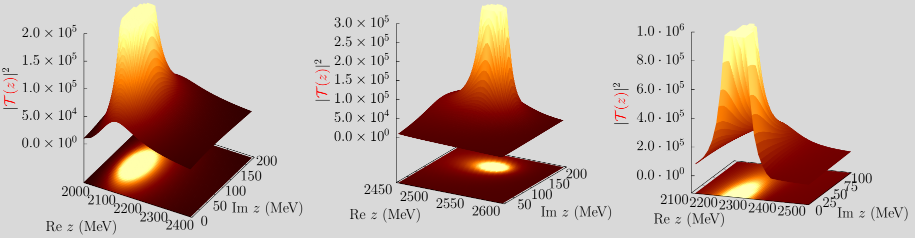
$$\mathcal{T}(s) = \frac{V(s)}{1 - G_2(s) V(s)}$$

Resonances and bound states

Poles

Resonances and Bound states: poles in the complex energy plane

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



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

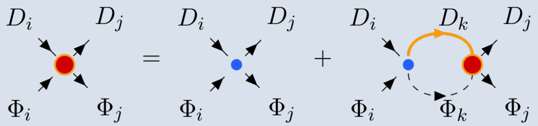
Double pole structure of $D_0^*(2300)$

Albadalejo *et al.* PLB 767 (2017) 465, Guo *et al.* EPJC79 (2019)13, Meißner, Symmetry 12 (2020) 6, 981

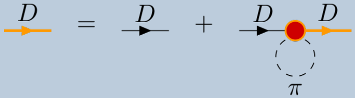
Finite temperature

At $T \neq 0$ we apply **Imaginary Time Formalism**

Bethe-Salpeter equation for $\mathcal{T}$-matrix



Dyson equation for propagator



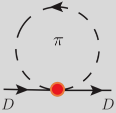
Self-consistency is required at $T \neq 0$

Montaña, Ramos, Tolos, JT-R, PLB 806 (2020) 135464

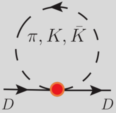
Montaña, Ramos, Tolos, JT-R, PRD102 (2020) 096020

Thermal masses

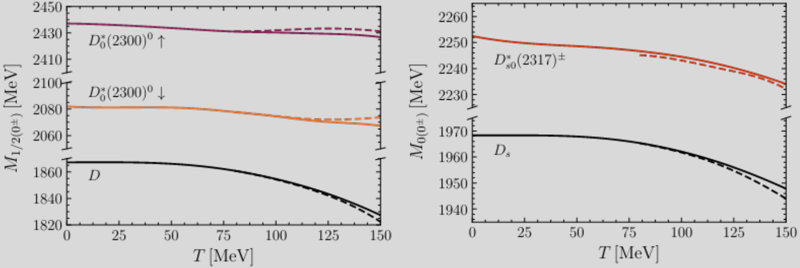
solid line:



dashed line:



Montaña, Ramos, Tolos, JT-R,
PLB 806 (2020) 135464,
PRD 102 (2020) 9, 096020



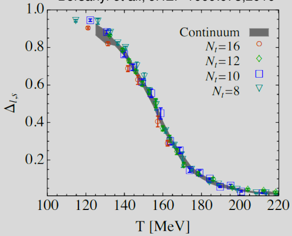
- Tiny variation of masses with temperature: no signatures of mass degeneracy
- Negligible contribution of $K, \bar{K}$ to D-meson self energy

Chiral condensate and f_π

Model doesn't know about chiral transition $\rightarrow$

Light sector drives the system towards chirally-restored phase

Borsanyi *et al.*, JHEP 1009:073,2010



Gell-Mann–Okubo–Renner relation

$$2m_q\langle\bar{\psi}\psi\rangle_l = -f_\pi^2 m_\pi^2$$

Gasser, Leutwyler, PLB (1987) 184, 83

Toublan, PRD (1997) 56, 5629

Pisarski, Tytgat, PRD (1996) 54, R2989

Thermal ChPT at LO (also in LσM)

$$\frac{f_\pi(T)}{f_\pi(0)} = 1 - \frac{T^2}{12 f_\pi^2(0)}$$

Gasser, Leutwyler, PLB (1987) 184, 83

Bochkarev, Kapusta, PRD (1996) 54, 4066

Weise, Nucl. Phys. A (2001) 690, 98

Poles evolution

- Simplified approach(!): $T = 0$ calculation with vacuum masses for ground states
- f_π decreased by hand up to 60% vacuum value (to mimic transition)

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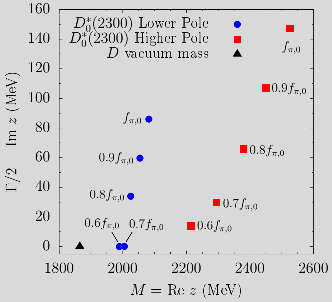
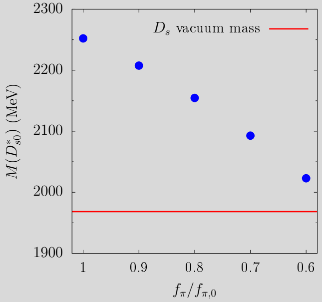


JT-R, Symmetry 2021, 13(8), 1400



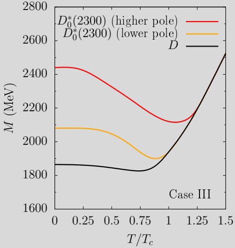
- + thermal decrease of ground states $\rightarrow \Delta M \sim -100$ MeV
- **Sequential Restoration favored**: Lower pole first degenerate with ground state, then higher pole

Conclusions

1. Different EFTs realize chiral symmetry with chiral partners of different nature: **fundamental** vs **dynamically generated states**

2. $D/D_0^*(2300)$ system encompass **three states** whose masses change with temperature

3. Preliminary computation including reduction of $f_\pi(T)$ favors a **sequential degeneracy pattern**



4. Experimental verification? Reconstruction of $D_0^*(2300)$ in different decay channels

$$D_0^*(2300)[\text{lower pole}] \to D\pi$$

$$D_0^*(2300)[\text{higher pole}] \to D_s\bar{K}$$

at RHICs (if partial chiral restoration is achieved at freeze-out temperature).

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Effective Lagrangian at NLO

L.S. Geng, N. Kaiser, J. Martin-Camalich and W. Weise *Phys.Rev.D82,05422 (2010)*

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

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

$$\mathcal{L}_{\text{NLO}} = -h_0 Tr[DD^\dagger] Tr[\chi_+] + h_1 Tr[D\chi_+ D^\dagger] + h_2 Tr[DD^\dagger] Tr[u^\mu u_\mu] + h_3 Tr[D u^\mu u_\mu D^\dagger]$$

$$+h_4 Tr[\nabla_\mu D \nabla_\nu D^\dagger] Tr[u^\mu u^\nu] + h_5 Tr[\nabla_\mu D\{u^\mu, u^\nu\}\nabla_\nu D^\dagger] \ + \ \{D \to D^\mu\}$$

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

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

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

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

Heavy meson—light meson interaction

Tree-level amplitudes to lowest-order in m_D^{-1} expansion

Perturbative amplitude

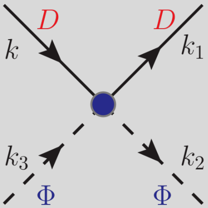
$$
\begin{aligned}
V(s,t,u) &= \frac{C_0}{4f_\pi^2}(s-u) + \frac{2C_1}{f_\pi^2}h_1 + \frac{2C_2}{f_\pi^2}h_3(k_2\cdot k_3) \\
&+ \frac{2C_3}{f_\pi^2}h_5[(k\cdot k_3)(k_1\cdot k_2) + (k\cdot k_2)(k_1\cdot k_3)]
\end{aligned}
$$

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)



Amplitude accounts for elastic scatterings:

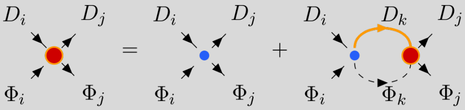
$D\pi$, DK, $D\bar{K}$, $D\eta$

$D_s\pi$, D_sK, $D_s\bar{K}$, $D_s\eta$ and their inelastic channels

back

Finite temperature

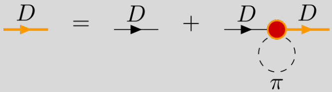
At $T \neq 0$ we use the **Imaginary Time Formalism**
(energies become Matsubara frequencies, $q^0 \to \omega_n = i2\pi Tn$)



$$T_{ij} = [1 - G_{D\Phi} V]^{-1}_{ik} V_{kj}$$

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

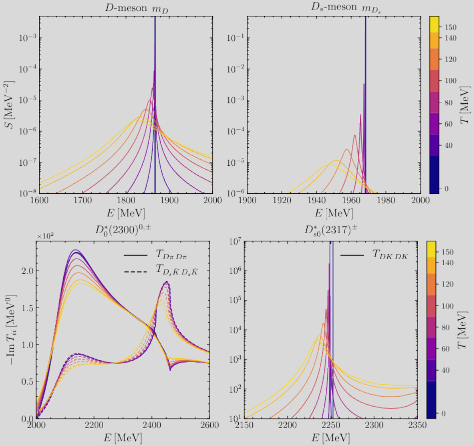
$$S_D(\omega, \vec{k}; T) = -\frac{1}{\pi} \mathrm{Im}\, \mathcal{D}_D(\omega, \vec{k}; T) = -\frac{1}{\pi} \mathrm{Im} \left(\frac{1}{\omega^2 - \vec{k}^2 - m_D^2 - \Pi_D(\omega, \vec{k}; T)} \right)$$



Self-consistency is required at $T \neq 0$

$$\Pi_D(\omega_n, \vec{k}; T) = T \int \frac{d^3p}{(2\pi)^3} \sum_m \mathcal{D}_\pi(\omega_m - \omega_n, \vec{p} - \vec{k}) T_{D\pi}(\omega_m, \vec{p})$$

Spectral functions



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

quasiparticle peak

$$E_q^2 - \mathbf{q}^2 - m^2 - \mathrm{Re}\,\Pi^R(E_q,\mathbf{q}) = 0$$

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

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

Ground and bound states reduce their mass and acquire a width.
Resonant states remain stable with temperature.

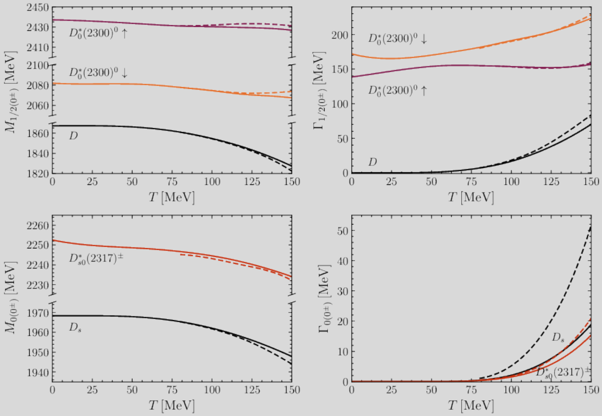
▸ back

Thermal masses and widths

Chiral parity partners

$D(1867)$
$\leftrightarrow$
$D_0^*(2300)$

$D_s(1968)$
$\leftrightarrow$
$D_{s0}^*(2317)$



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

No evidence of chiral partner degeneracy due to chiral symmetry restoration