Heavy mesons at finite temperature

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Based on work with A. Ramos, L. Tolos, J. Torres-Rincon, V. Montesinos

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UNIVERSITAT DE BARCELONA

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EXCELENCIA MARÍA DE MAEZTU 04/2025-03/2031

beatriu de pinós

Outline

- Hadronic effective field theories
- Thermal EFT for heavy mesons
- Open heavy-flavor mesons: Thermal properties
- $X(3872)$ & $T_{cc}(3875)$
- Transport coefficients
- Summary

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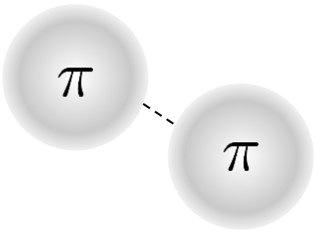
The chiral unitary approach

Dobado, Herrero, Truong (1990)
Oller, Oset, Peláez (1997-1999)



χPT + exact two-body unitarity = UχPT

- Describes non-perturbative interactions between Goldstone bosons
- Extends the range of applicability of the ChPT Lagrangian to higher energies

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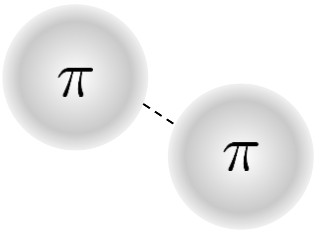
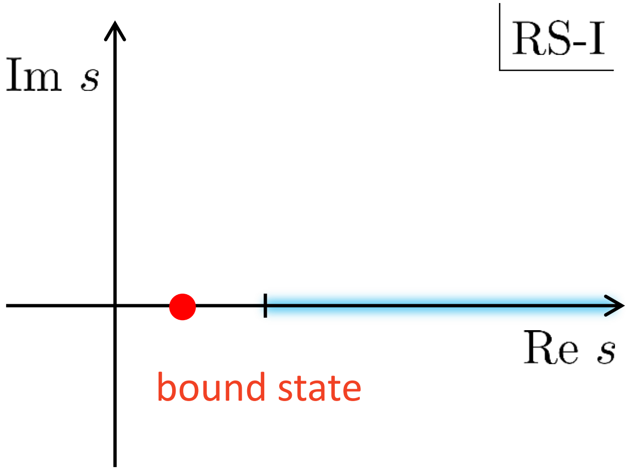
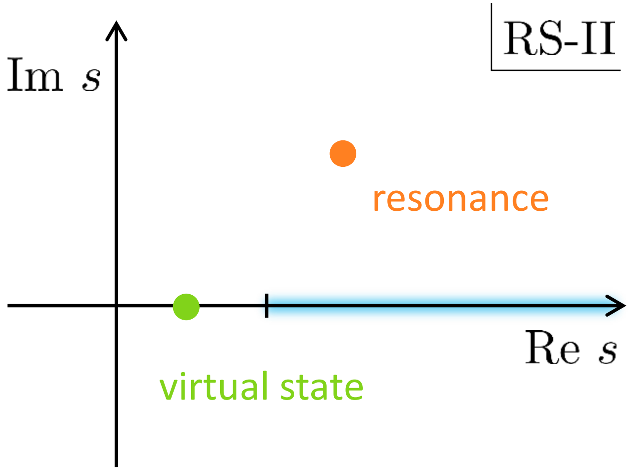
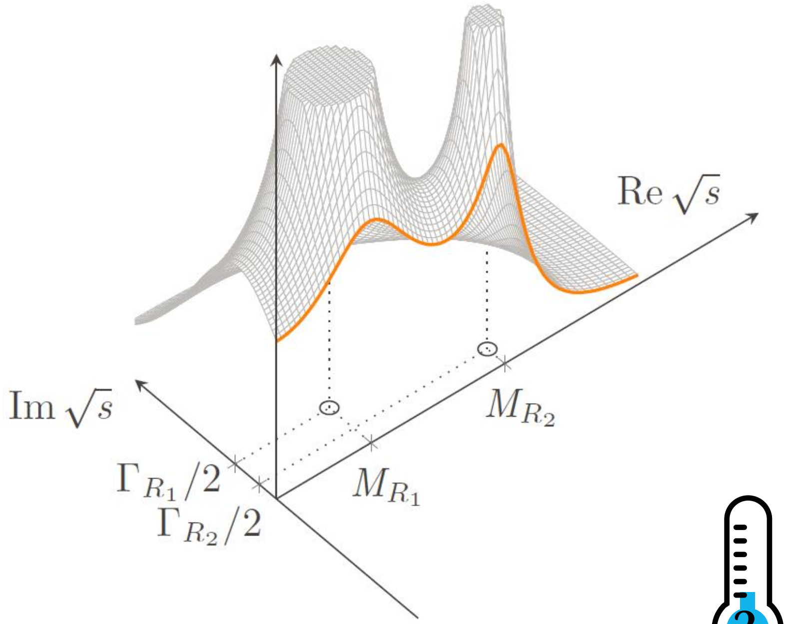


- Describes non-perturbative interactions between Goldstone bosons
- Extends the range of applicability of the ChPT Lagrangian to higher energies
- Gives rise to poles of the scattering amplitude ("dynamically generated" states ⊳ hadronic molecules)





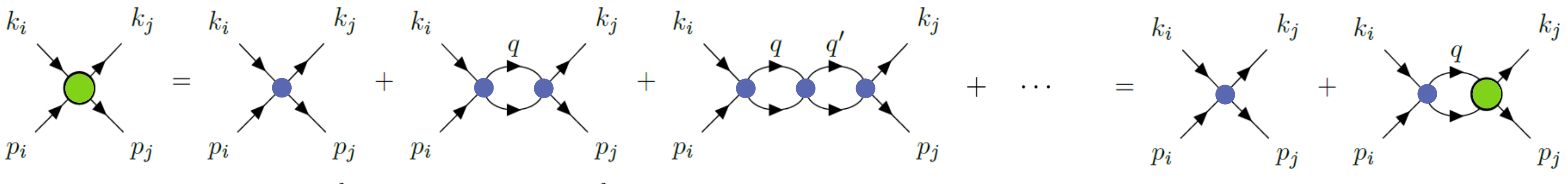


The chiral unitary approach

Bethe-Salpeter equation in coupled channels

Salpeter, Bethe (1951)

$$T_{ij}(k_i,k_j;P) = V_{ij}(k_i,k_j;P) + i\sum_l \int \frac{d^4q}{(2\pi)^4} V_{il}(k_i,q;P) \frac{1}{q^2 - m_{l,1}^2 + \mathrm{i}\,\varepsilon} \frac{1}{(P-q)^2 - m_{l,2}^2 + \mathrm{i}\,\varepsilon} T_{lj}(q,k_j;P)$$



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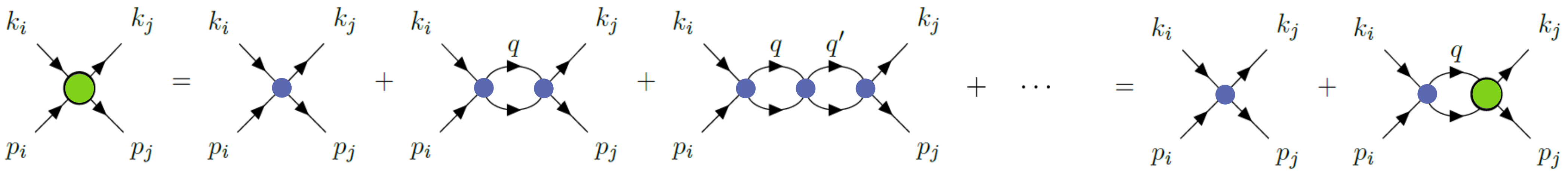


On-shell approximation (s-wave): $T = V + VGT$ Oller, Ramos (1997)

$$G_l(s) = \mathrm{i}\int \frac{d^4q}{(2\pi)^4}\frac{1}{q^2-m_{l,1}^2+\mathrm{i}\,\varepsilon}\frac{1}{(P-q)^2-m_{l,2}^2+\mathrm{i}\,\varepsilon}$$

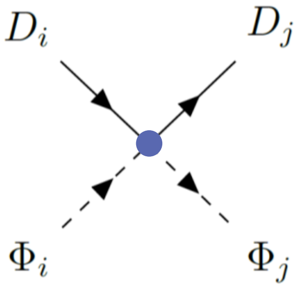
- Hard cut-off ($\Lambda \sim 0.8 \pm 0.2$ GeV in UχPT)
- Dimensional regularization ⊳ subtraction constant $a_l(\mu = 1\ \mathrm{GeV})$

Unitarized EFTs for heavy mesons

Interaction kernel from an appropriate EFT Lagrangian

- Heavy-light mesons + light mesons: heavy meson effective theory (HMET)

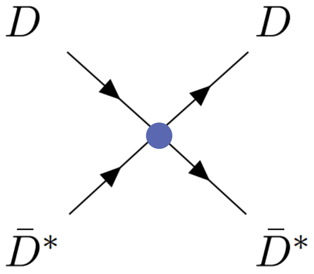
Wise (1992)
Burdman and Donoghue (1992)
Casalbuoni, Deandrea, et al (1997)



⊳ single heavy quark $m_Q \gg \Lambda_{\rm QCD}$
⊳ consistent with chiral and heavy-quark symmetries

$$U = e^{i\frac{\sqrt{2}}{f}\Phi} \qquad \mathcal{H}_a = \frac{1+\not{v}}{2}(H_a^{*\mu}\gamma_\mu - H_a\gamma_5)$$

- Two heavy-light mesons: extended hidden-gauge formalism



⊳ vector mesons V_μ as gauge bosons of a hidden local symmetry

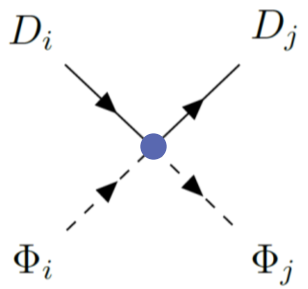
Bando, Kugo et al (1985,1988), Meißner (1988)

⊳ extended to SU(4), conveniently broken

Xiao, Nieves, Oset (2013)

HMET

- Heavy-light mesons + light mesons



▻ Chiral symmetry in the limit $m_u, m_d, m_s \to 0$

▻ Heavy-quark symmetries in the limit $m_c, m_b \to \infty$

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

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HMET

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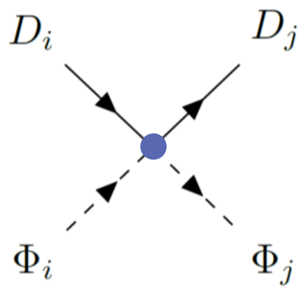

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Lagrangian at NLO in the chiral expansion and LO in $1/m_Q$

Liu, Orginos, Guo, Hanhart and Meißner (2013)
Tolos and Torres-Rincon (2013)

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

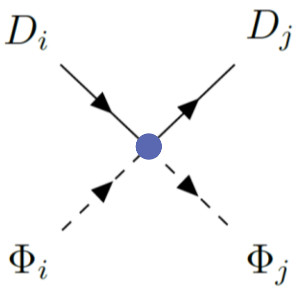
$$\begin{aligned}\mathcal{L}_{\rm LO} &= \mathcal{L}_{\rm LO}^{\chi{\rm PT}} + \langle \nabla^\mu D \nabla_\mu D^\dagger \rangle - m_D^2 \langle D D^\dagger \rangle - \langle \nabla^\mu D^{*\nu} \nabla_\mu D_\nu^{*\dagger} \rangle + m_D^2 \langle D^{*\nu} D_\nu^{*\dagger} \rangle \\ &\quad + {\rm i}\,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

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

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

HMET

- Heavy-light mesons + light mesons



- ▻ Chiral symmetry in the limit $m_u, m_d, m_s \to 0$
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Lagrangian at NLO in the chiral expansion and LO in $1/m_Q$

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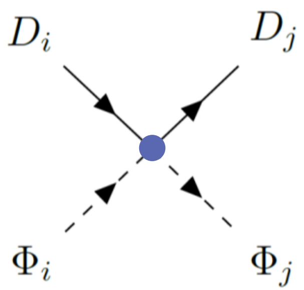
$$\mathcal{L} = \mathcal{L}_{\rm LO} + \mathcal{L}_{\rm NLO}$$

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

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

Unitarized HMET

- Interaction kernel (tree level)



$$V^{ij}(s,t,u) = \frac{1}{f_\pi^2}\Big[\frac{C_{\rm LO}^{ij}}{4}(s-u) - 4C_0^{ij}h_0 + 2C_1^{ij}h_1$$
$$- 2C_{24}^{ij}\Big(2h_2(p_2\cdot p_4) + h_4\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big)$$
$$+ 2C_{35}^{ij}\Big(h_3(p_2\cdot p_4) + h_5\big((p_1\cdot p_2)(p_3\cdot p_4) + (p_1\cdot p_4)(p_2\cdot p_3)\big)\Big)\Big]$$

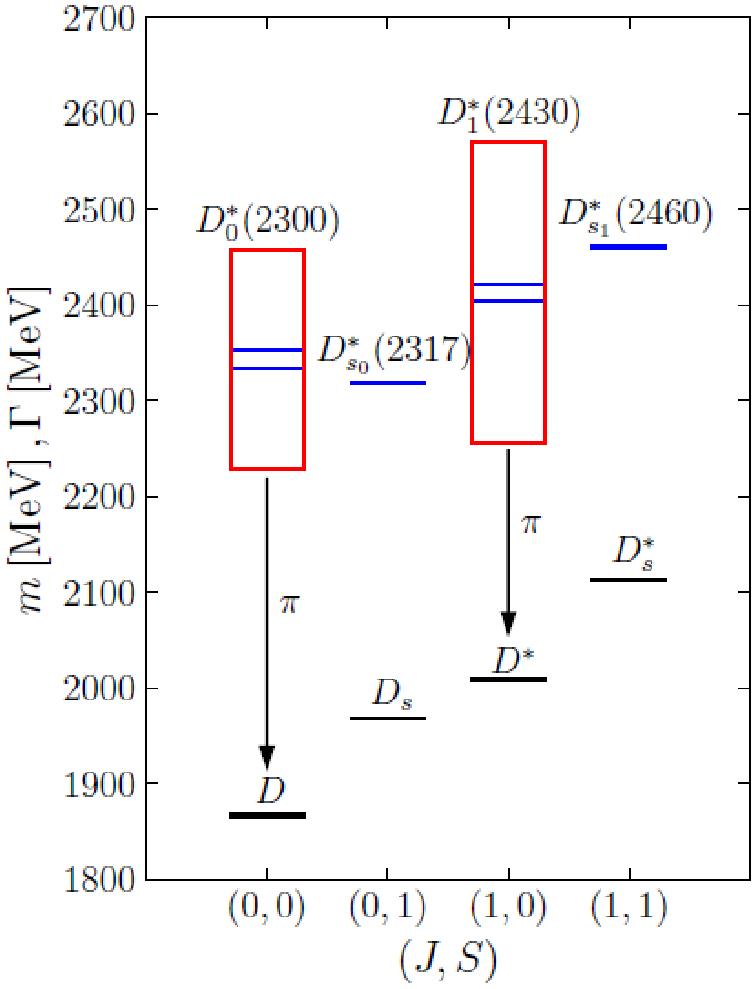
C_k^{ij} isospin coefficients

LECs fitted to lattice QCD data

Guo, Liu, Meißner, Oller and Rusetsky (2019)

- S-wave projection
- Unitarized through the Bethe-Salpeter equation $T = \dfrac{V}{1-VG}$

The charmed meson spectrum



- Similarly to the $X(3872)$ in the charmonium sector, the nature of the $D_{s0}^*(2317)$, discovered in 2003 (and $D_{s1}^*(2460)$ shortly after) has long been debated

BABAR, PRL,90,242001(2003)
CLEO, PRD,68,032002(2003)

  ▻ Puzzles: masses lower than quark-model expectations
  + mass splitting $m_{D_{s1}^*(2460)} - m_{D_{s0}^*(2317)} \approx m_{D^*} - m_D$

  ▻ Plausible DK, D^*K molecules

- Non-strange states $D_0^*(2300)$ and $D_1^*(2430)$

FOCUS, PRB,586,11(2004)
Belle, PRD,69,112002(2004)
BABAR, PRD,79,112004(2009)

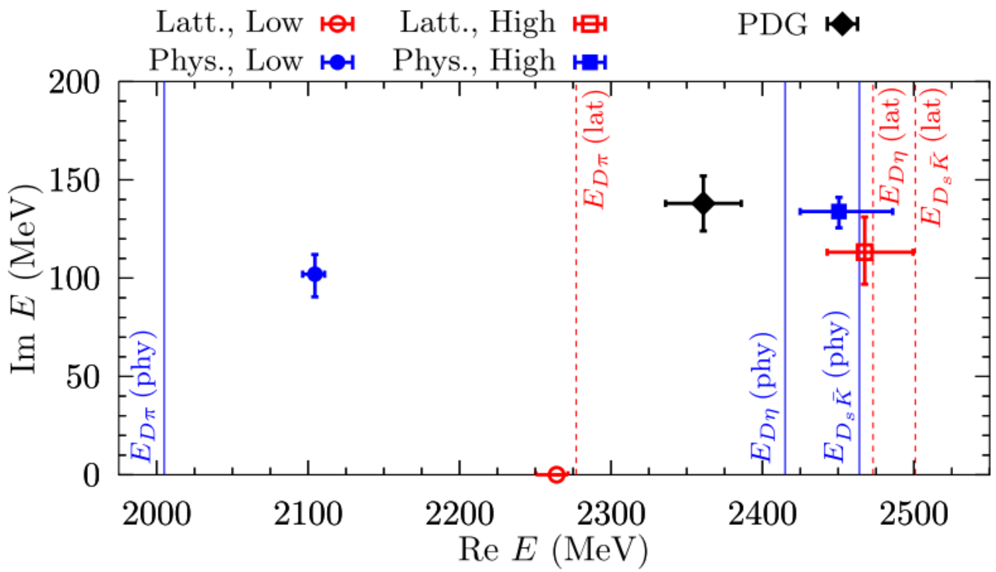
  ▻ Puzzles: mass hierarchy $m_{D_0^*(2300)} > m_{D_{s0}^*(2317)}$
  + large widths and differences in mass between experiments

  ▻ Explained by a two-pole (molecular) structure

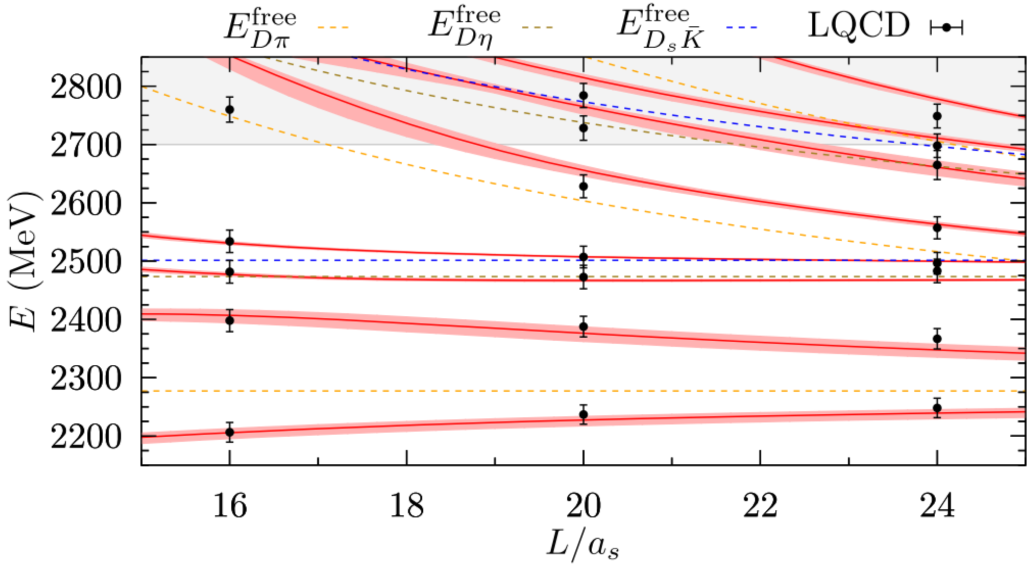
Some results from unitarized HMET

Albaladejo, Fernandez-Soler, Guo, Nieves (2017)

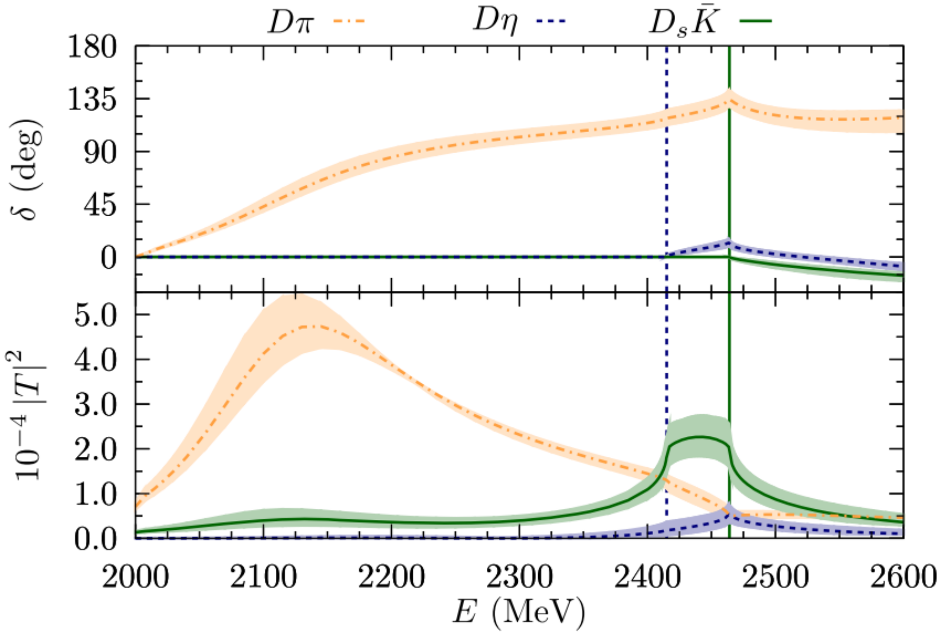
Two-pole structure:



Energy levels compared to lattice QCD data: HADSPEC, JHEP,10,011(2016)



Amplitudes:



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- **Thermal EFT for heavy mesons**
- Open heavy-flavor mesons: Thermal properties
- $X(3872)$ & $T_{cc}(3875)$
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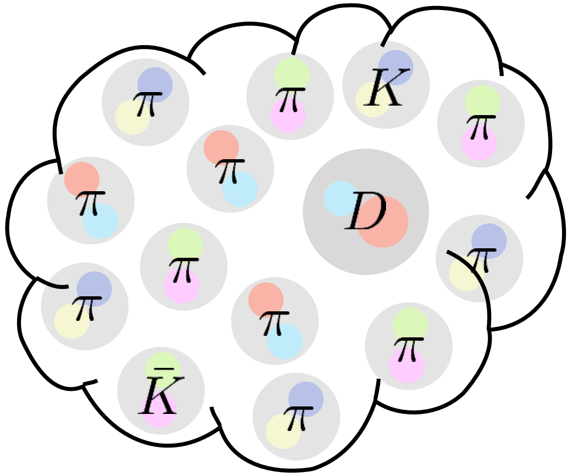
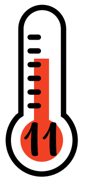
Hot hadronic medium

- 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





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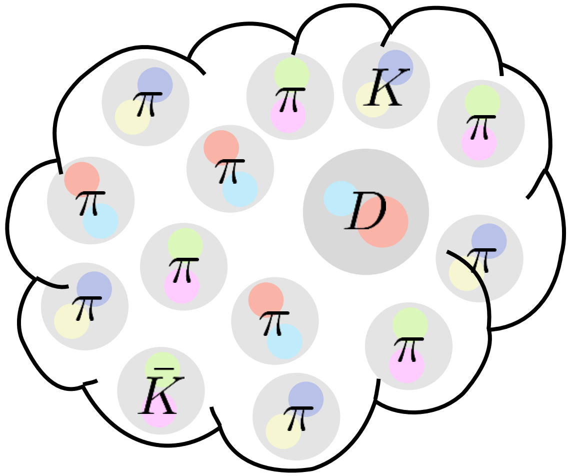

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Thermal hadronic effective theory

Unitarized HMET + thermal quantum field theory

- Thermal scattering amplitudes ⊳ temperature dependence of the dynamically generated states
- Thermal spectral functions ⊳ temperature dependence of the ground states

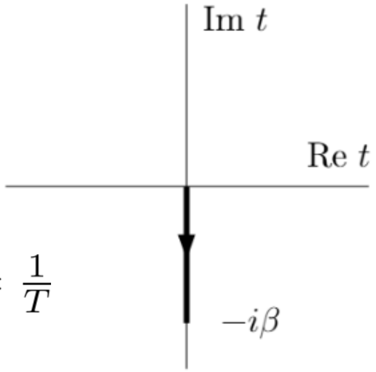
Thermal hadronic EFT

Imaginary time formalism

- Discrete Matsubara frequencies $q^0 \to \mathrm{i}\,\omega_n = \mathrm{i}\,\dfrac{2n\pi}{\beta}$ (bosons)

$$\hookrightarrow \quad \int \frac{d^4q}{(2\pi)^4} \to \frac{1}{\beta} \sum_n \int \frac{d^3q}{(2\pi)^3}$$

$\beta = \frac{1}{T}$



- After summation, thermal processes weighted by Bose-Einstein distribution functions

$$f(\omega, T) = \frac{1}{e^{\omega/T} - 1}$$

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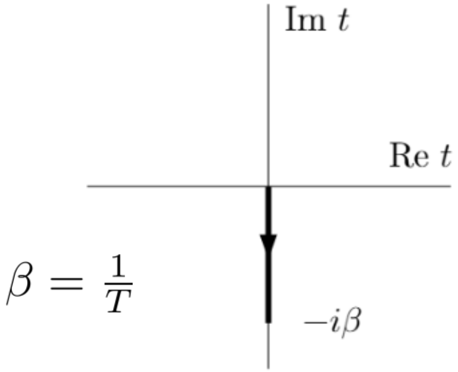

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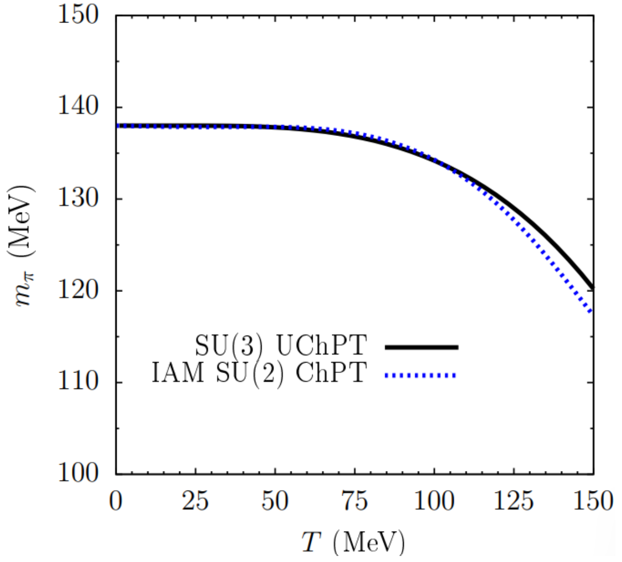
Torres-Rincon, Symmetry 13,1400(2020)



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 hadronic EFT

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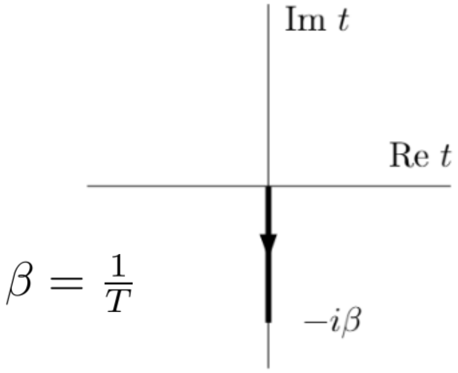

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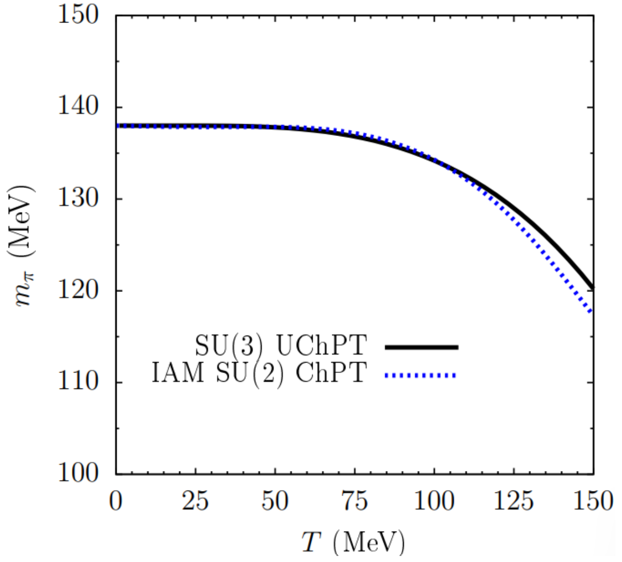
Torres-Rincon, Symmetry 13,1400(2020)



Dressing of the mesons in the loop functions with their spectral functions

- Self-energy corrections to the heavy meson propagator
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→ Approximation: only the heavy meson is dressed

Temperature dependence of the $D\Phi$ interaction potential is ignored

Self-consistent approach

Loop function

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

Self-consistent approach

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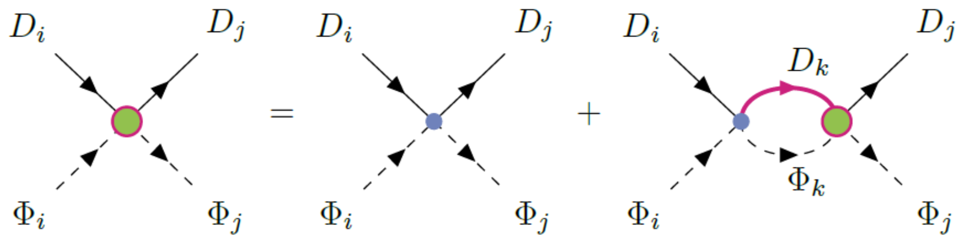
Unitarized amplitude

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



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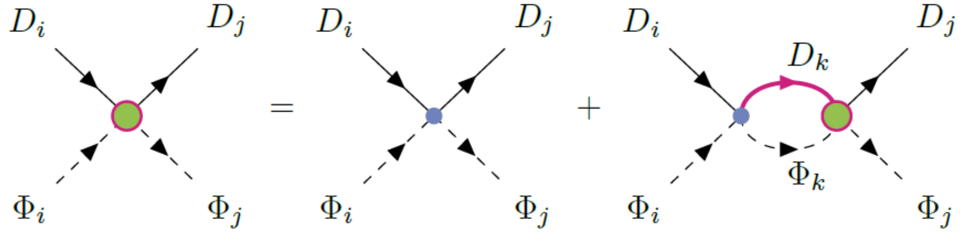
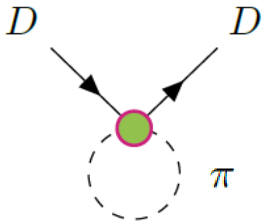


Self-energy

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



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Unitarized amplitude

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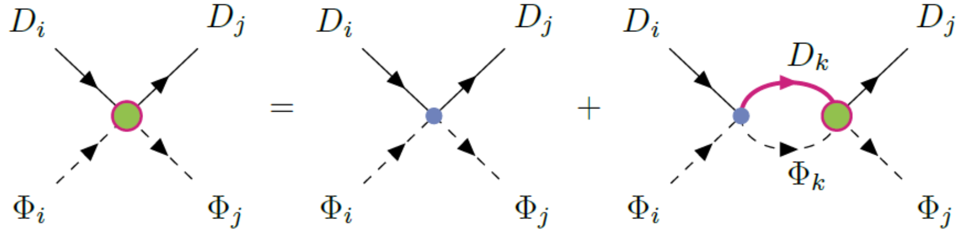
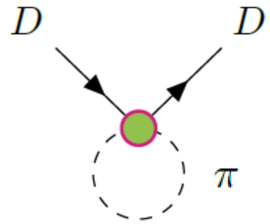


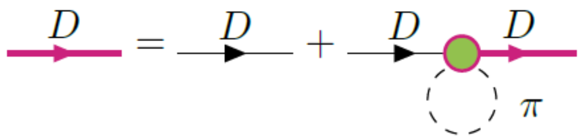
Self-energy

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



Spectral function

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



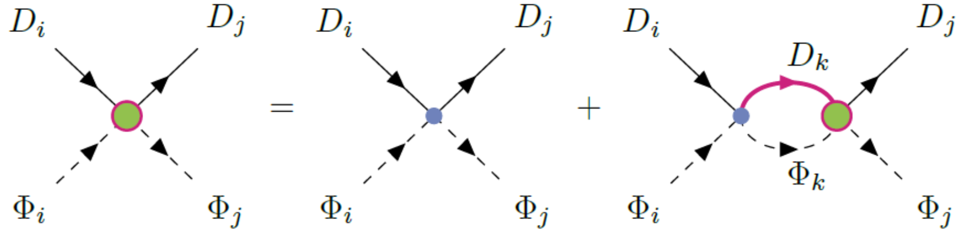
Self-consistent approach

Loop function

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

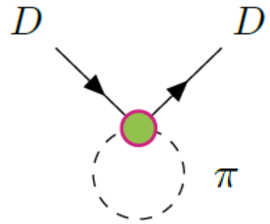
Unitarized amplitude

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



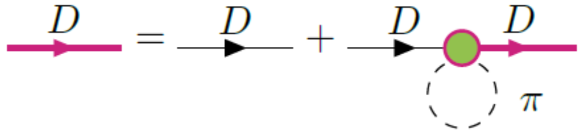
Self-energy

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



Spectral function

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



Set of coupled integral equations → solved iteratively

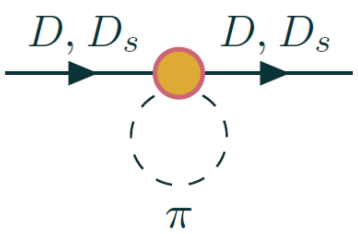
Outline

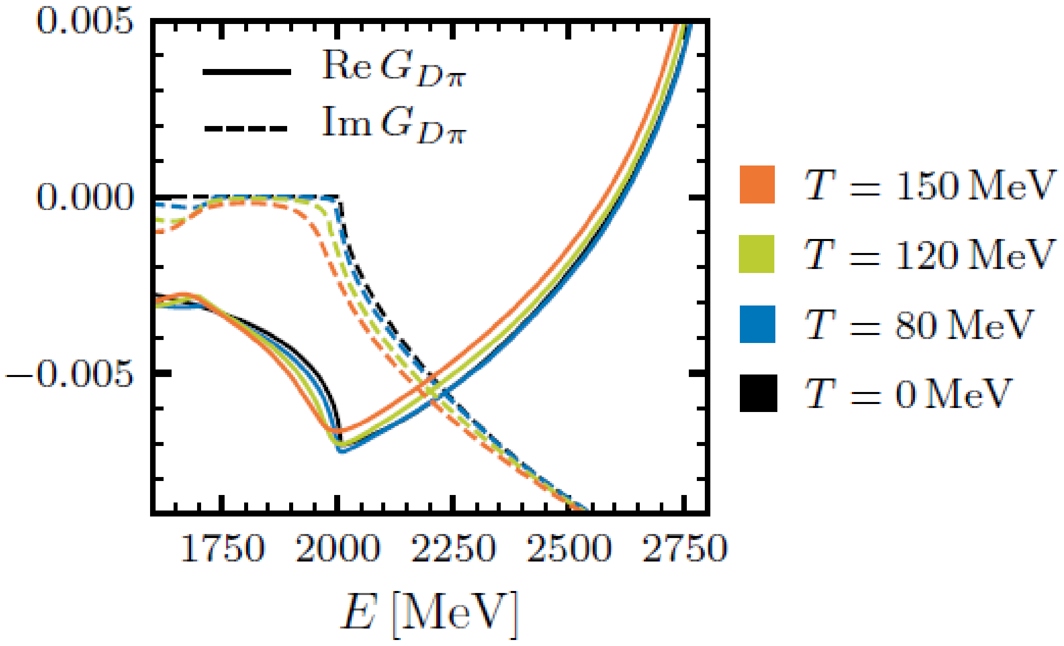
- Hadronic effective field theories
- Thermal EFT for heavy mesons
- **Open heavy-flavor mesons: Thermal properties**
- $X(3872)$ & $T_{cc}(3875)$
- Transport coefficients
- Summary

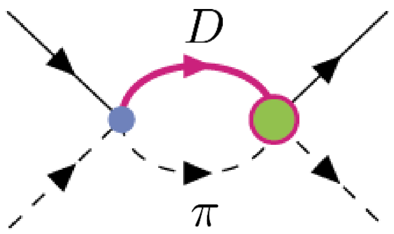
Thermal loop function

GM, Ramos, Tolos, Torres-Rincon, PLB 806, 135464(2020), PRD 102,096020(2020)

Pionic bath



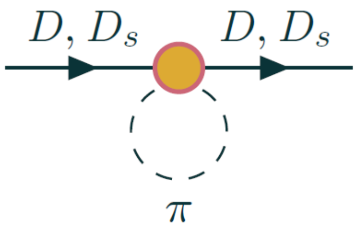


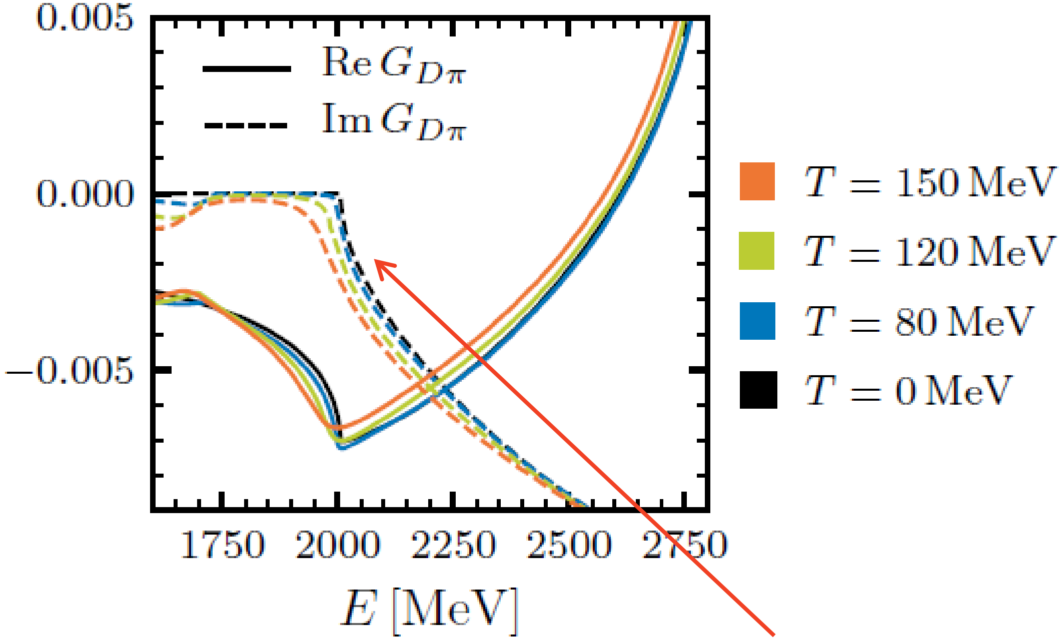


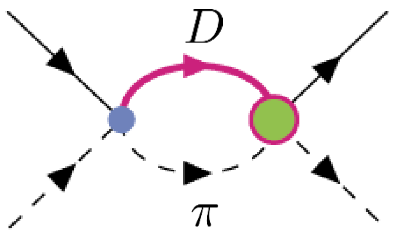
Thermal loop function

GM, Ramos, Tolos, Torres-Rincon, PLB 806, 135464(2020), PRD 102,096020(2020)

Pionic bath

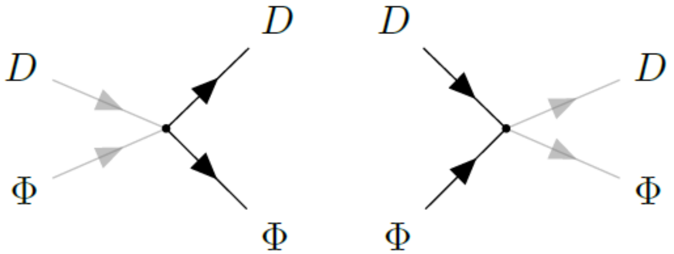






Unitarity cut

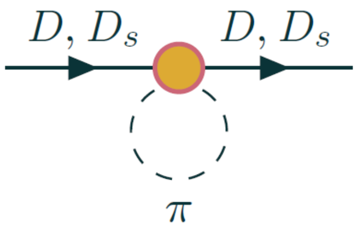
$$|E| \geq (m_D + m_\Phi)$$

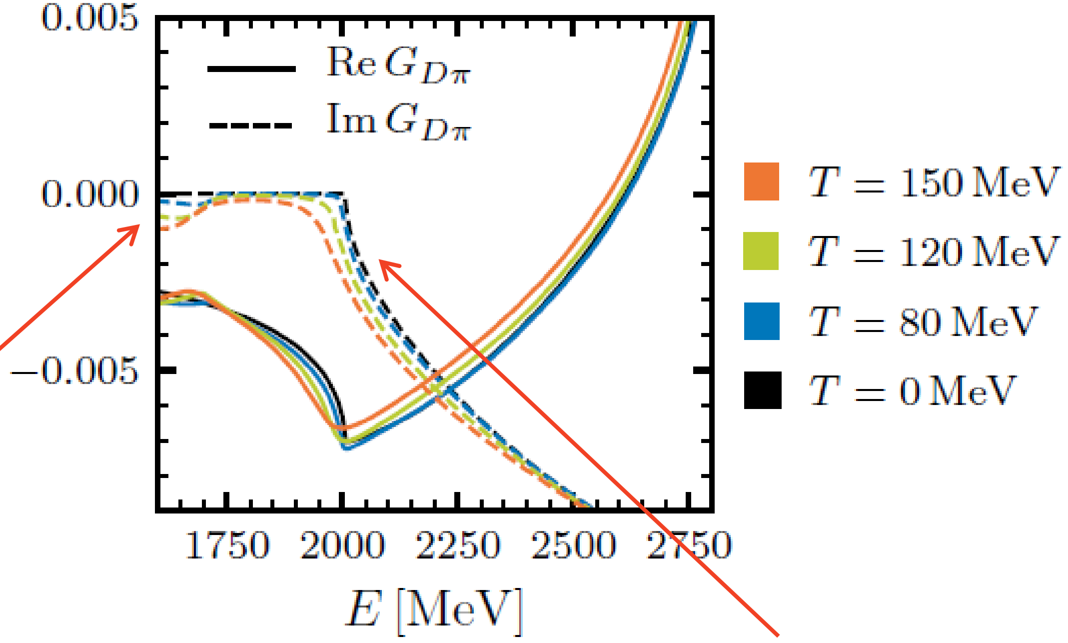


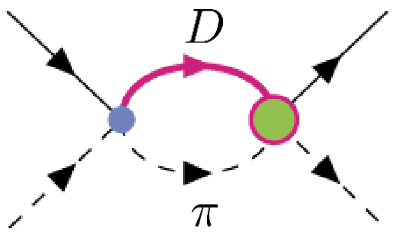
Thermal loop function

GM, Ramos, Tolos, Torres-Rincon, PLB 806, 135464(2020), PRD 102,096020(2020)

Pionic bath

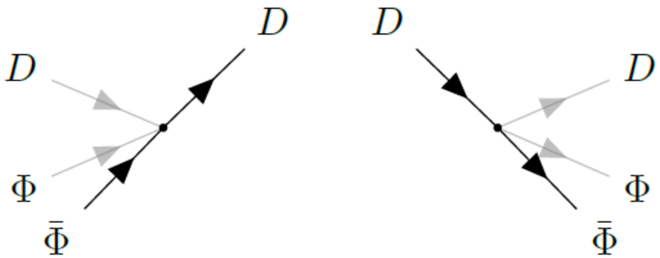






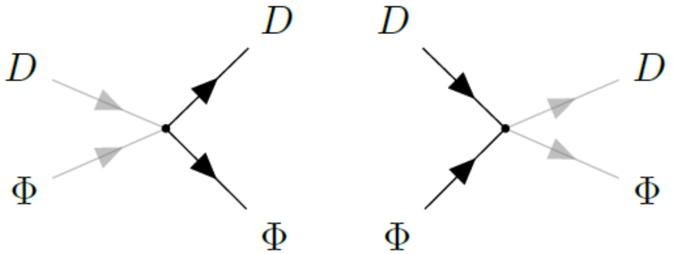
Landau cut

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



Unitarity cut

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

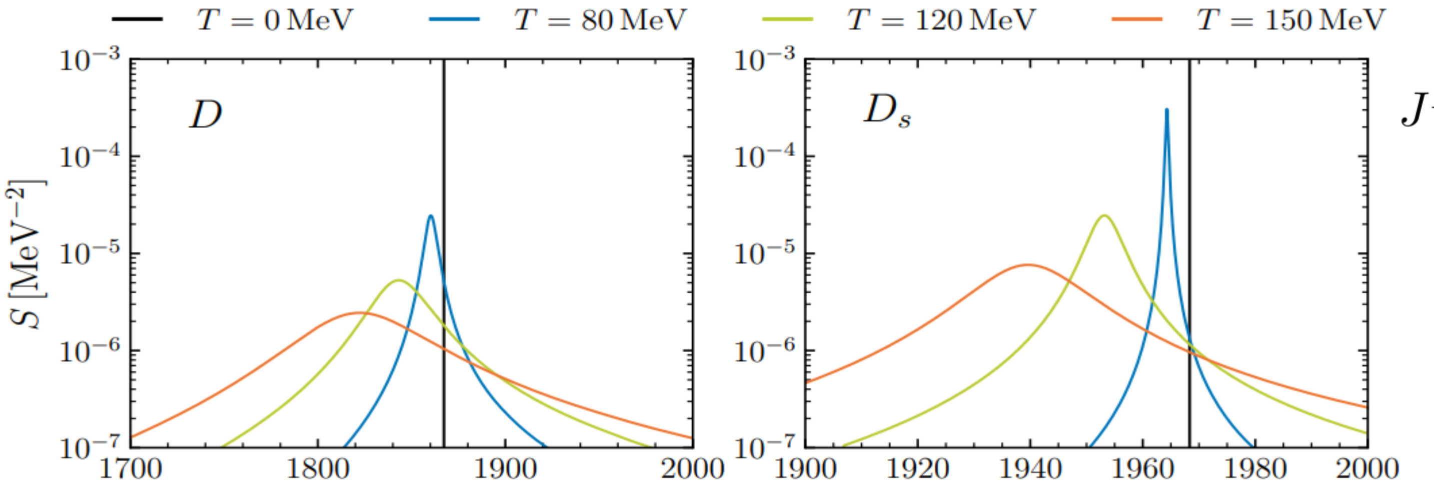


Thermal spectral functions

GM, Ramos, Tolos, Torres-Rincon, PLB 806, 135464(2020), PRD 102,096020(2020)

Ground-state spectral functions:

$$S_D(\omega, \vec{q}; T) = -\frac{1}{\pi} \, \mathrm{Im} \, \mathcal{D}_D$$



$J^P = 0^-$

Thermal spectral functions

GM, Ramos, Tolos, Torres-Rincon, PLB 806, 135464(2020), PRD 102,096020(2020)

Ground-state spectral functions:

$$S_D(\omega, \vec{q}; T) = -\frac{1}{\pi}\,\mathrm{Im}\,\mathcal{D}_D$$

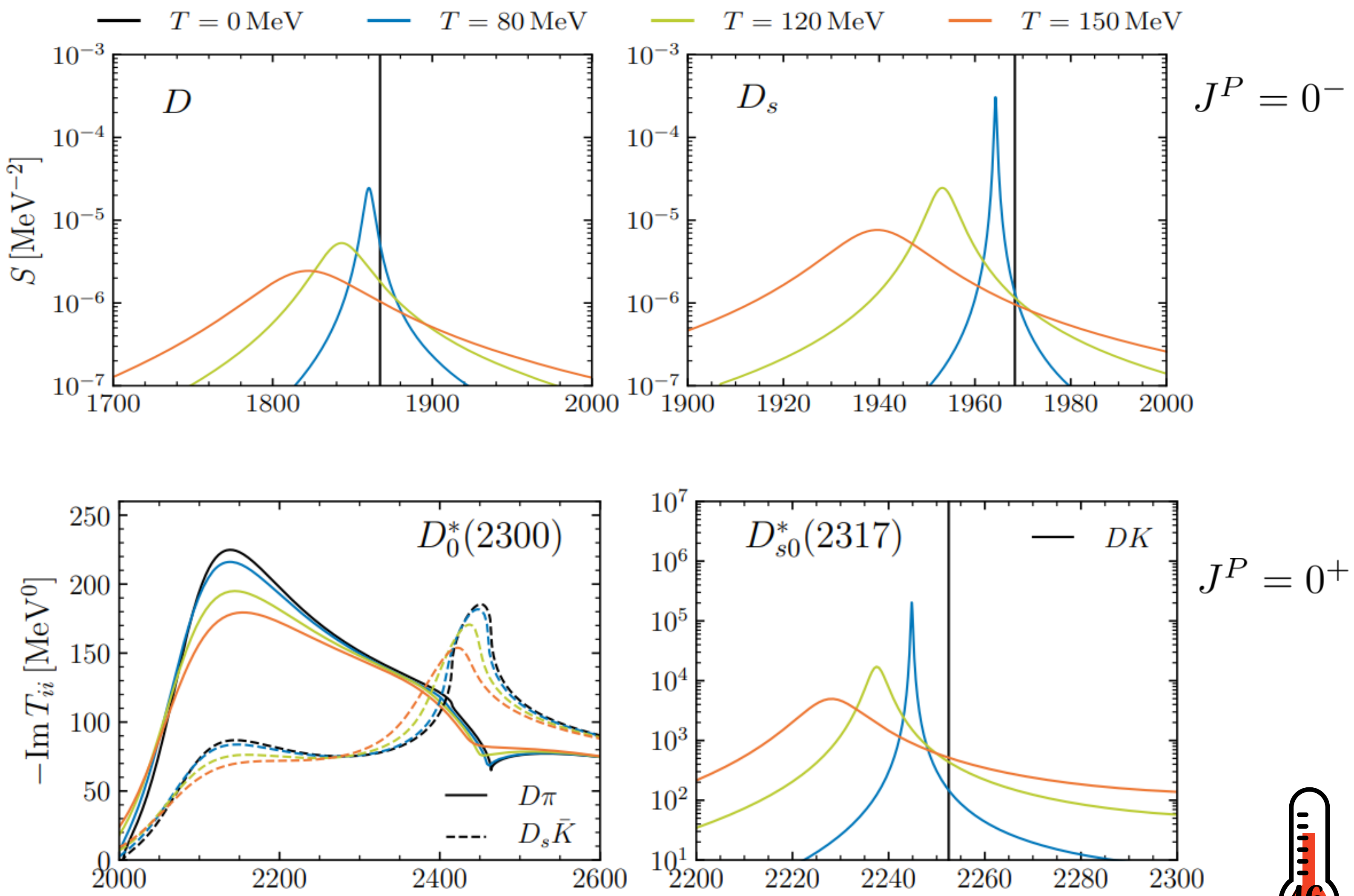
Dynamically generated states:

$$S_{D_{\rm dyn}}(\omega, \vec{q}; T) \sim -\,\mathrm{Im}\,T_{D\Phi}$$

In vacuum $(T=0)$

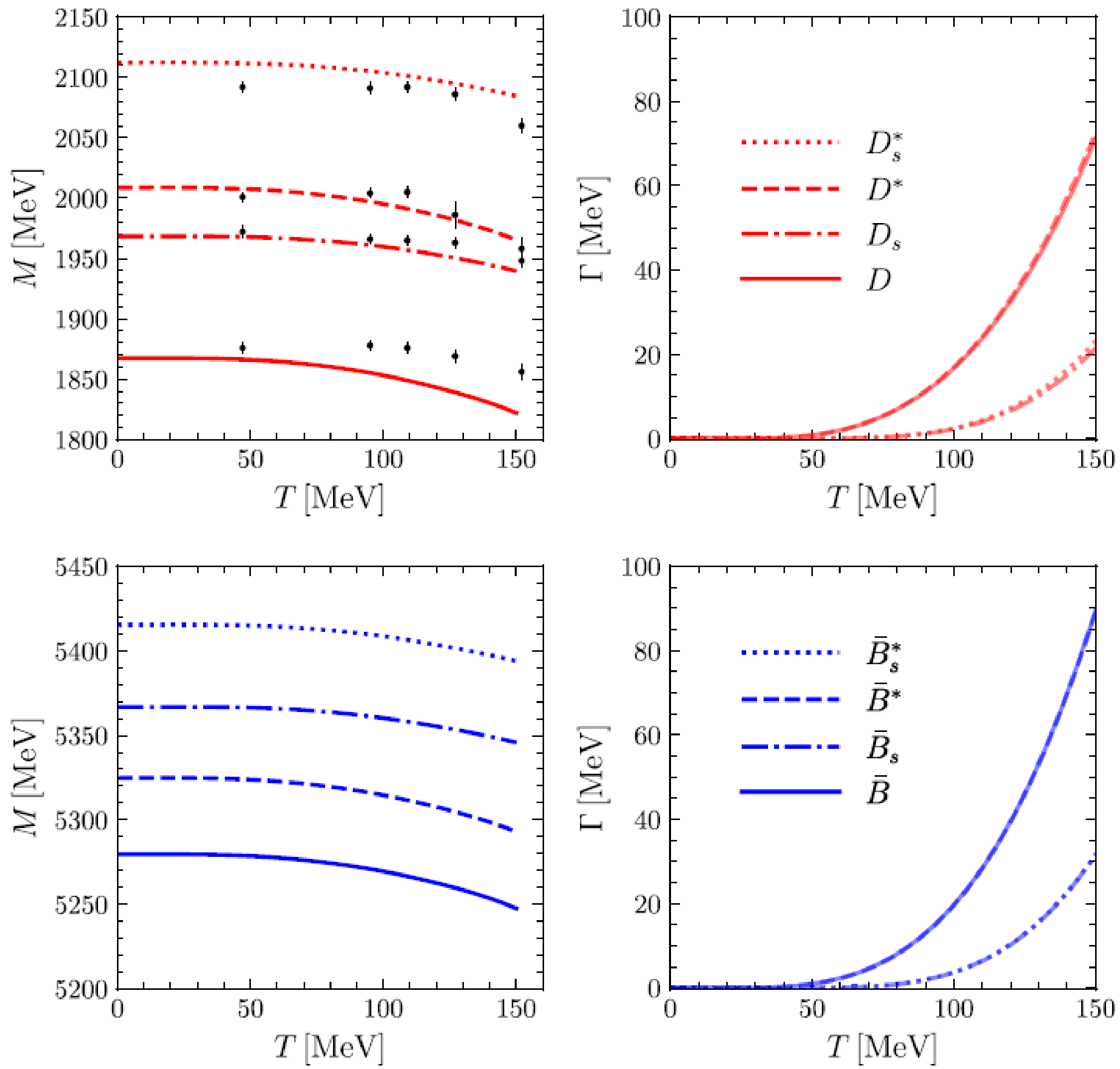
$D_0^*(2300)$: Two-pole structure

$D_{s0}^*(2317)$: Bound state



Thermal masses and widths

GM, Ramos, Tolos, Torres-Rincon, PLB 806, 135464(2020), PRD 102,096020(2020)
Front.in Phys. 11,1250939(2023)



With increasing temperature:

- Reduction of the in-medium mass
- Thermal widening

Reduction of the mass also seen in lattice QCD (data points in black)

Aarts et al. 2209.14681 (2022)

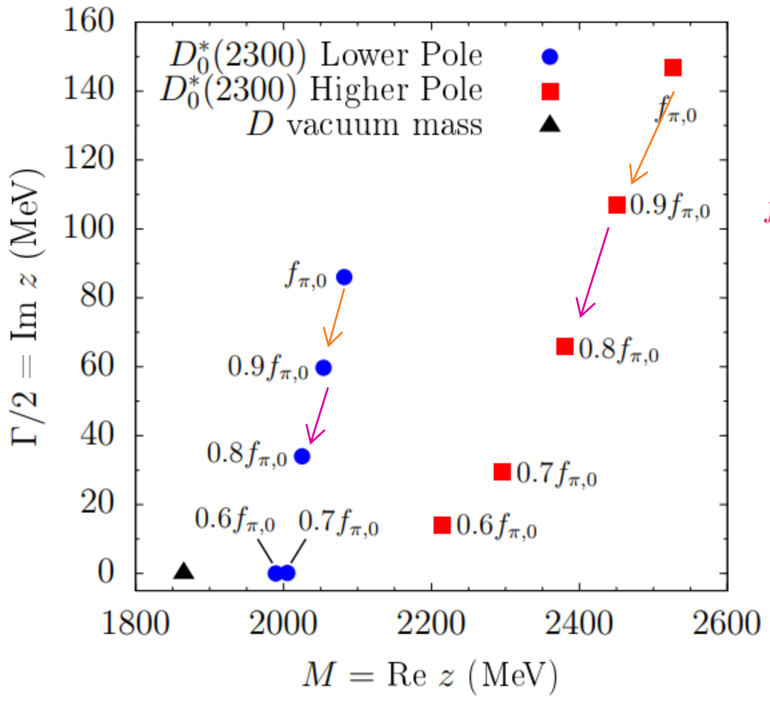
Impact of a temperature-dependent potential

- By implementing the reduction of the pion decay constant with T $\qquad \dfrac{f_\pi(T)}{f_\pi(0)} \approx 1 - \dfrac{T^2}{12 f_\pi(0)^2}$

  Gasser, Leutwyler (1987)

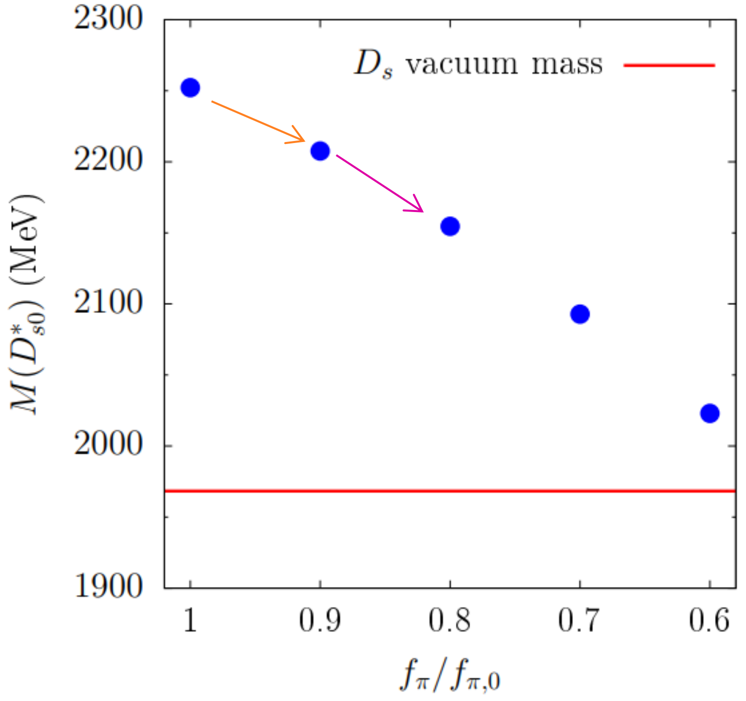
- Vacuum calculation (not implemented in the self-consistent thermal approach)

Torres-Rincon, Symmetry 13,1400(2020)



$f_\pi(T \approx 100$ MeV)

$f_\pi(T \approx 150$ MeV)



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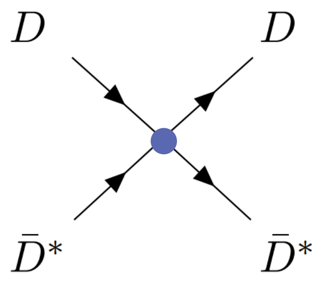
Local hidden gauge approach



- Assume $X(3872)$ is a $D\bar{D}^*$ molecule
- Interaction mediated by the exchange of vector mesons
- Extended to SU(4), broken by physical masses (exchange of charm is suppressed)

Bando, Kugo et al (1985,1988), Meißner (1988)

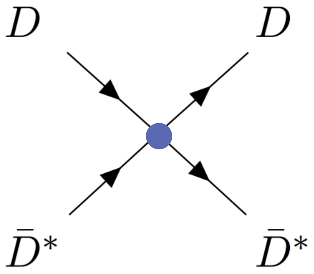
Xiao, Nieves, Oset (2013)

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

$$\begin{cases} \mathcal{L}_{\rm VVVV} = \dfrac{g^2}{2}\langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu\rangle \\ \mathcal{L}_{\rm PPV} = -ig\langle V^\mu[P, \partial_\mu P]\rangle \\ \mathcal{L}_{\rm VVV} = ig\langle (V^\mu\partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)V^\nu\rangle \end{cases}$$

$$P = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta + \frac{1}{\sqrt{3}}\eta' & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta + \frac{1}{\sqrt{3}}\eta' & K^0 & D^- \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta + \frac{1}{\sqrt{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix} \quad V^\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}(\rho^0 + \omega) & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{1}{\sqrt{2}}(-\rho^0 + \omega) & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}^\mu$$

Local hidden gauge approach



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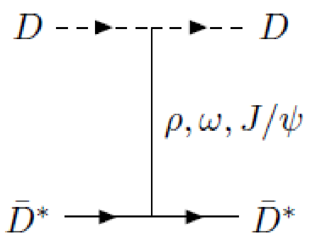
$X(3872)$

$I(J^{PC}) = 0(1^{++})$

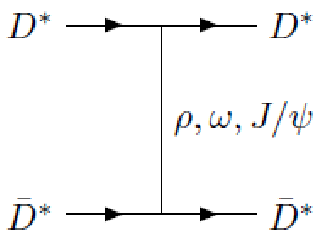
$D\bar{D}^* + c.c.$
$D_s\bar{D}_s^* - c.c.$

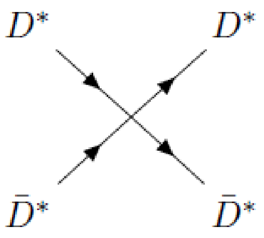


$X(4014)$ Belle, PRD 105,112011(2022)

$I(J^{PC}) = 0(2^{++})$

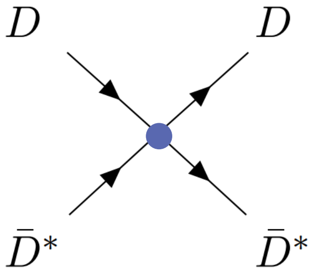
$D^*\bar{D}^* + c.c.$
$D_s^*\bar{D}_s^* - c.c.$





⊳ HQSS partner Nieves, Valderrama (2012)

Local hidden gauge approach



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$X(3872)$

$$V_{ij}^{PV\to PV}(s) = \xi_{ij}(s-u)$$

$X(4014)$

$$V_{ij}^{VV\to VV}(s) = C_{ij} + \tilde{\xi}_{ij}(s-u)$$

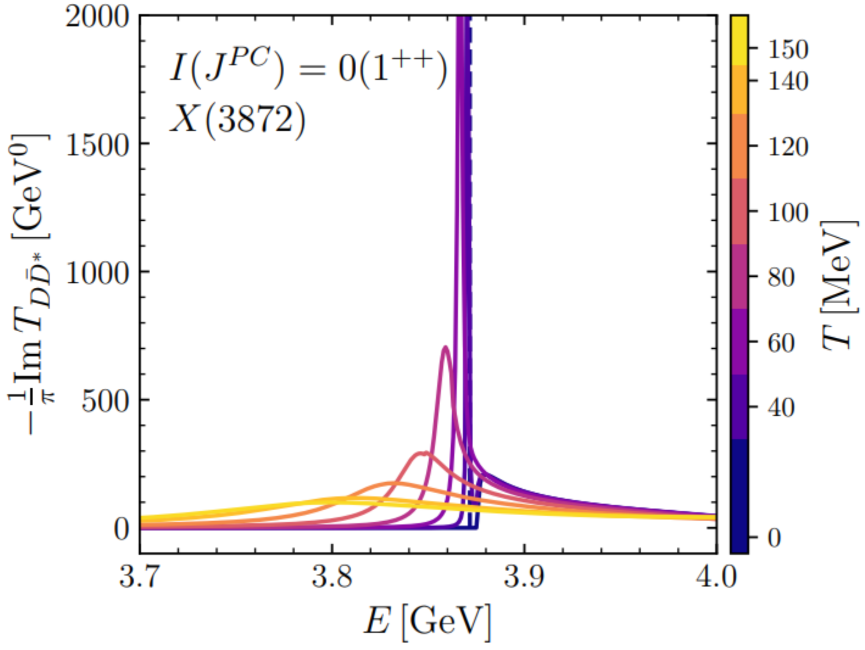
isospin coefficients

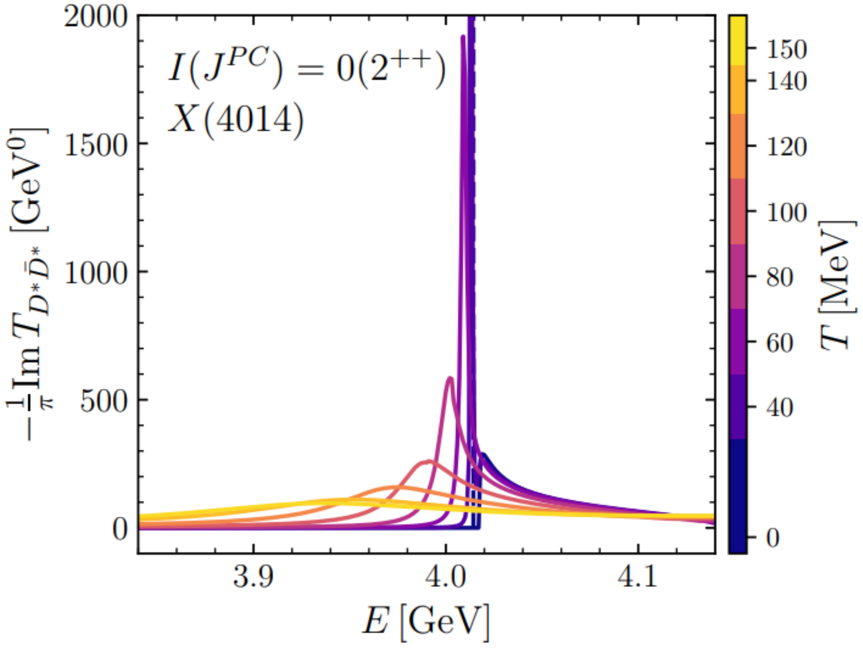
Thermal modification of the $X(3872)$ and its HQSS partner

GM, Ramos, Tolos, Torres-Rincon, PRD 107,054014(2023)

- Hidden gauge interaction kernel + Bethe-Salpeter equation with cutoff
- At finite temperature, ITF + meson loop dressed with spectral functions of the D/D_s and D^*/D_s^* mesons

Thermal spectral functions





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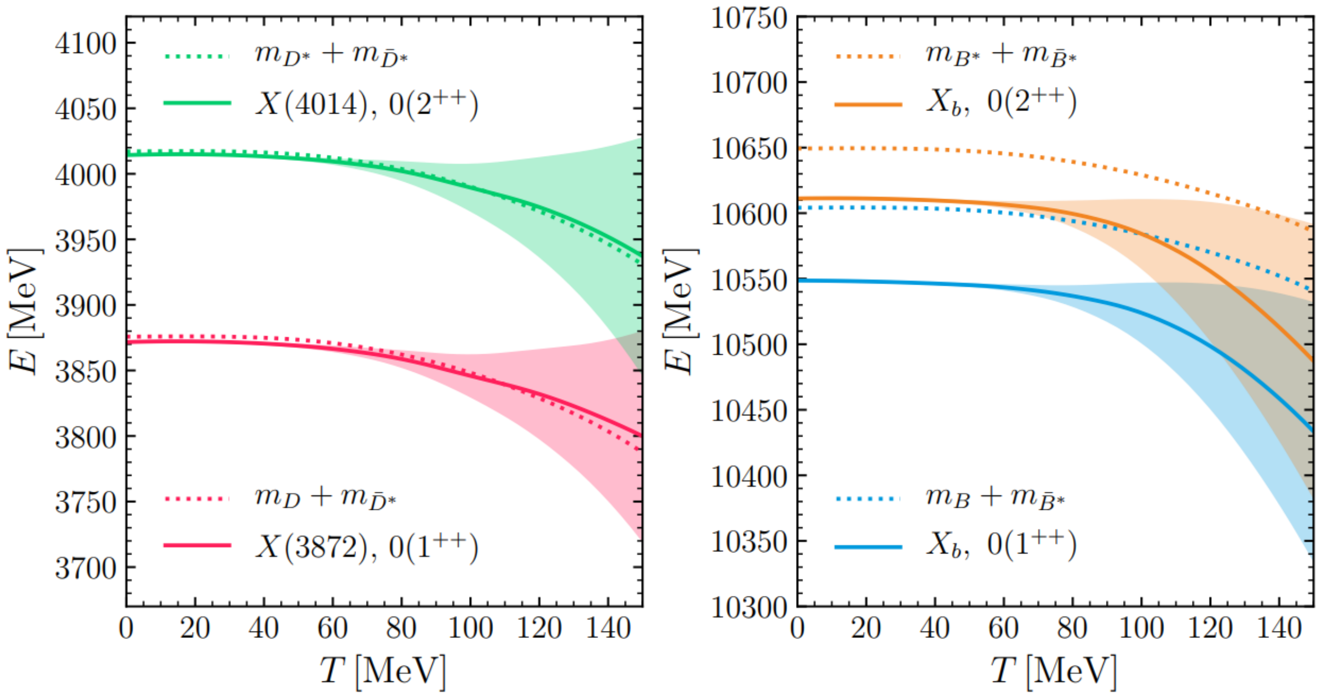
Thermal masses and widths



Dashed lines: “threshold”

Solid lines: thermal mass

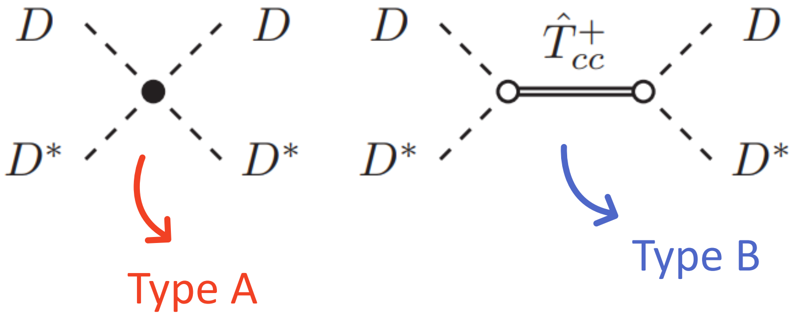
Shaded bands: thermal decay width

Mixed molecular-compact scenario

- Assume $T_{cc}(3875)$ is a mixture of DD^* molecule + compact tetraquark
- Consider two classes of potentials

Albaladejo, Nieves, Tolos, PRC 104,035203(2021)
Montesinos, Albaladejo, Nieves, Tolos, PRC 108,035205(2023)

$$V_A(s) = C_1 + C_2\left[s - (m_D + m_{D*})^2\right]$$
$$V_B(s) = \left(C_1' + C_2'\left[s - (m_D + m_{D*})^2\right]\right)^{-1}$$



→ LECs fixed by: binding energy in vacuum $T^{-1}(m_0^2;0) = 0$

residue at the pole $\left.\dfrac{dT(s;0)}{ds}\right|_{s=m_0^2} = \dfrac{1}{g_0^2}$

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Montesinos, Albaladejo, Nieves, Tolos, PRC 108,035205(2023)

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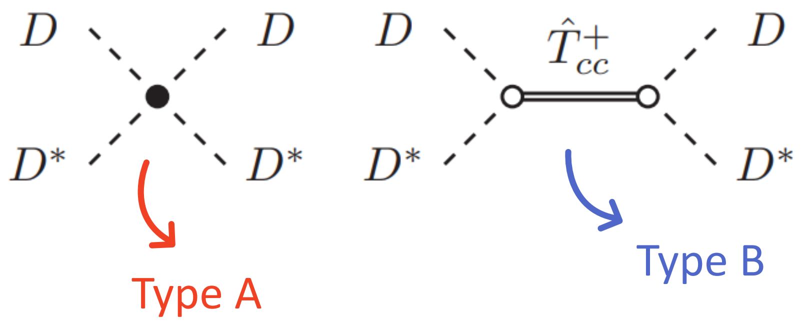

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→ Weinberg compositeness condition Weinberg (1965), Gamermann, Nieves, Oset, Ruiz Arriola (2010)

$$P_0 = -g_0^2 \left.\frac{\partial G(s,0)}{\partial s}\right|_{s=m_0^2}$$

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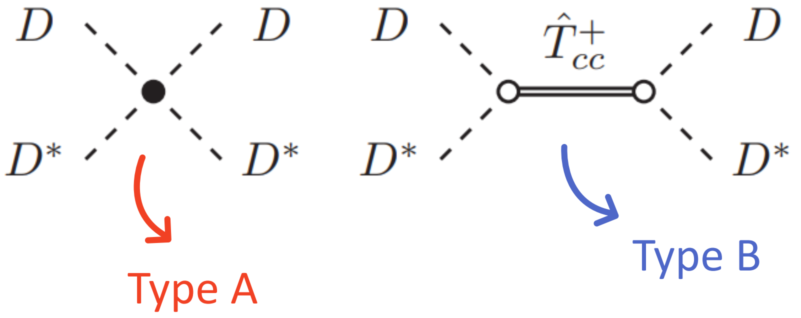

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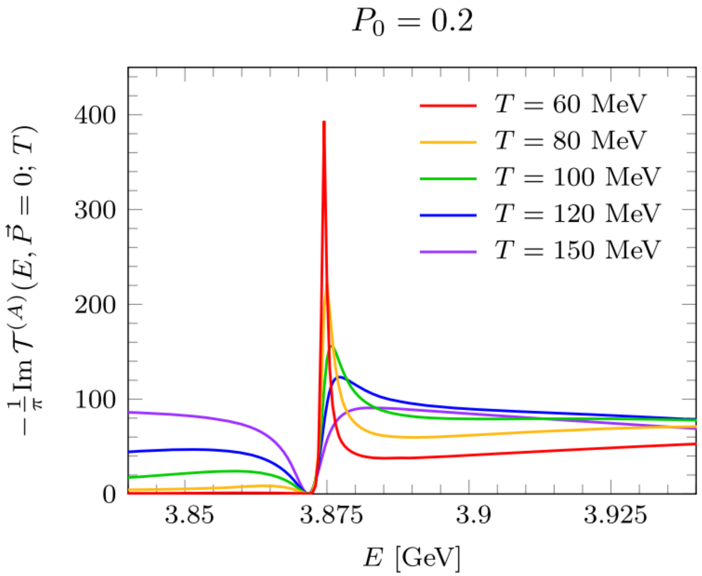
$$P_0 = -g_0^2 \left.\frac{\partial G(s,0)}{\partial s}\right|_{s=m_0^2}$$

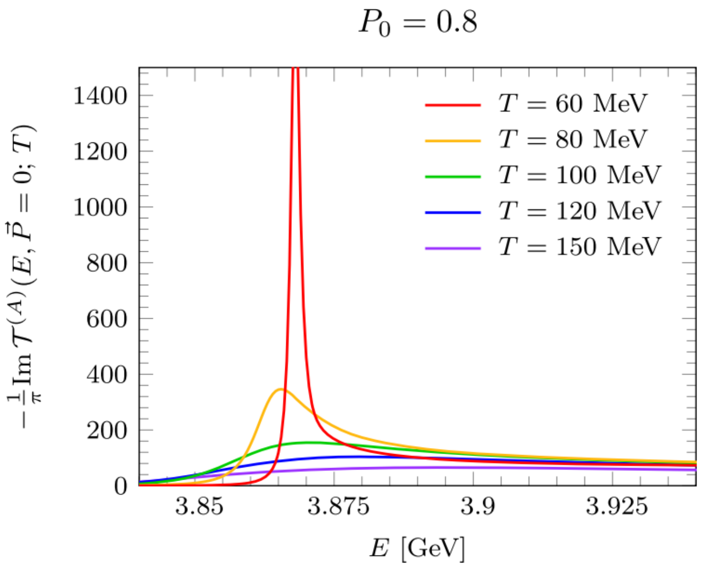
- Solve Bethe-Salpeter at finite temperatura
- Meson loop dressed with $D,\ D^*$ spectral functions

Thermal modification of the $T_{cc}(3875)$

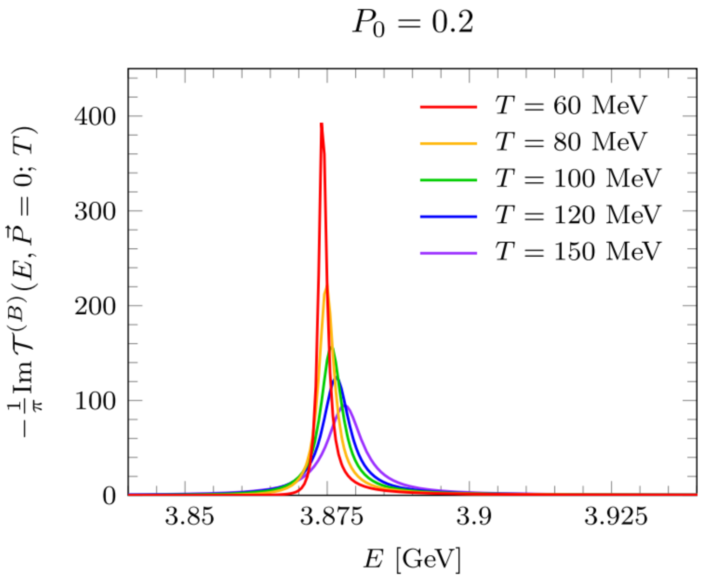
Montesinos, GM, Albaladejo, Nieves, Tolos,
PLB 871,140020(2025)

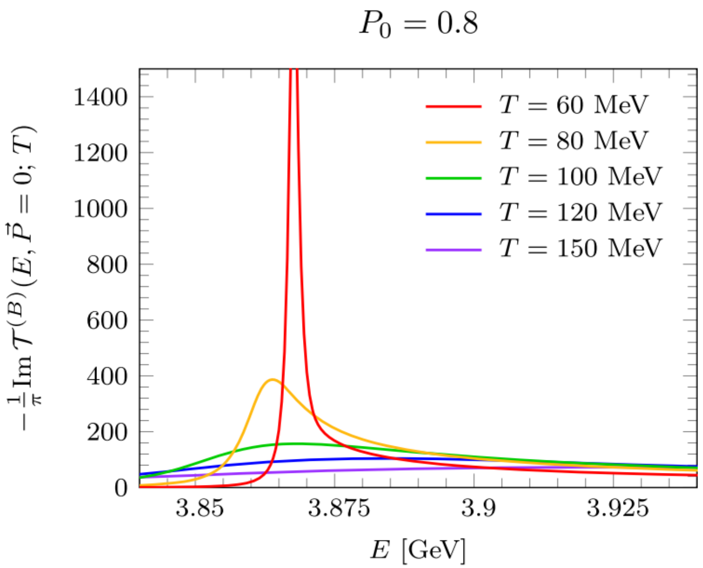
Potential type A





Potential type B

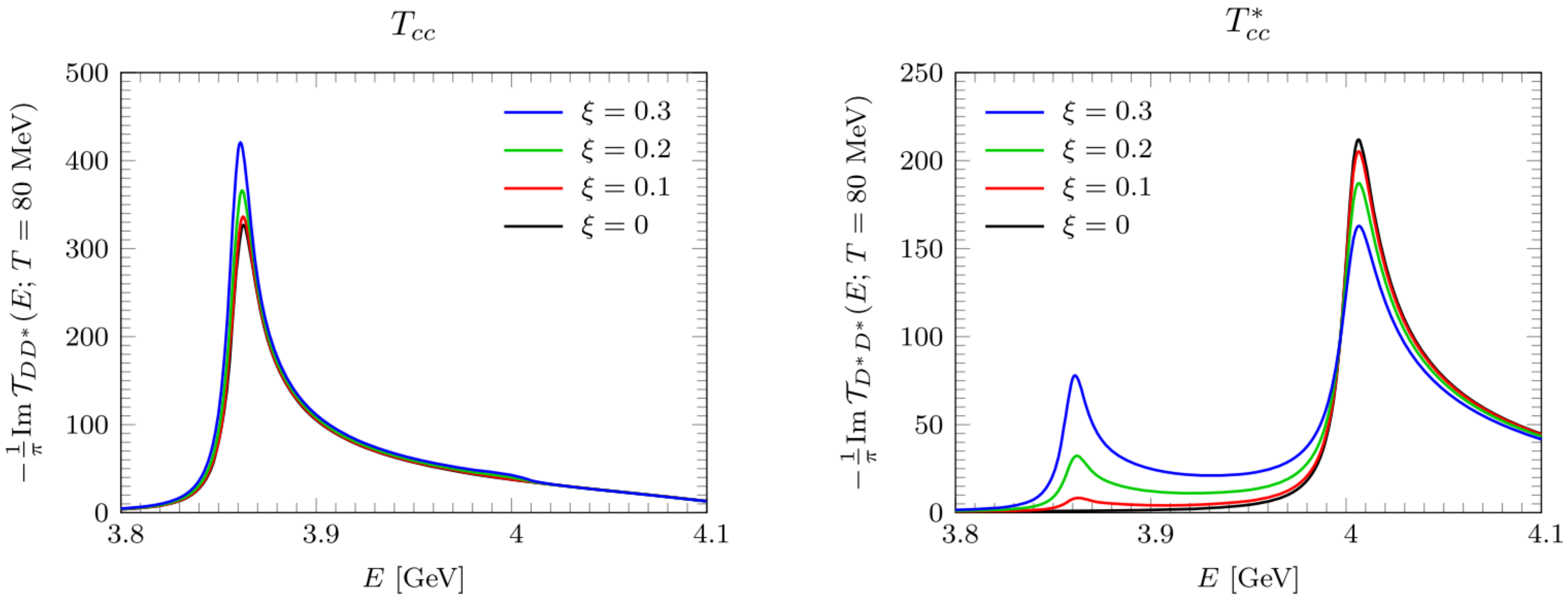




Impact of coupled channels

Montesinos, GM, Albaladejo, Nieves, Tolos,
PLB 871,140020(2025)

- The DD^* and D^*D^* channels can, in principle couple (suppressed in the hidden-gauge formalism)
- Consider the potential (consistent with HQSS) in the basis $\{|DD^*\rangle, |D^*D^*\rangle\}$: $V = \begin{pmatrix} v & \xi v \\ \xi v & v \end{pmatrix}$

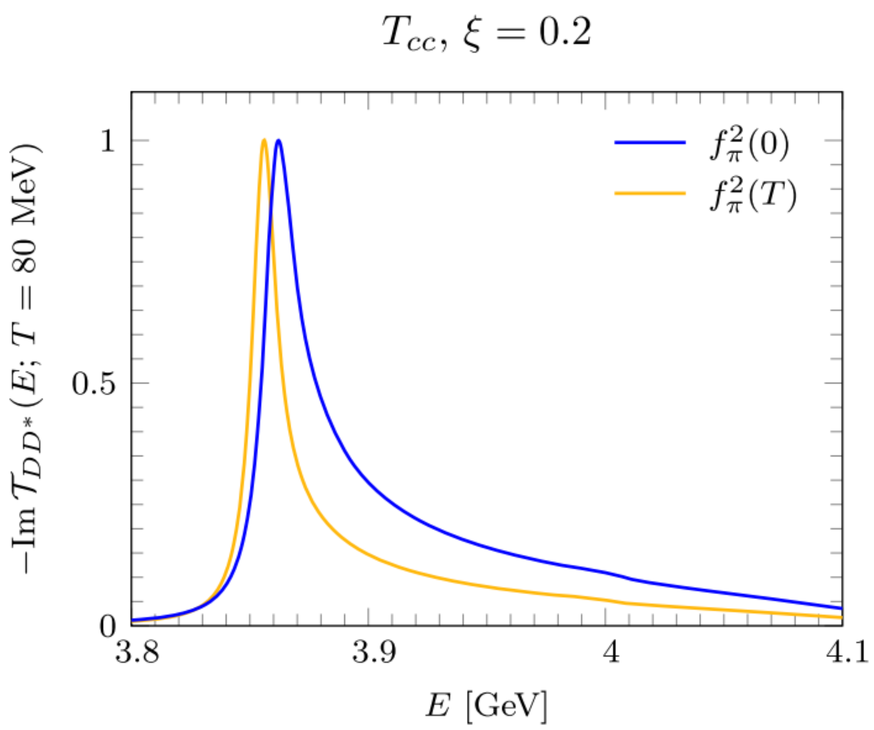


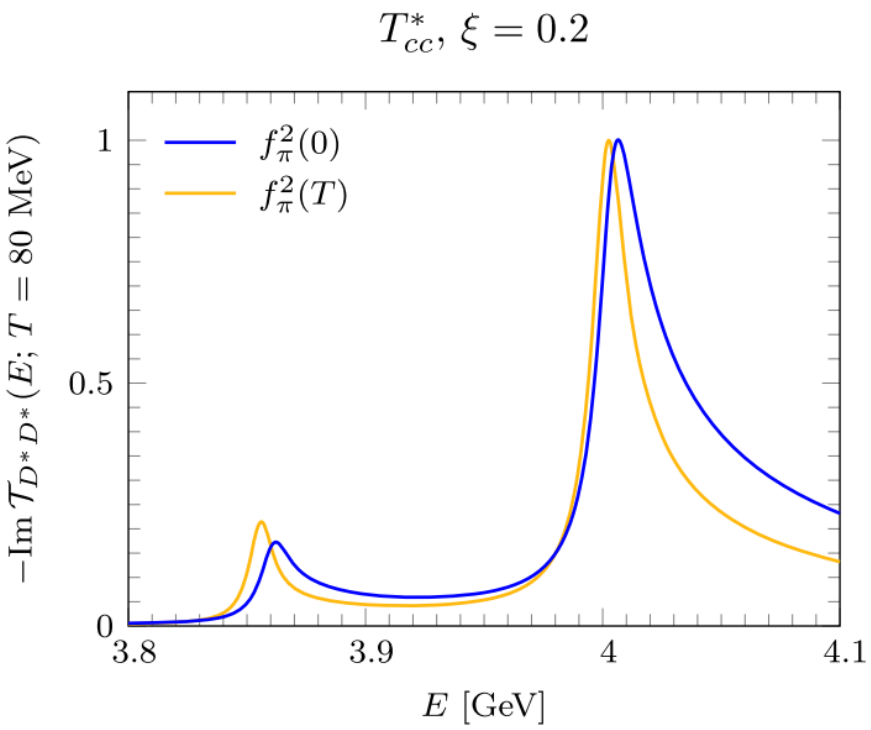
Impact of a temperature-dependent potential

Montesinos, GM, Albaladejo, Nieves, Tolos,
PLB 871,140020(2025)

- Assume that the dominant dependence comes from the pion decay constant

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





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In-medium D meson kinetic theory

Torres-Rincon, GM, Ramos, Tolos, PRC 105,025203(2022)

- Incorporate thermal and off-shell effects
- Start from the Kadanoff-Baym equations and derive an off-shell Fokker-Planck equation

Kadanoff, Baym (1962), Danielewicz (1984), Botermans, Malfliet (1990), Blaizot, Iancu (1999), Rammer (2007), Cassing (2009)

$$\left(k^\mu - \frac{1}{2}\frac{\partial \mathrm{Re}\,\Pi^R(X,k)}{\partial k_\mu}\right)\frac{\partial i G_D^<(X,k)}{\partial X^\mu} = \underbrace{\frac{1}{2} i\Pi^<(X,k) i G_D^>(X,k)}_{\text{Gain term}} - \underbrace{\frac{1}{2} i\Pi^>(X,k) i G_D^<(X,k)}_{\text{Loss term}}$$

In-medium D meson kinetic theory

Torres-Rincon, GM, Ramos, Tolos, PRC 105,025203(2022)

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- Kadanoff-Baym Ansatz

$$iG_D^<(X,k) = 2\pi S_D(X,k) f_D(X,k^0)$$
$$iG_D^>(X,k) = 2\pi S_D(X,k)\left[1 + f_D(X,k^0)\right]$$

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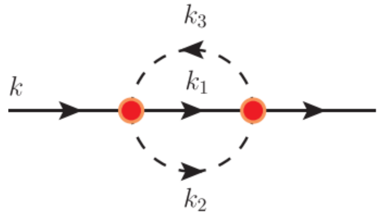
- T-matrix approximation



$$i\Pi^<(X,k) = \sum_{\{a,b,c\}} \int \frac{d^4k_1}{(2\pi)^4} \int \frac{d^4k_2}{(2\pi)^4} \int \frac{d^4k_3}{(2\pi)^4} (2\pi)^4 \delta^{(4)}(k_1 + k_2 - k_3 - k)$$
$$\times |T(k_1^0 + k_2^0 + i\epsilon, \mathbf{k}_1 + \mathbf{k}_2)|^2\ iG_{D_a}^<(X,k_1) iG_{\Phi_b}^<(X,k_2) iG_{\Phi_c}^>(X,k_3)$$
$$i\Pi^>(X,k) = \cdots$$

Transport coefficients

Torres-Rincon, GM, Ramos, Tolos, PRC 105,025203(2022)

Off-shell Fokker-Planck equation

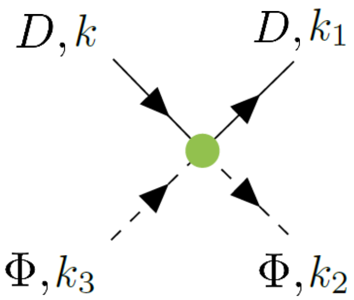
$$\frac{\partial}{\partial t} G_D^{<}(t,k) = \frac{\partial}{\partial k^i}\left\{ \hat{A}(k;T) k^i\, G_D^{<}(t,k) + \frac{\partial}{\partial k^j}\left[\hat{B}_0(k;T)\Delta^{ij} + \hat{B}_1(k;T)\frac{k^i k^j}{\vec{k}^{\,2}} \right] G_D^{<}(t,k) \right\}$$

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

Off-shell transport coefficients

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

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



Transport coefficients

Torres-Rincon, GM, Ramos, Tolos, PRC 105,025203(2022)

Spectral function

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

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

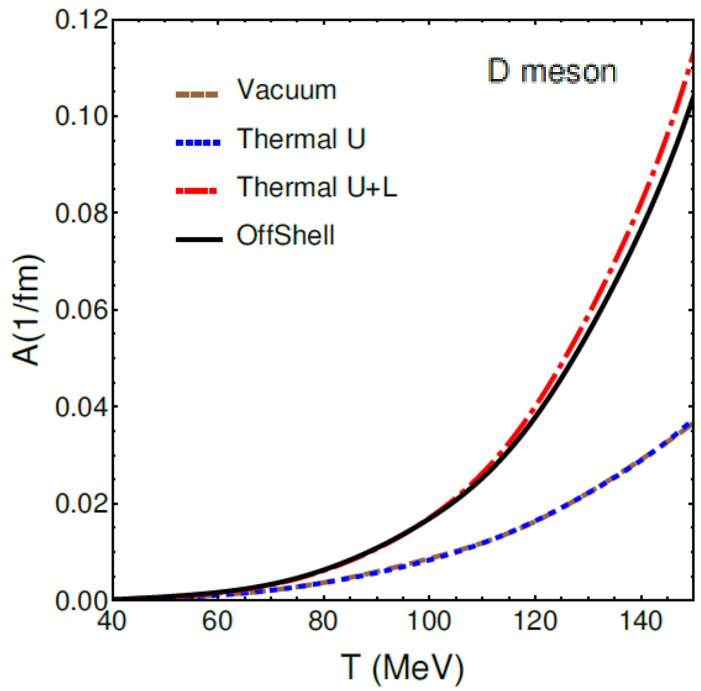
Thermal
unitarized amplitude

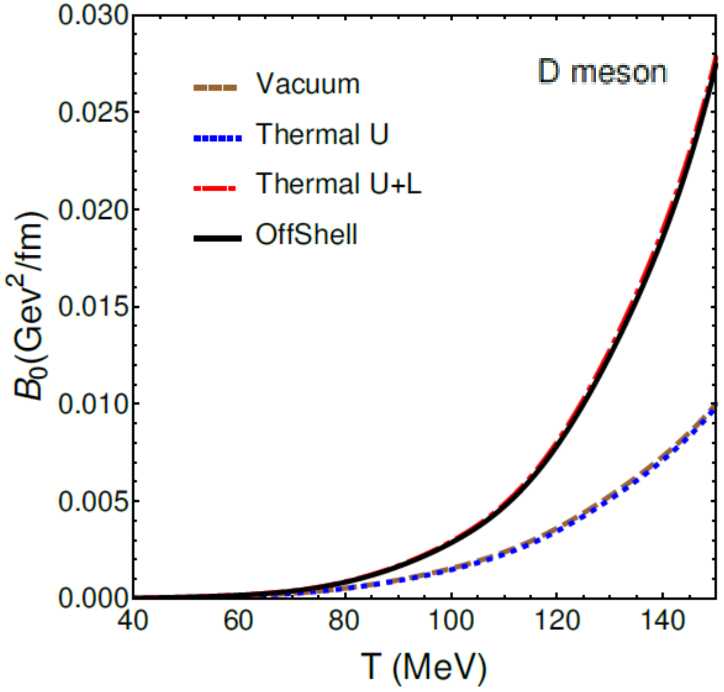
Equilibrium
distribution functions

- Thermal effects
- Off-shell effects
- Landau cut contribution

Drag force and momentum diffusion coefficient

Torres-Rincon, GM, Ramos, Tolos, PRC 105,025203(2022)





In the static limit

$$\vec{k} \to 0 \ , \quad B_0 = B_1$$

Vacuum vs **Thermal U**: thermal effects in the amplitudes are small

Thermal U vs **Thermal U+L**: Landau contribution is very important at finite temperature

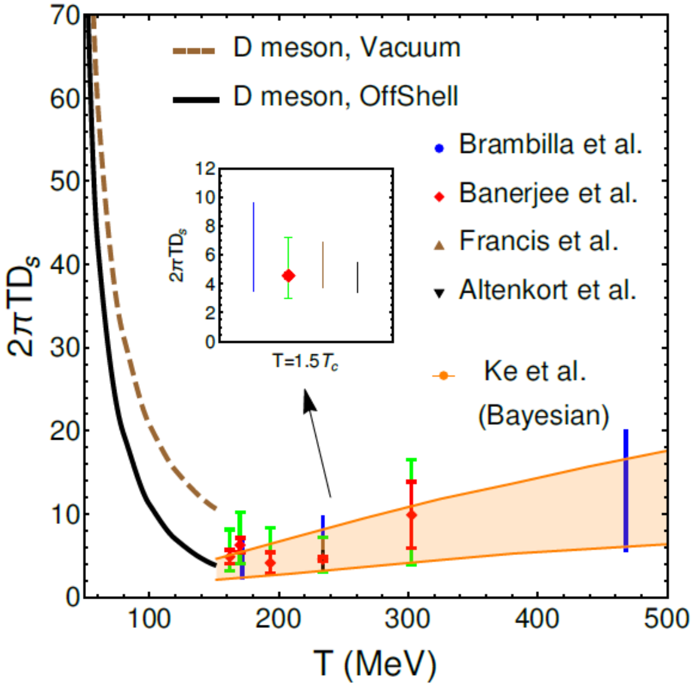
Thermal U+L vs **OffShell**: off-shell effects are small

Main contribution comes from the pions in the bath

Spatial diffusion coefficient

Torres-Rincon, GM, Ramos, Tolos, PRC 105,025203(2022)

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



Comparison with:

- Lattice QCD calculations
- Bayesian analysis of HICs

W. Ke et al, PRC 98,064901(2018)

Brambilla et al, PRD 102,074503(2020)
Banerjee et al, PRD 85,014510(2012)
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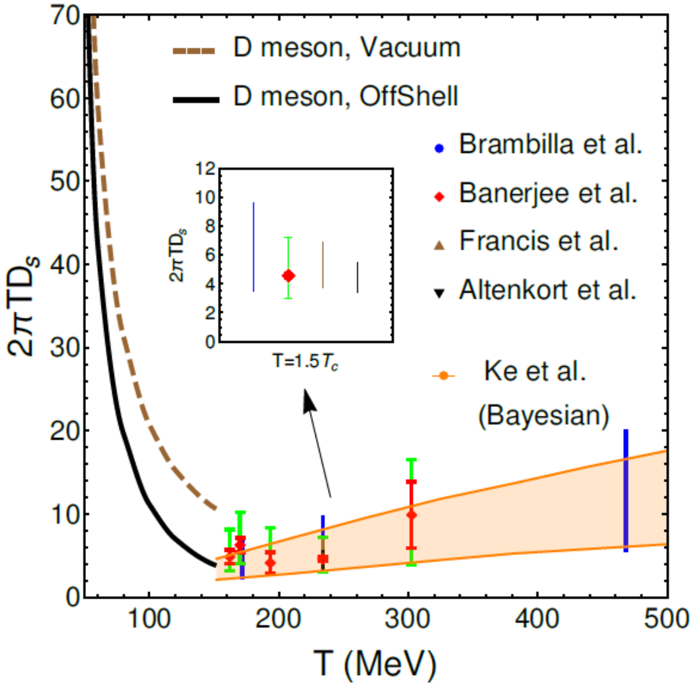
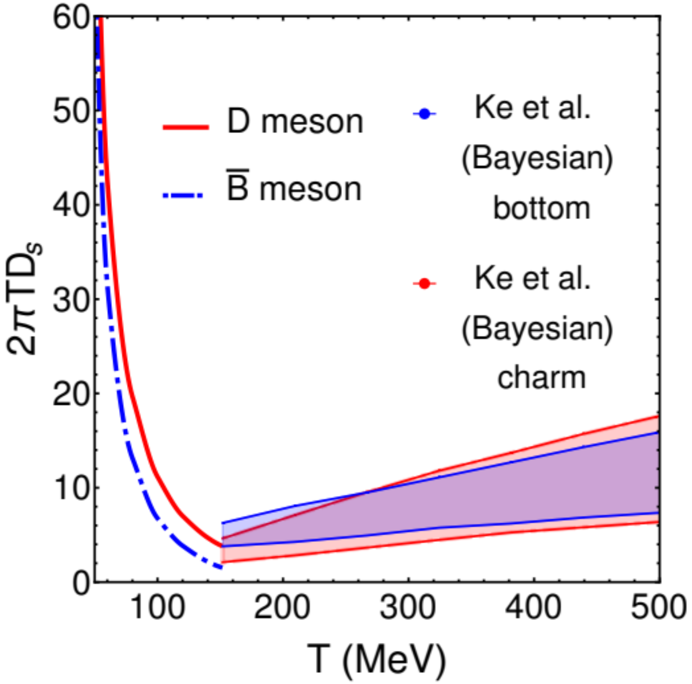
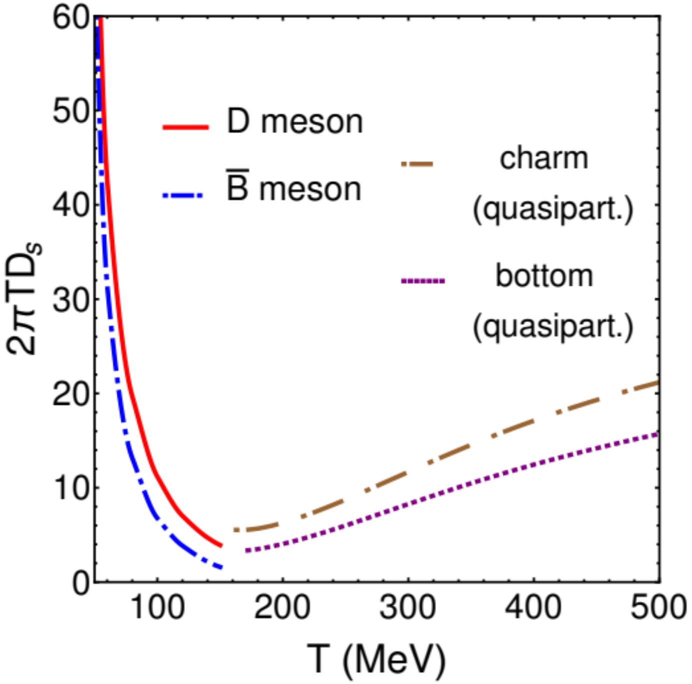


Charm vs Bottom





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Altenkort et al, PRD 103,014511(2021)

Comparison with:

- Quasiparticle model

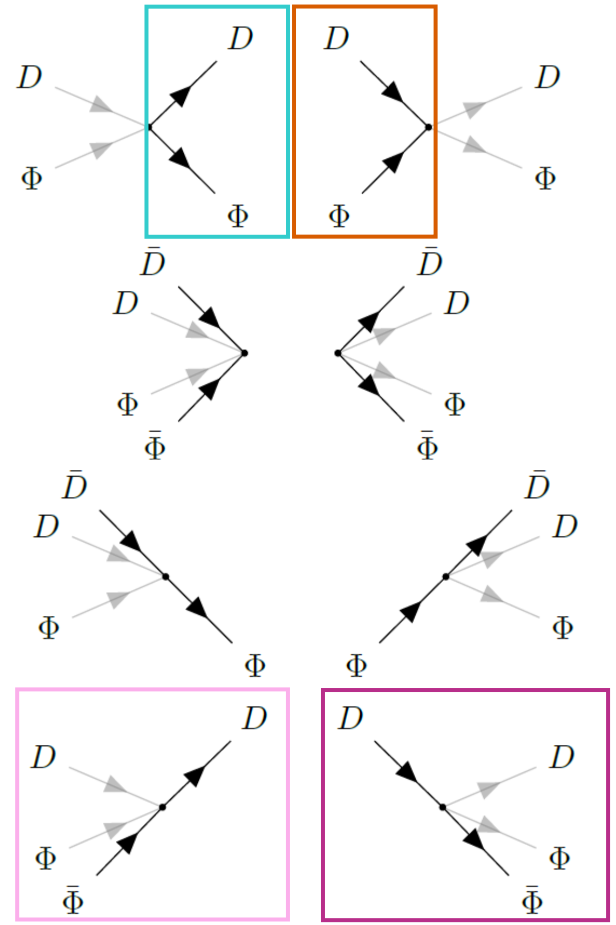
Das, Torres-Rincon et al, PRD 94,114039(2016)

Summary

- Developed a self-consistent thermal unitarized EFT framework for heavy mesons at $T < T_c$
- Open heavy-flavor mesons: moderate decrease of the masses and substantial increase of the decay widths with temperature
- $X(3872)$ and $T_{cc}(3875)$: similar mass shift and widening (depending on the molecular content)
- Transport coefficients in the hadronic phase: large contribution from the Landau cut of the thermal scattering amplitude

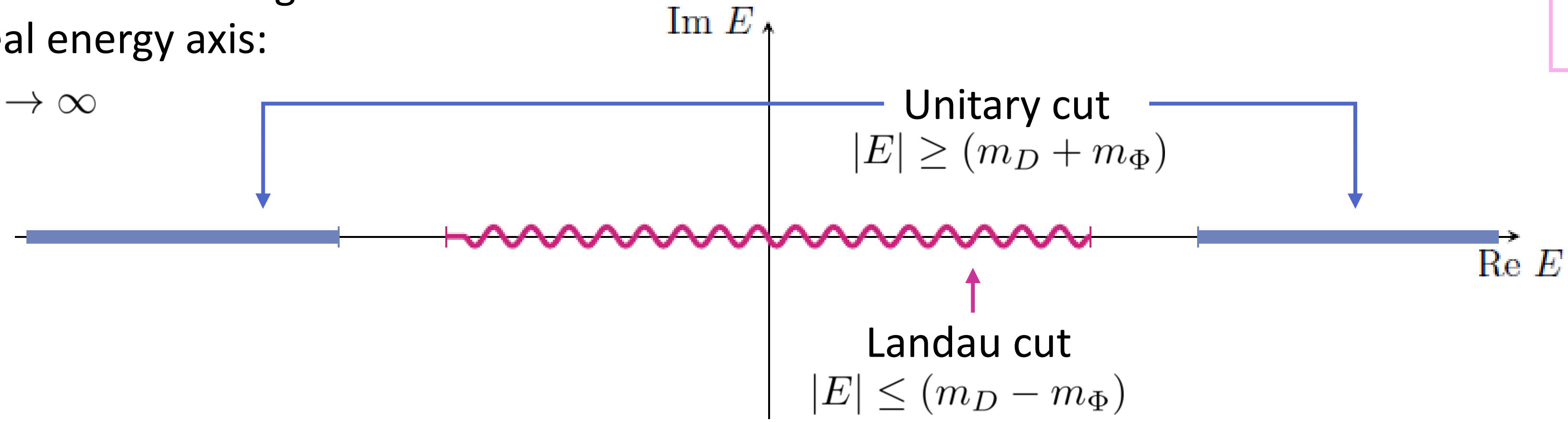
Physical interpretation and cuts of the thermal propagator

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



Branch cuts along the real energy axis:

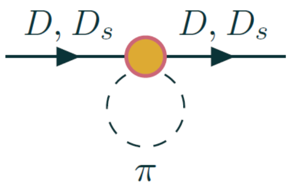
$\Lambda \to \infty$



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

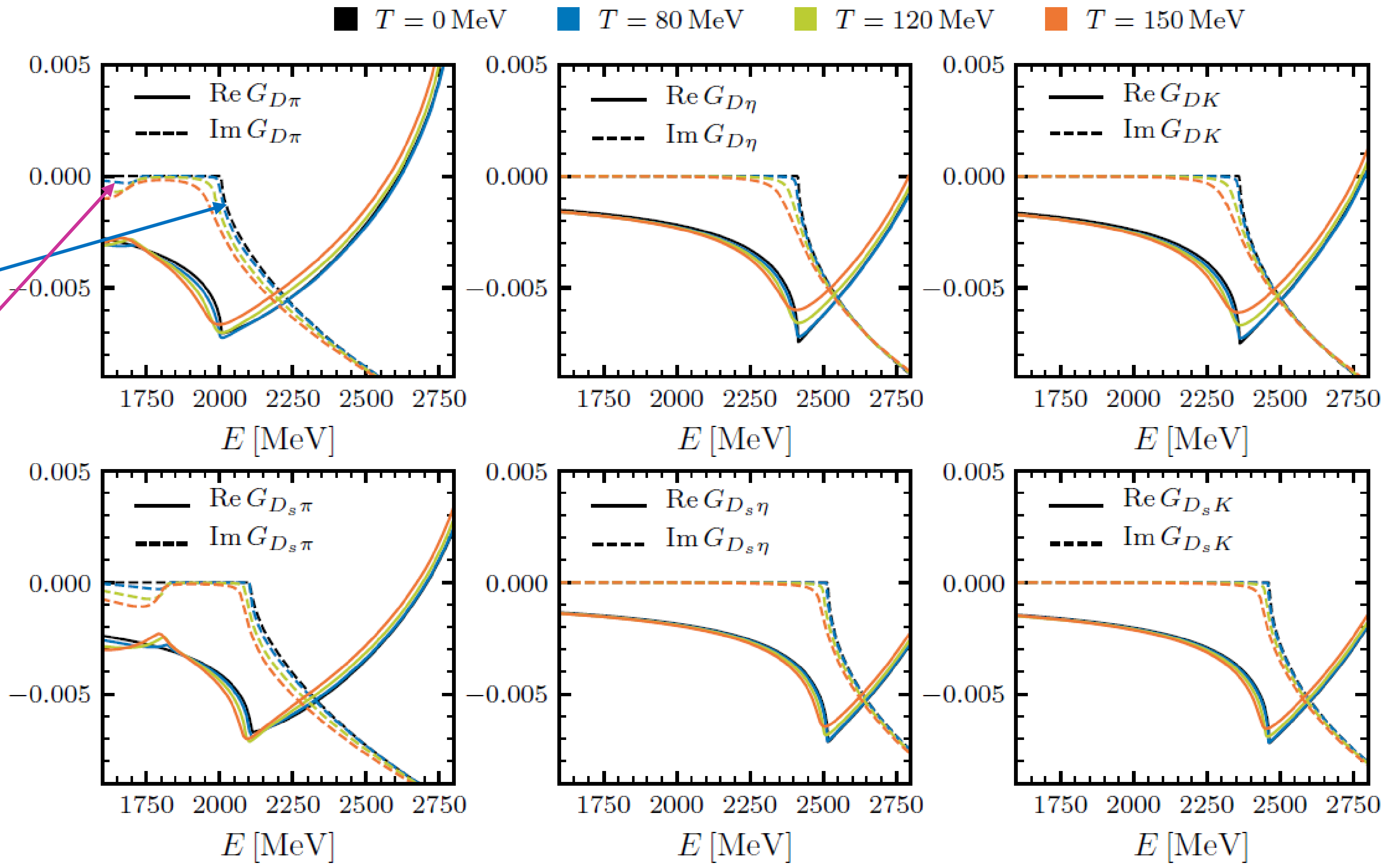


- Unitary cut

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

- Landau cut

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

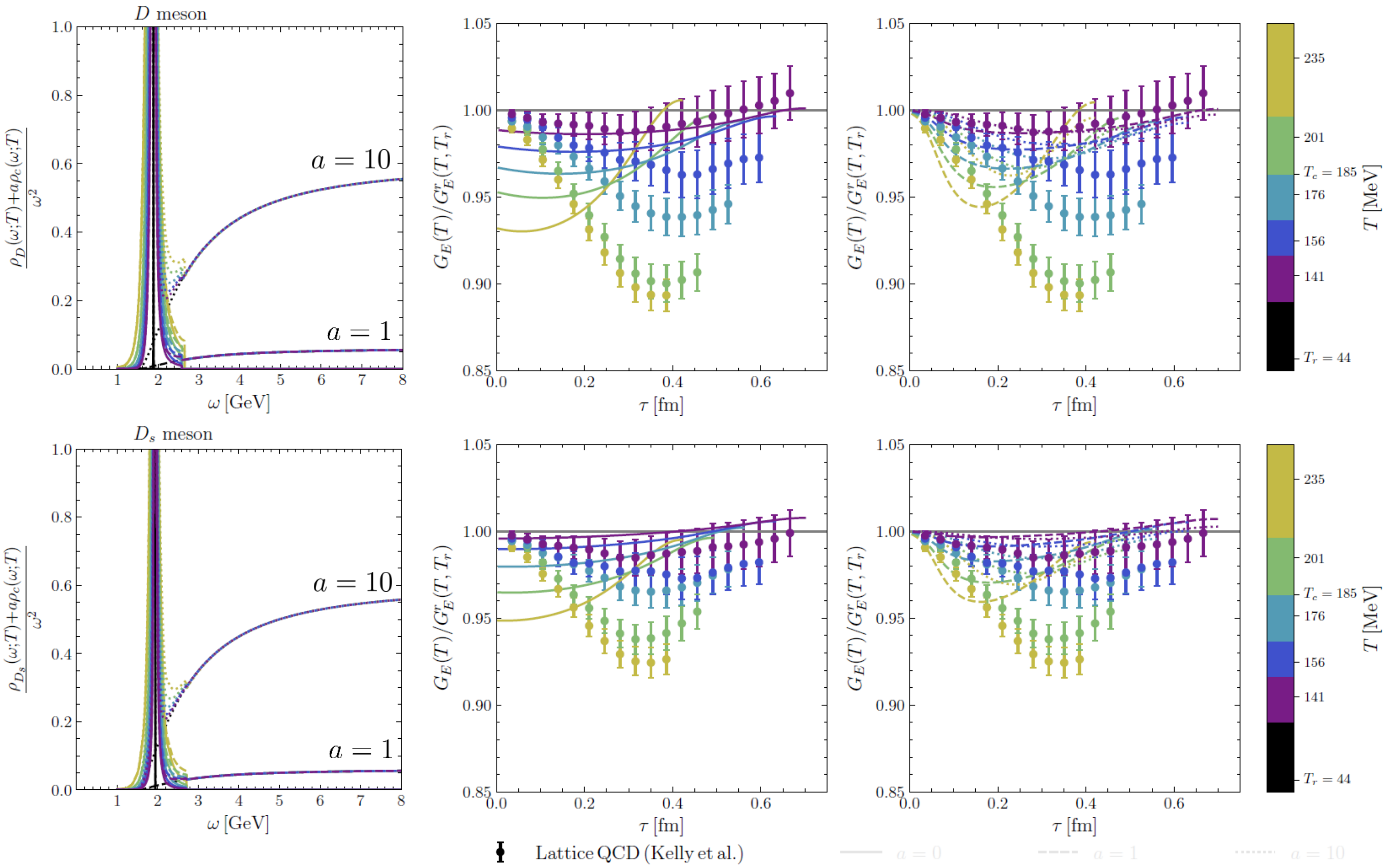


Results: Euclidean correlators and comparison with lattice QCD

Without continuum

With continuum

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



- 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)