Heavy meson properties in dense matter: the $T_{cc}(3875)^+$ and $D_{s0}^*(2317)$ cases

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Juan Nieves and **Laura Tolós**

Montesinos, Albaladejo, Nieves and Tolos, Phys. Rev. C 108 (2023) 035205
Montesinos, Albaladejo, Nieves and Tolos, Phys. Lett. B 853 (2024) 138656

Institute of Space Sciences
CSIC IEEC

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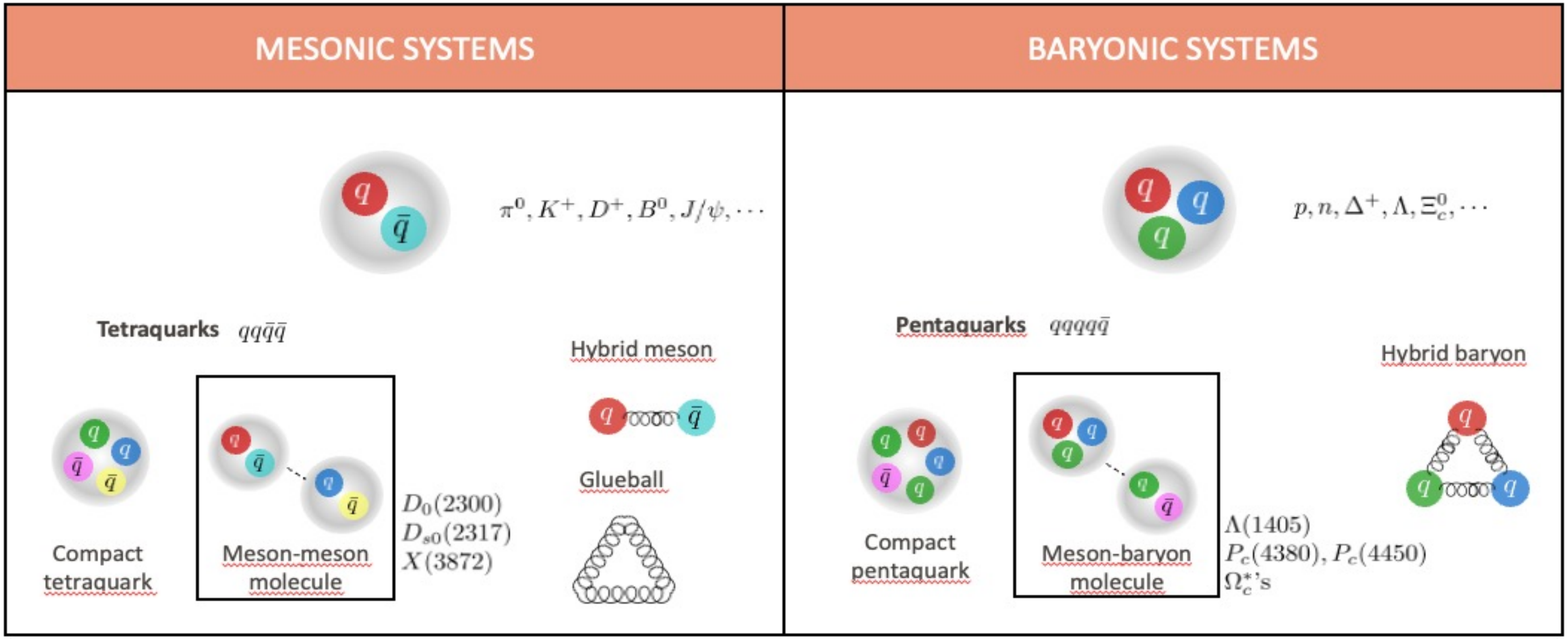
Heavy hadrons: non-exotic versus exotic



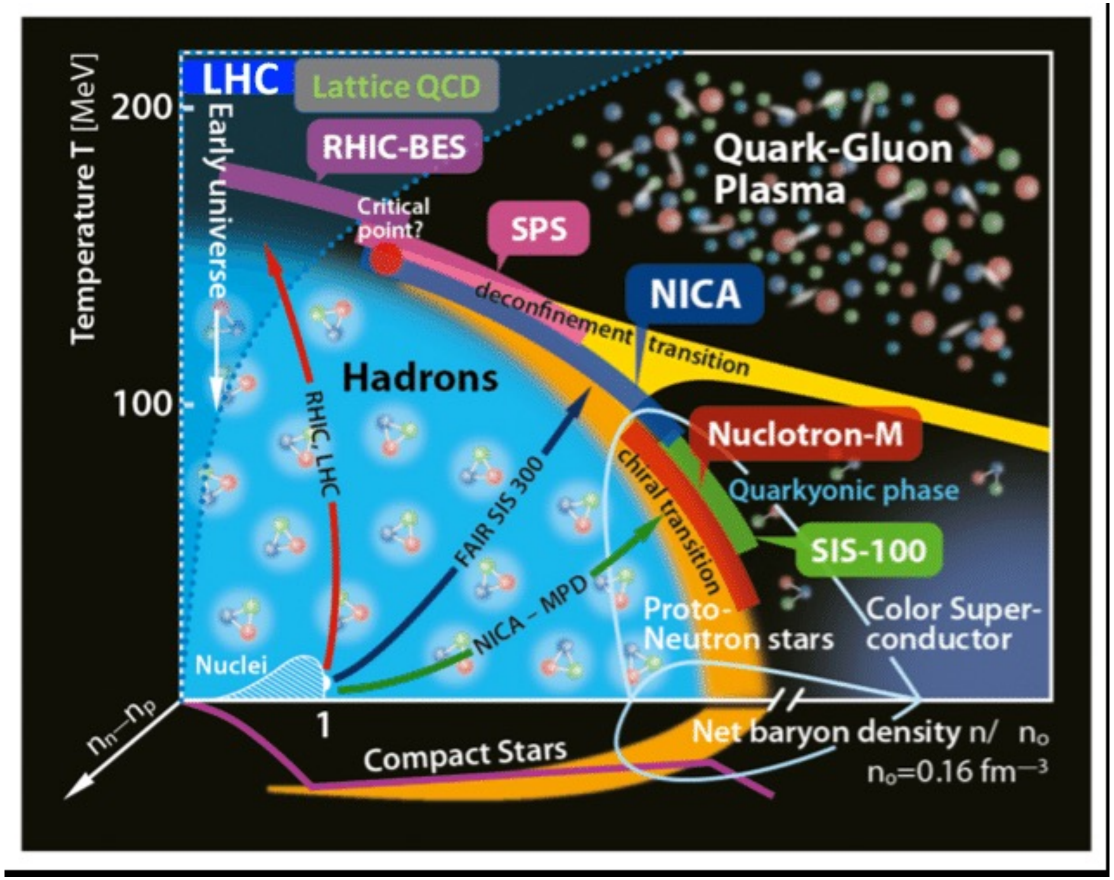
credit: G. Montana

There are many (excited) hadrons that do not accommodate in the qqq or $q\bar{q}$ picture

Other configurations allowed by QCD, e.g., $qqqq\bar{q}$, $qq\bar{q}\bar{q}$, etc., are called **exotic**

Heavy hadrons: hadrons containing at least one heavy quark (c/c̄ or b/b̄)

A dense and/or hot medium



Sahoo and Nayak ‘22

Several experimental facilities addressing matter under extreme conditions: LHC, RHIC, FAIR, J-PARC..

Theoretical tools to study QCD matter at density and/or high temperatures:

- Perturbative theories

(at very high temperatures or densities)

- Lattice QCD

(at high temperatures and small baryon densities)

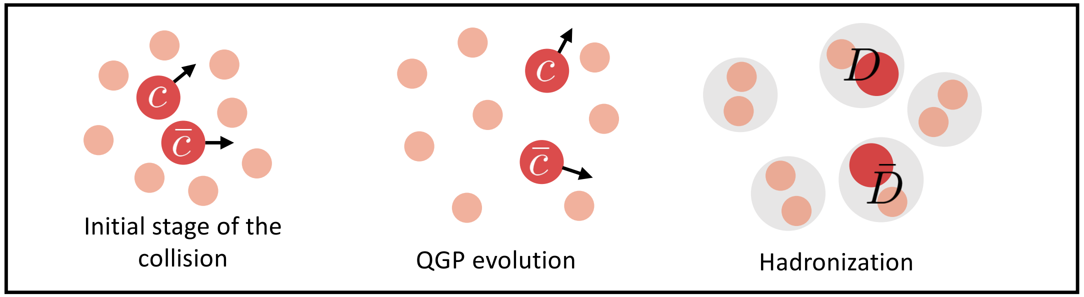
- **Non-perturbative effective hadronic theories**
- ..

Why heavy flavor in matter?

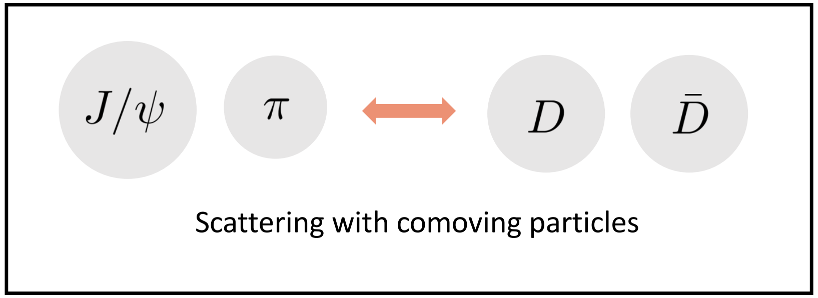
❖ A powerful probe for Quark Gluon Plasma (QGP)

Heavy quarks are created in the initial stage of the collision. Due to its large relaxation time, they can test QGP by analysing their properties in matter

color screening



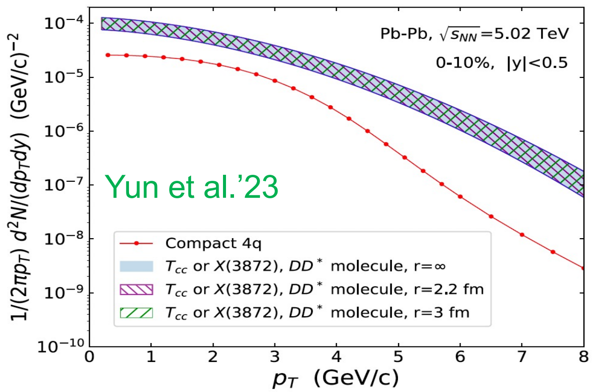
comover scattering



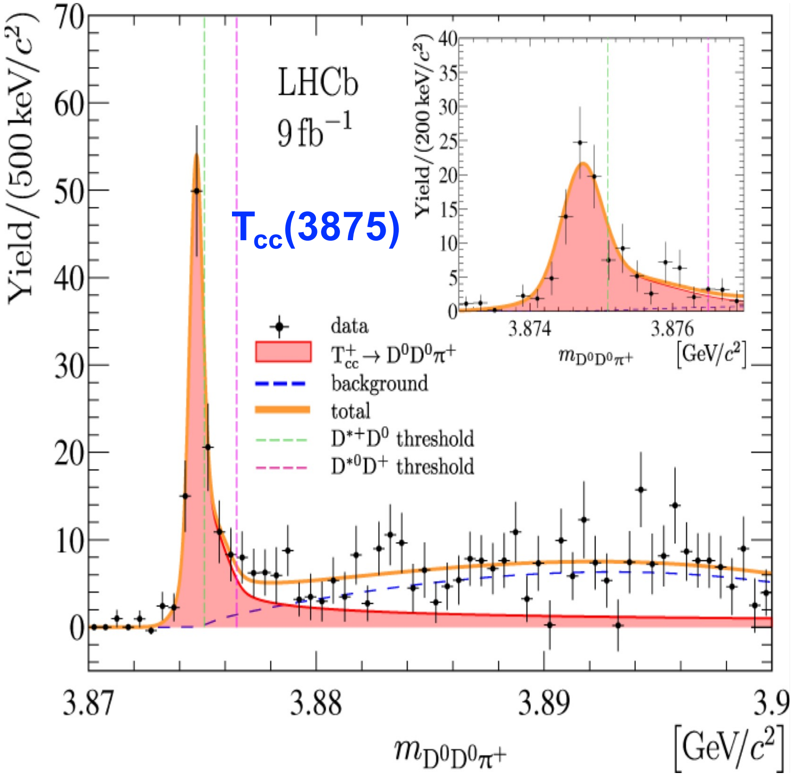
credit: G. Montana

❖ Interesting by itself, to understand their nature

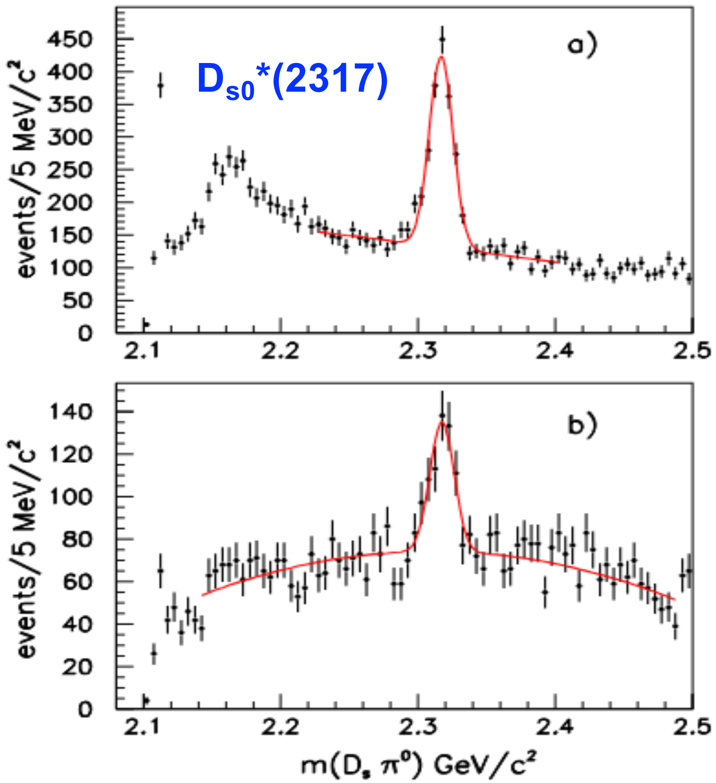
quark pure states or meson molecules or combination of both



the $T_{cc}(3875)^+$ and $D_{s0}^*(2317)$ cases



Aaij et al. (LHCb Collaboration),
Nature Communications 13 (2022) 3351



Aubert et al (BaBar Collaboration),
Phys. Rev. Lett. 90 (2003) 242001

$T_{cc}(3875)^+$ in dense matter

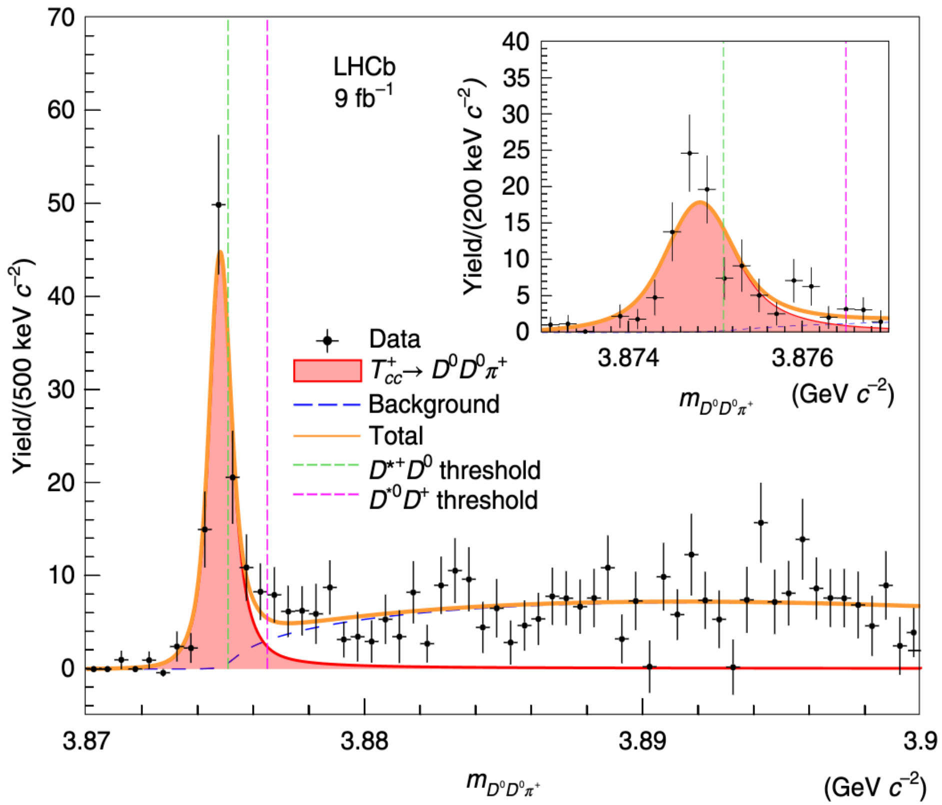
Montesinos, Albaladejo, Nieves and Tolos,
Phys. Rev. C 108 (2023) 035205

$T_{cc}(3875)^+$

observed in the
$D^0D^0\pi^+$ mass distribution

mass of $m_{thr} + \delta m_{exp}$
with m_{thr} =3875.09 MeV the $D^0\, D^{*+}$ threshold
$\delta m_{exp} = -360 \pm 40^{+4}{}_{-0}$ keV

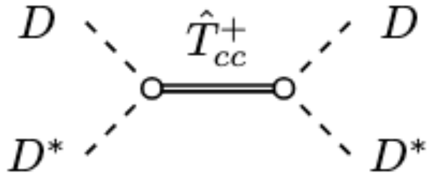
$\Gamma = 48 \pm 2^{+0}{}_{-14}$ keV



Aaij et al. (LHCb Collaboration), Nature Physics 18 (2022) 751
Aaij et al. (LHCb Collaboration), Nature Communications 13 (2022) 3351

$T_{cc}(3875)^+$ as an s-wave DD* state with $I(J^P)=0(1^+)$

We take two families of energy dependent potentials, expanded around threshold



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

By solving the on-shell Bethe-Salpeter equation

$$T^{-1}(s) = V^{-1}(s) - \Sigma_0(s)$$

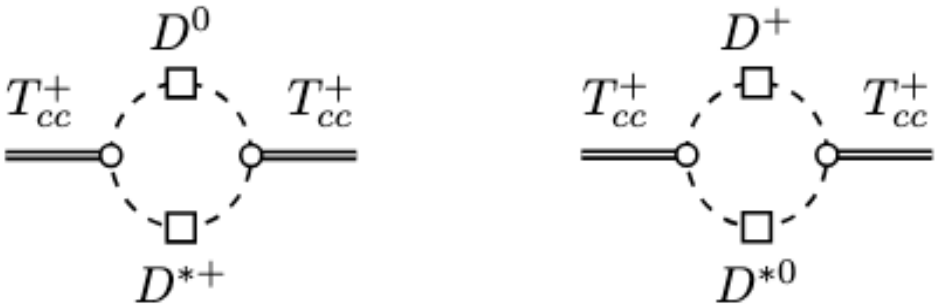
with $\Sigma_0(s)$ the D*D loop function in vacuum

We fix $C_1^{(')}$ and $C_2^{(')}$ to generate the $T_{cc}(3875)^+$ bound state at its mass (m_0) with certain molecular probability P_0

$$T^{-1}(m_0^2) = 0, \qquad \left.\frac{dT^{-1}(s)}{ds}\right|_{s=m_0^2} = \frac{1}{g_0^2} = -\frac{1}{P_0}\left.\frac{\partial \Sigma_0(s)}{\partial s}\right|_{s=m_0^2}$$

coupling to DD*

DD* scattering in dense matter



$$T^{-1}(s\,;\,\rho) = V_0^{-1}(s) - \Sigma(s\,;\,\rho)$$

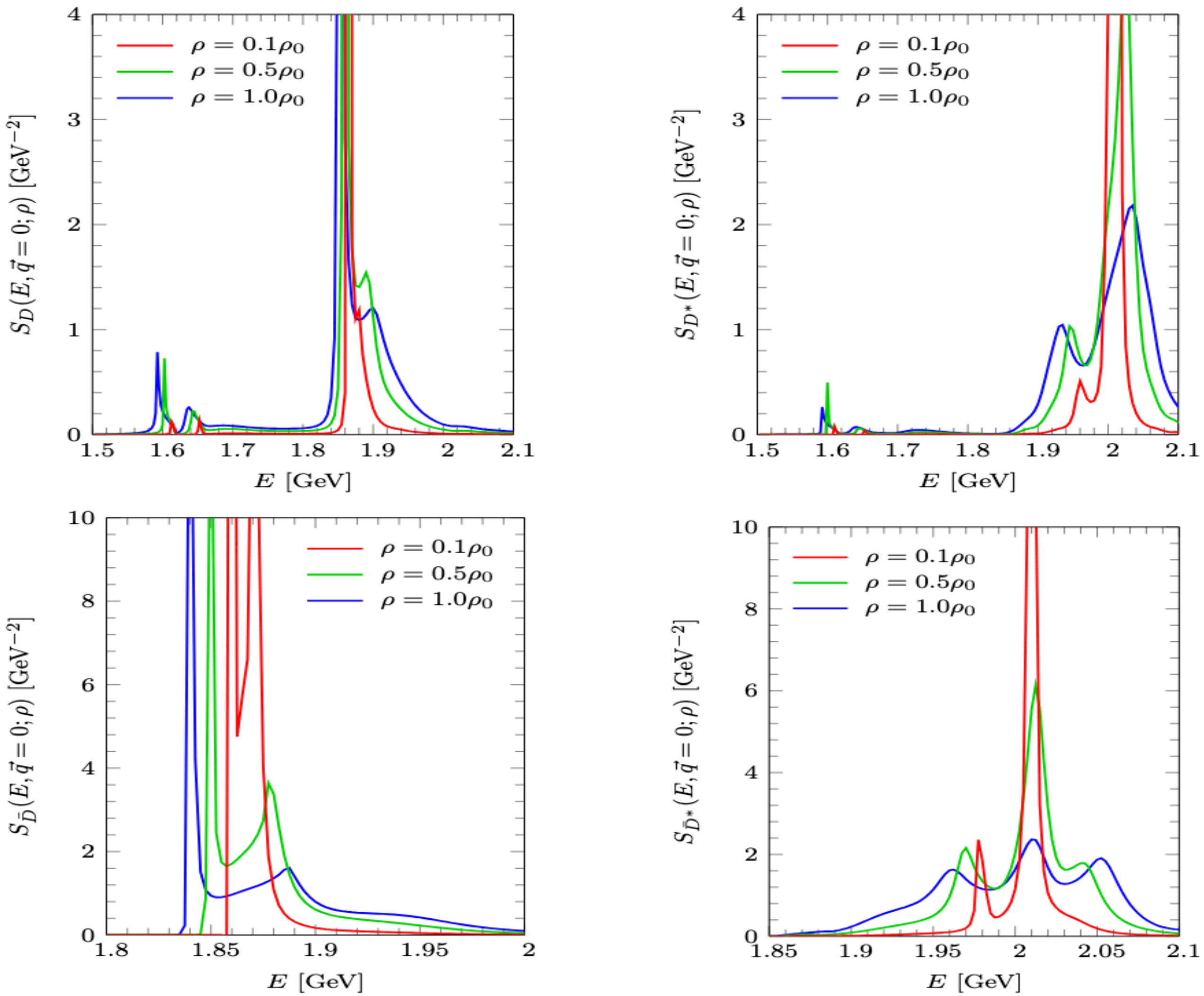
with $\Sigma(s;\rho)$ the D*D loop function in vacuum

We study not only T_{cc}^{+} (DD* state) but also $T_{\bar{c}\bar{c}}^{-}$ ($\bar{D}\bar{D}^{*}$ state)

The vacuum line shapes are the same (invariance under charge-conjugation symmetry)
What about in nuclear matter?

D, D*, $\bar{D}$, $\bar{D}$*
in nuclear matter

$D^{(*)}N$ interactions
different from $\bar{D}^{(*)}N$

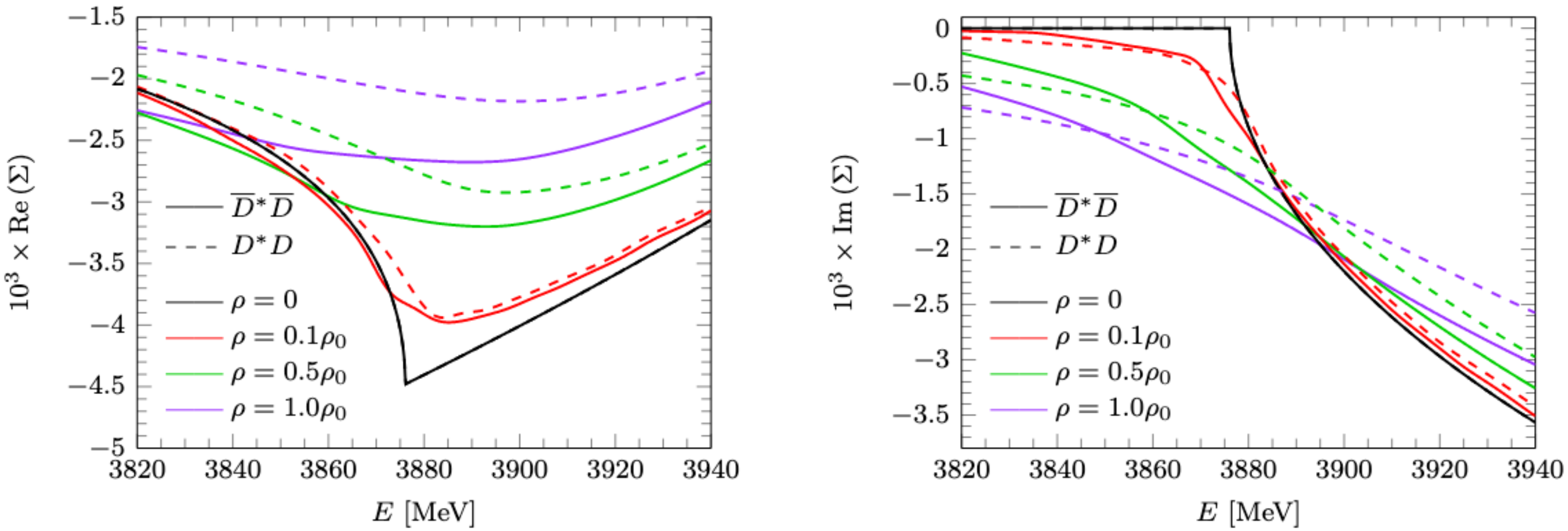


Tolos, Garcia-Recio, Nieves,
Phys. Rev. C 80 (2009) 065202

Garcia-Recio, Nieves and Tolos,
Phys. Lett. B 690 (2010) 369

Garcia-Recio, Nieves, Salcedo and Tolos,
Phys. Rev. C 85 (2012) 025203

DD* and $\bar{D}\bar{D}$* loop functions in nuclear matter



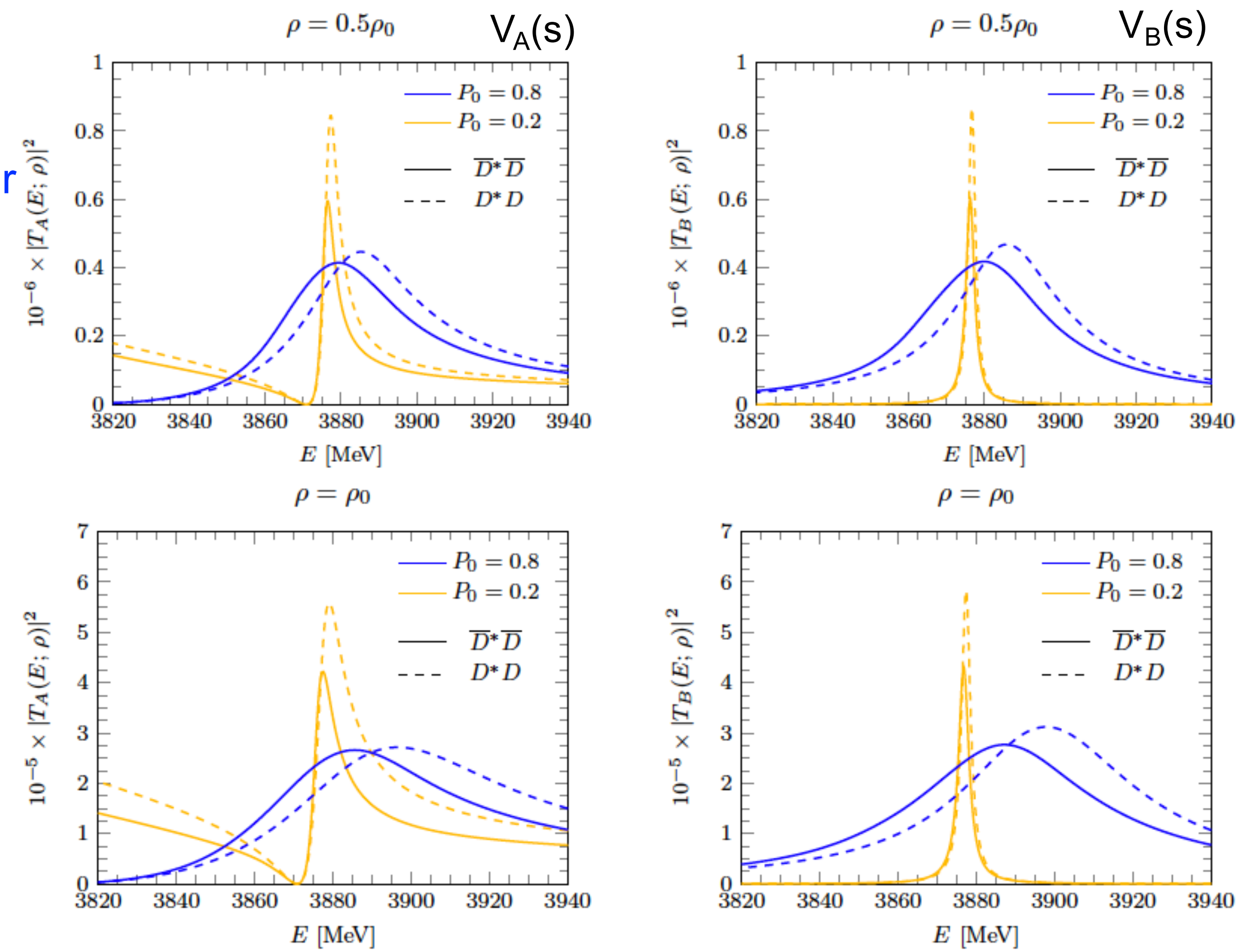
real part of loop functions smooths out with density

loop functions develop an imaginary part below vacuum threshold

different density dependence between DD* and $\bar{D}\bar{D}$* loop functions in nuclear matter

DD* and $\bar{D}\bar{D}^*$ scattering amplitudes in nuclear matter

T_{cc}^+ and $T_{\bar{c}\bar{c}}^-$
behave differently in nuclear matter



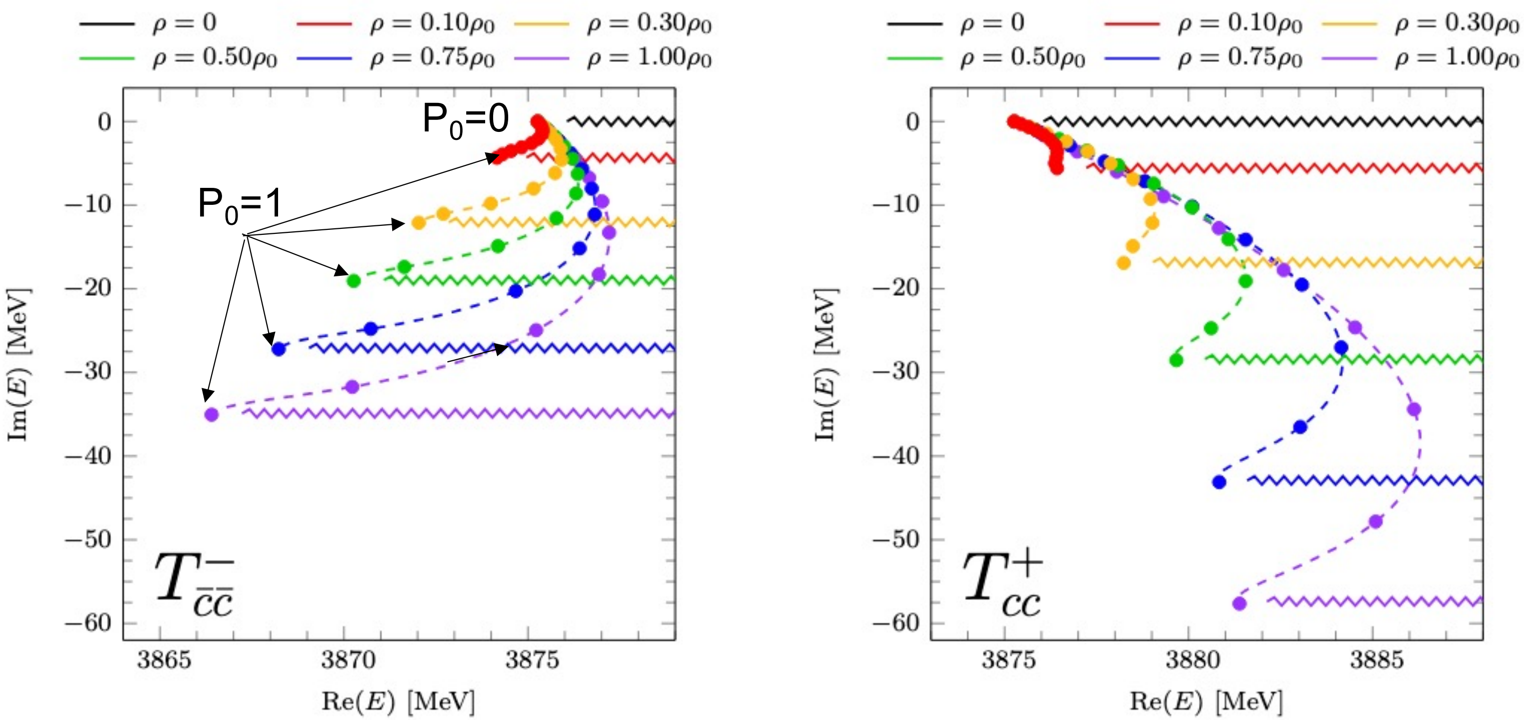
widths of T_{cc}^+ and $T_{\bar{c}\bar{c}}^-$ grow with density, specially for high P_0

differences between positions and widths of T_{cc}^+ and $T_{\bar{c}\bar{c}}^-$ arise with P_0 and density:

- $T_{\bar{c}\bar{c}}^-$ less massive than T_{cc}^+

- $T_{\bar{c}\bar{c}}^-$ narrower than T_{cc}^+

T_{cc}^+ and $T_{\bar{c}\bar{c}}^-$ pole positions in nuclear matter



quite different (ρ,P_0) pattern for T_{cc}^+ and $T_{\bar{c}\bar{c}}^-$:

T_{cc}^+ becomes broader and with larger mass in nuclear matter

$D_{s0}^*(2317)$ in dense matter

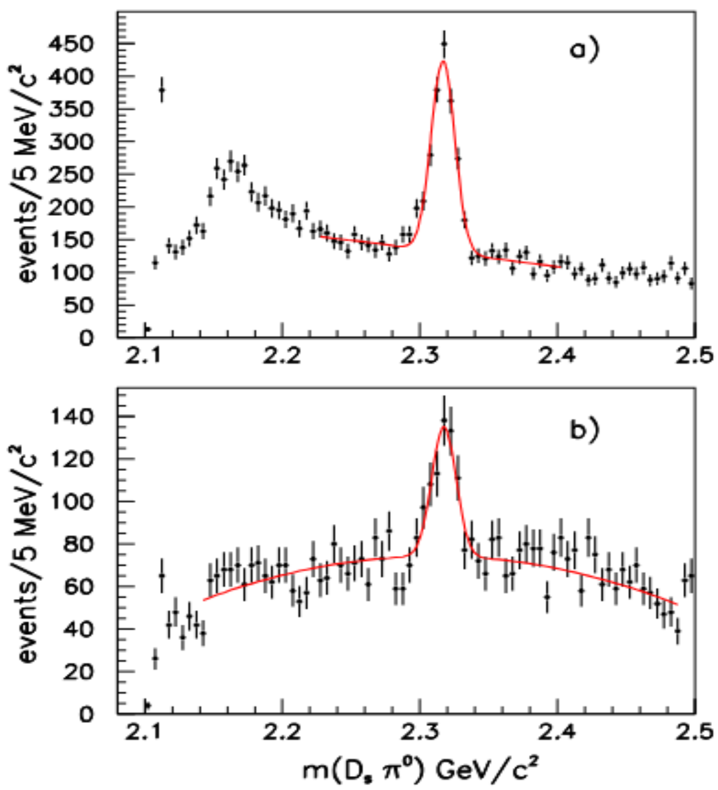
Montesinos, Albaladejo, Nieves and Tolos,
Phys. Lett. B 853 (2024) 138656

$D_{s0}^*(2317)$

first observed by BaBar in 2003 in inclusive $D_s^+\pi^0$ invariant mass and later confirmed by CLEO

far below predictions of quark model

located near DK and D*K thresholds



Aubert et al (BaBar Collaboration),
Phys. Rev. Lett. 90 (2003) 242001

$D_{s0}^*(2317)$ as an s-wave DK state with $I(J^P)=0(0^+)$

We take two families of energy dependent potentials, expanded around threshold

$$V_A(s) = C_1 + C_2[s - (m_D + m_K)^2]$$

$$V_B(s) = \frac{1}{C_1' + C_2'[s - (m_D + m_K)^2]}$$

By solving the on-shell Bethe-Salpeter equation

$$T^{-1}(s) = V^{-1}(s) - \Sigma_0(s)$$

with $\Sigma_0(s)$ the DK loop function in vacuum

We fix $C_1^{(')}$ and $C_2^{(')}$ to generate the $D^*_{s0}(2317)$ bound state at its mass (m_0) with certain molecular probability P_0

$$T^{-1}(m_0^2) = 0, \qquad \left.\frac{dT^{-1}(s)}{ds}\right|_{s=m_0^2} = \frac{1}{g_0^2} = -\frac{1}{P_0} \left.\frac{\partial \Sigma_0(s)}{\partial s}\right|_{s=m_0^2}$$

coupling to DK

DK scattering in dense matter

$$T^{-1}(s\,;\,\rho) = V_0^{-1}(s) - \Sigma(s\,;\,\rho)$$

with $\Sigma(s;\rho)$ the D*D loop function in vacuum

We study not only $D^*_{s0}(2317)^+$ (DK state) but also $D^*_{s0}(2317)^-$ ($\bar{D}\bar{K}$ state)

The vacuum line shapes are the same (invariance under charge-conjugation symmetry).
What about in nuclear matter?

D, K, D̄, K̄
in nuclear matter

DN different from D̄N

Tolos, Garcia-Recio, Nieves,
Phys. Rev. C 80 (2009) 065202

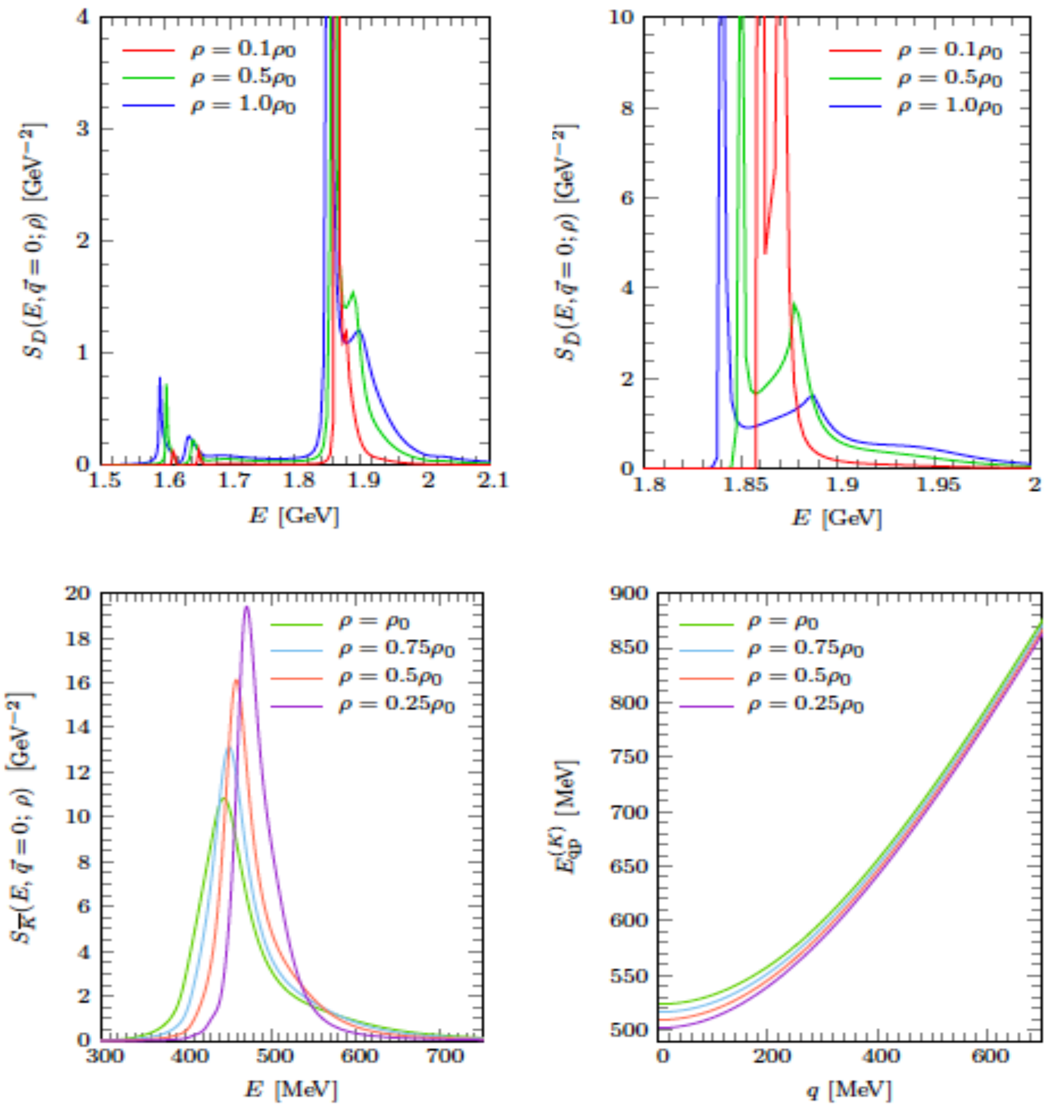
Garcia-Recio, Nieves and Tolos,
Phys. Lett. B 690 (2010) 369

Garcia-Recio, Nieves, Salcedo and Tolos,
Phys. Rev. C 85 (2012) 025203

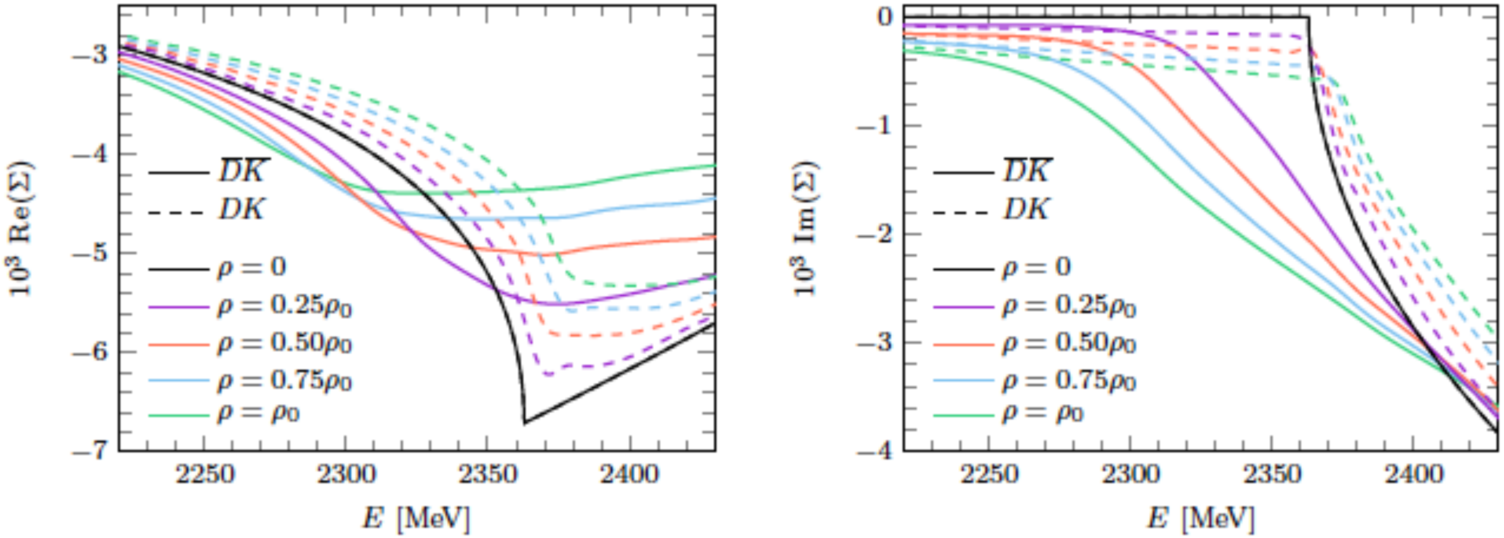
KN much more different from K̄N
than D*N from D̄*N

Tolos, Ramos and Oset,
Phys. Rev. C 74 (2006) 01520377

Tolos, Cabrera and Ramos,
Phys. Rev. C 78 (2008) 045205



DK and $\bar{D}\bar{K}$ loop functions in nuclear matter



different density dependence between DK and $\bar{D}\bar{K}$ loop functions in nuclear matter

difference between DK and $\bar{D}\bar{K}$ loop functions in matter larger than for DD* and $\bar{D}\bar{D}$*:
D_{s0}^{*+} and D_{s0}^{*-} behave in matter much differently than T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$

DK and $\bar{D}\bar{K}$ scattering amplitudes in nuclear matter

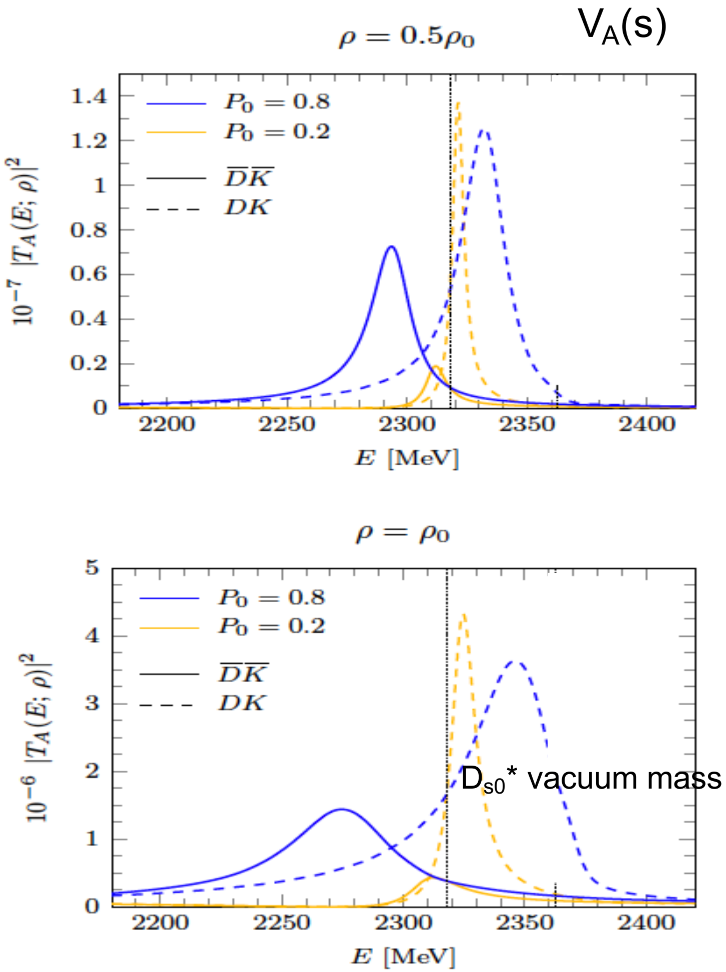
D_{s0}^{*+} and D_{s0}^{*-}
behave very differently
in nuclear matter

widths of D_{s0}^{*+} and D_{s0}^{*-} grow with density, specially for high P_0

differences between positions and widths of D_{s0}^{*+} and D_{s0}^{*-} arise with P_0 and density:

- D_{s0}^{*-} less massive than D_{s0}^{*+}

- D_{s0}^{*-} is wider than D_{s0}^{*+}



Conclusions

- Lines shapes of $T_{cc}(3875)^+$ vs $T_{\bar{c}\bar{c}}(3875)^-$ as well as $D_{s0}^*(2317)^+$ vs $D_{s0}^*(2317)^-$ are necessarily the same in free space, but they are different in nuclear matter

- This large charge-conjugation asymmetry in matter stems from the very different meson and antimeson interactions with the nucleons in the dense medium

- The changes strongly depend on the molecular probability of these states, as the compact and molecular components of the wave function will get renormalized differently

- These effects are more drastic in the $D_{s0}^*(2317)^+$ vs $D_{s0}^*(2317)^-$ case that those found for the $T_{cc}(3875)^+$ vs $T_{\bar{c}\bar{c}}(3875)^-$ due to the larger differences for KN and $\bar{K}$N interactions as compared to D*N and $\bar{D}$*N ones

- If these distinct density patterns were confirmed experimentally(?), it would give support to the presence of important molecular components in these exotic states.

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