“QNP2024 - The 10th International Conference on Quarks and Nuclear Physics"

QNP 2024

The $\chi_{c1}(3872), T_{cc}(3875)$ and $D^*_{s0}(2317)$ in nuclear matter

PRC 104 (2021) 035203, PRC 108 (2023) 035205, PLB 853 (2024) 138656

V. Montesinos, M. Albaladejo, J. Nieves, L. Tolós

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC Institute of Space Sciences

EXCELENCIA MARÍA DE MAEZTU

EUROPEAN UNION EUROPEAN REGIONAL DEVELOPMENT FUND A WAY TO MAKE EUROPE

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

VNIVERSITAT DE VALÈNCIA

EXCELENCIA SEVERO OCHOA

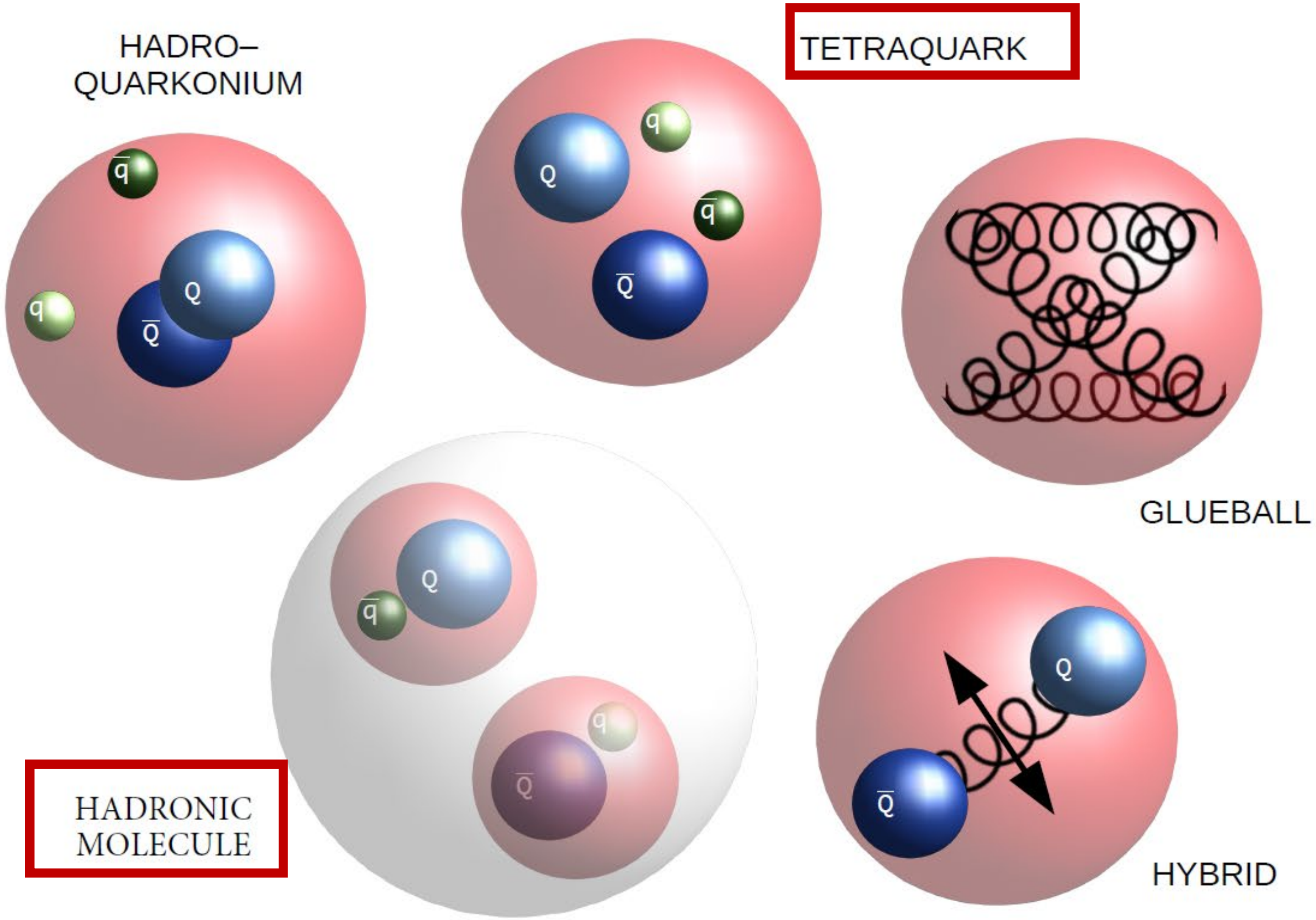
STRONG-2020

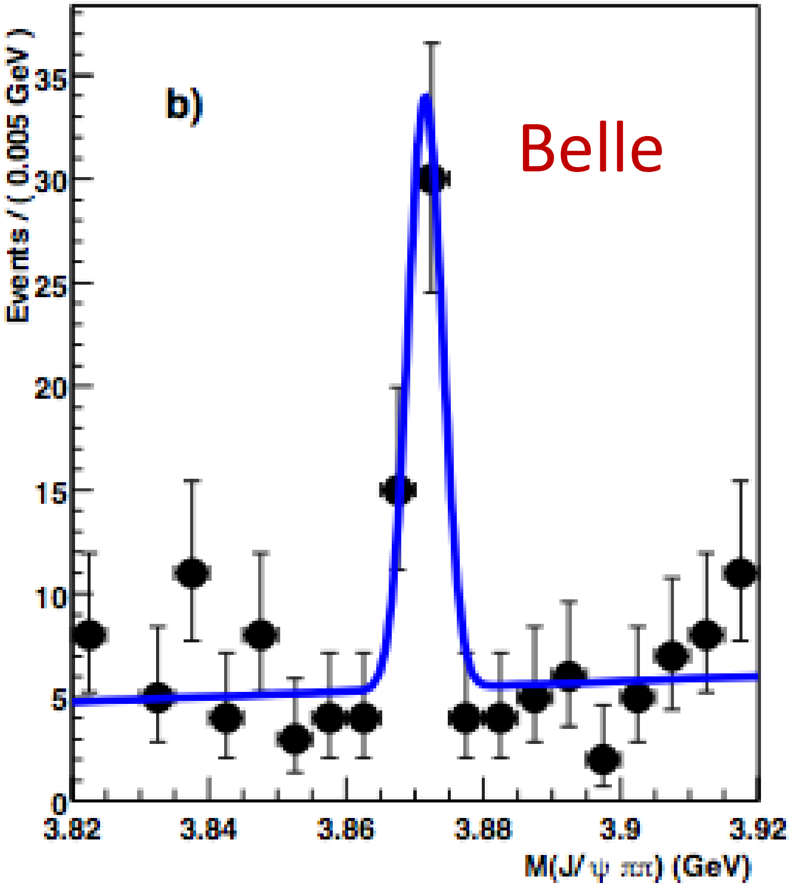
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 824093

Outline

exotic states: difficult to accommodate within constituent quark models

- $D\bar{D}^*$ scattering and $\chi_{c1}(3872)$ in nuclear matter
- Properties of the $T_{cc}(3875)^+$ and $T_{\bar{c}\bar{c}}(3875)^-$ in nuclear matter
- The $D^*_{s0}(2317)^{\pm}$ in matter: charge-conjugation asymmetry and molecular content



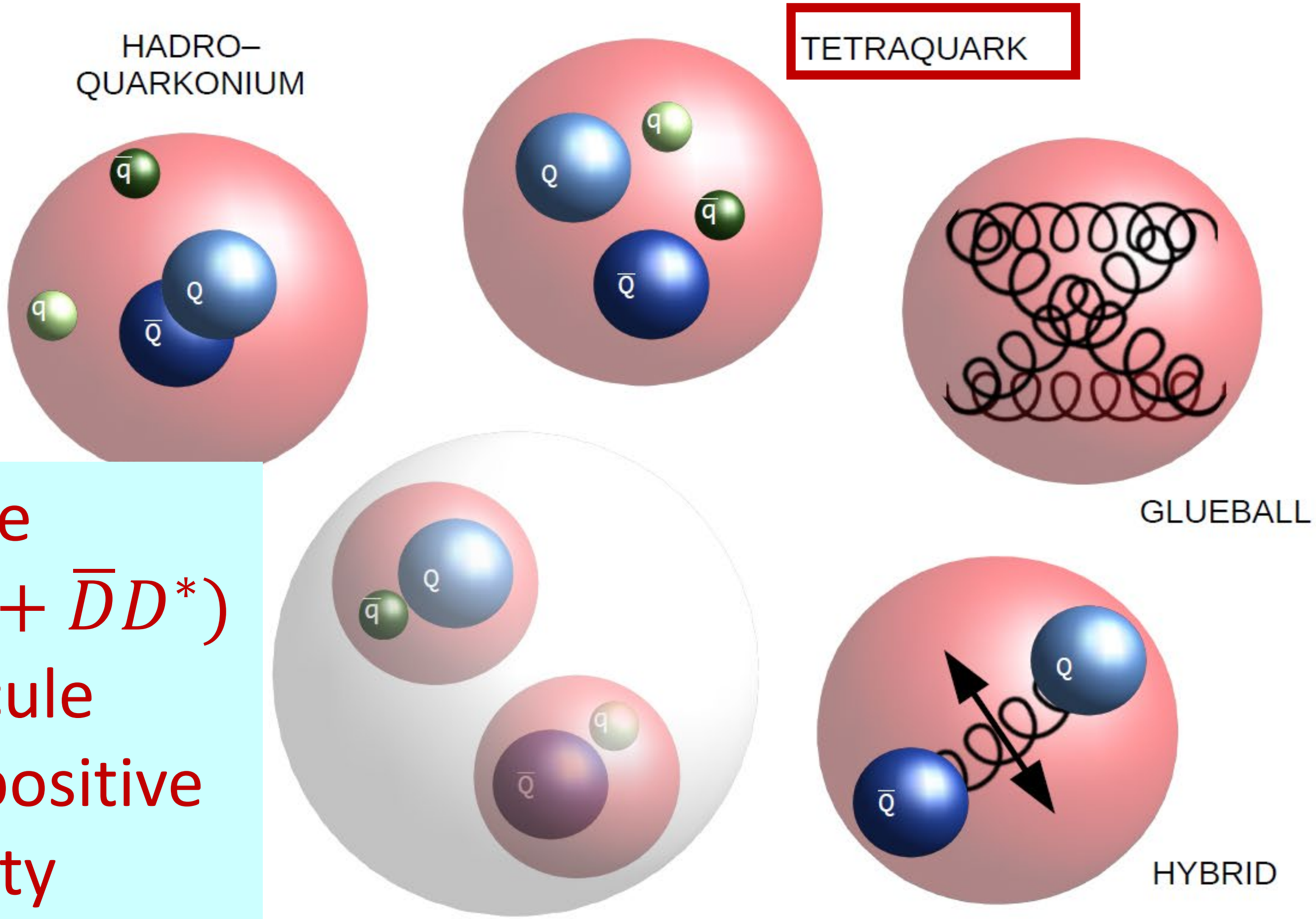


$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ **Decay**

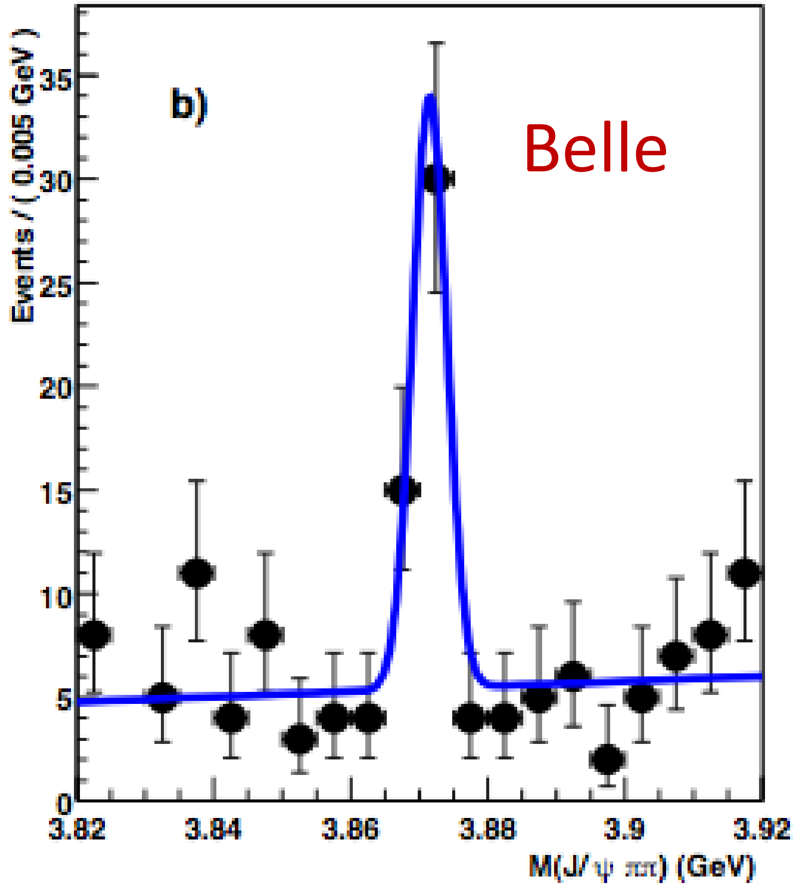
$\chi_{c1}(3872)$ aka $X(3872)$, $J^{PC} = 1^{++}$

First charmonium-like state discovered [Belle, PRL91 (2003) 262001] (> 2500 cites)

the mass of the $\chi_{c1}(3872)$ was found to be 3871.64±0.06 MeV, **just 70±120 keV below the $D^0\bar{D}^{*0}$ threshold and the width is of the order of 1 MeV.** The proximity of the χc1(3872) the $D^0\bar{D}^{*0}$ threshold → Breit-Wigner function ??



S-wave $(D\bar{D}^* + \bar{D}D^*)$ molecule with positive C-parity



Picture by Soeren Lange

$B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-} J/\psi$ Decay

$\chi_{c1}(3872)$ aka $X(3872)$, $J^{PC} = 1^{++}$

First charmonium-like state discovered [Belle, PRL91 (2003) 262001] (> 2500 cites)

the mass of the $\chi_{c1}(3872)$ was found to be 3871.64±0.06 MeV – **just 70±120 keV below the $D^0\bar{D}^{*0}$ threshold**
the width is of the order of 1 MeV. The proximity of the χc1(3872) the $D^0\bar{D}^{*0}$ threshold → Breit-Wigner function ??

$\chi_{c1}(3872)$ in the free space: study $D\bar{D}^*$ scattering in the $(I)J^{PC} = (0)1^{++}$ channel

$$1 - P_0 = g^2 \left.\frac{\partial V^{-1}}{\partial s}\right|_{s=m_0^2}$$

$$1/g^2 = -\Sigma_0'(m_0^2)$$

$T = V + V\Sigma T$, Bethe-Salpeter equation:

- restores elastic unitary
- poles FRS & SRS: bound states, resonances

$$V(s) = \frac{1}{\Sigma_0(m_0^2)} + \frac{\Sigma_0'(m_0^2)}{[\Sigma_0(m_0^2)]^2}\frac{1-P_0}{P_0}(s-m_0^2)$$

P_0: molecular probability (Weinberg)

m_0 is the mass of the $\chi_{c1}(3872)$ in the vacuum

meson propagators in the free space

$$\Sigma_{UW}(s) = i\int \frac{d^4q}{(2\pi)^4}\Delta_U(P-q)\Delta_W(q)$$

$D\bar{D}^*$ loop function in the free space

$\chi_{c1}(3872)$ embedded in a nuclear medium: study $D\bar{D}^*$ scattering in presence of nucleons

$T = V + V\Sigma T$, Bethe-Salpeter equation:

- restores elastic unitary
- poles FRS & SRS: bound states, resonances

$$V(s) = \frac{1}{\Sigma_0(m_0^2)} + \frac{\Sigma_0'(m_0^2)}{[\Sigma_0(m_0^2)]^2} \frac{1 - P_0}{P_0} (s - m_0^2)$$

P_0: molecular probability (Weinberg)

m_0 is the mass of the $\chi_{c1}(3872)$ in the vacuum

meson propagators in the nuclear medium

$$\Sigma_{UW}(s) = i \int \frac{d^4q}{(2\pi)^4} \Delta_U(P-q)\Delta_W(q)$$

$D\bar{D}^*$ loop function inside of the nuclear environment

$$\Delta_Y(q\,;\rho) = \frac{1}{(q^0)^2 - \omega_Y^2(\vec{q}^{\,2}) - \Pi_Y(q^0,\vec{q}\,;\rho)}$$

meson in the nuclear medium acquires a **density-dependent self-energy**

$$= \int_0^\infty d\omega\left(\frac{S_Y(\omega,|\vec{q}\,|)}{q^0-\omega+i\varepsilon} - \frac{S_{\bar{Y}}(\omega,|\vec{q}\,|)}{q^0+\omega-i\varepsilon}\right)$$

Källen-Lehmann representation

with $\omega_Y(\vec{q}^{\,2}) = \sqrt{m_Y^2+\vec{q}^{\,2}}$. From the above equation, it follows that for $q^0 > 0$

$$S_{D^{(*)},\bar{D}^{(*)}}(q^0,\vec{q}\,;\rho) = -\frac{1}{\pi}\mathrm{Im}\,\Delta_{D^{(*)},\bar{D}^{(*)}}(q^0,\vec{q}\,;\rho)$$
$$= -\mathrm{Im}\Pi_{D^{(*)},\bar{D}^{(*)}}(q^0,\vec{q}\,;\rho) \times \frac{|\Delta_{D^{(*)},\bar{D}^{(*)}}(q^0,\vec{q}\,;\rho)|^2}{\pi}.$$

$\chi_{c1}(3872)$ embedded in a nuclear medium: study $D\bar{D}^*$ scattering in presence of nucleons

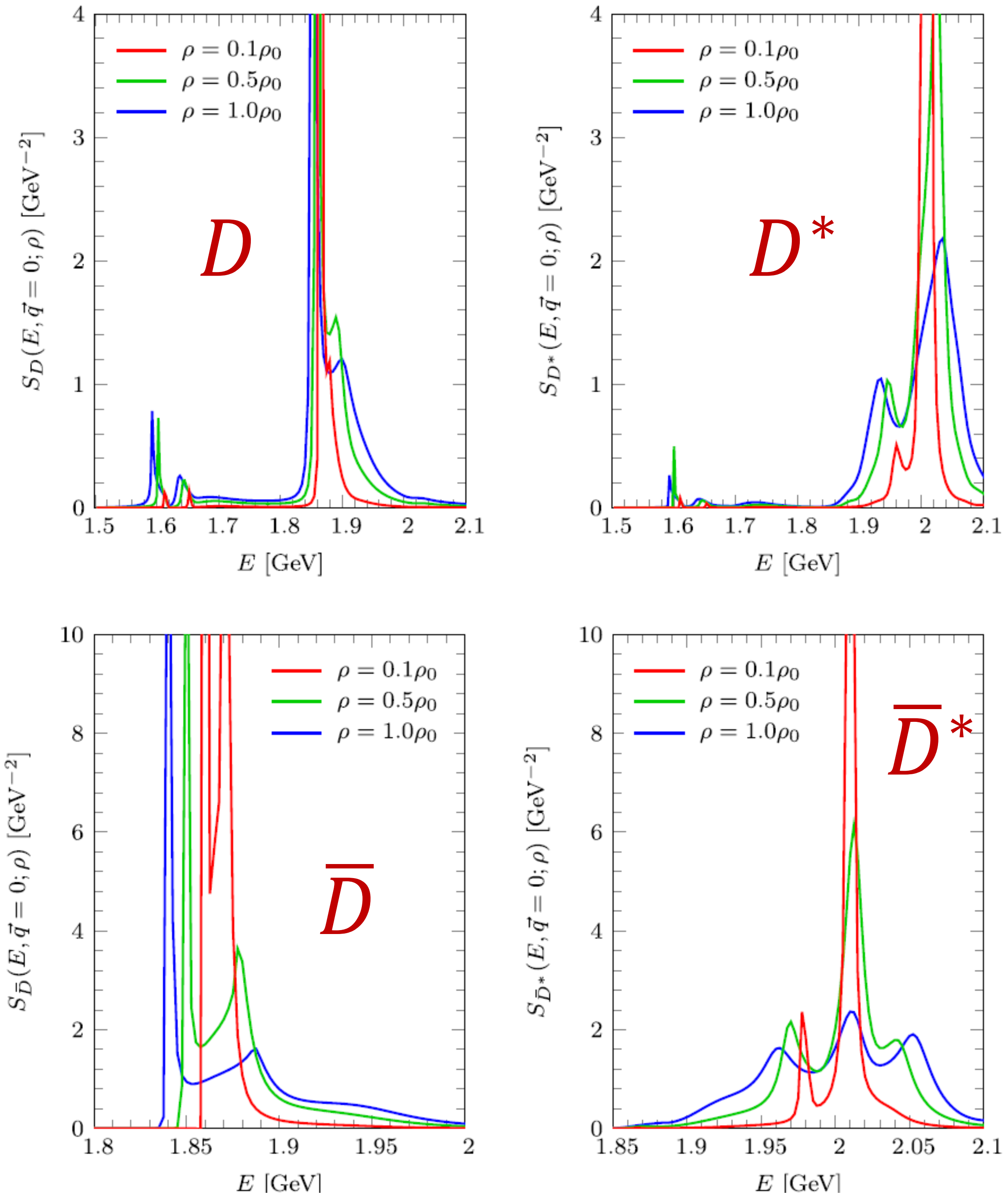
spectral function is determined by the self-energy

$T = V + VGT$, Bethe-Salpeter equation:

- restores elastic unitary
- poles FRS & SRS: bound states, resonances

$$\Sigma_{UW}(s;\rho) = i\int \frac{d^4q}{(2\pi)^4}\Delta_U(P-q)\Delta_W(q),$$

meson propagators in the nuclear medium



Nuclear medium spectral functions:

- L. Tolós, C. García-Recio, JN, Phys. Rev. C80 (2009) 065202; Phys. Lett. B690 (2010) 369
- C. García-Recio, JN, L. L. Salcedo, L. Tolos, Phys. Rev. C85 (2012) 025203

$$t^{\rho,CSIJ}(R) = \left[1 - v^{CSIJ}(\sqrt{t})\, g^{\rho}_{CSIJ}(R)\right]^{-1} v^{CSIJ}(\sqrt{t}),$$

$$\Pi_{D(\bar{D})}(q^0, \vec{q};\, \rho) = \int_{p \leq p_F} \frac{d^3p}{(2\pi)^3} \left[t^{\rho,0,1/2}_{D(\bar{D})N}(R^0, \vec{R}) + 3\, t^{\rho,1,1/2}_{D(\bar{D})N}(R^0, \vec{R}) \right],$$

v^{CSIJ}: $D^{(*)}N$ and $\bar{D}^{(*)}N$ potential, C. García-Recio et al PRD79 (2009) 054004

g^{ρ}_{CSIJ}: charmed meson-baryon loop in nuclear matter. We consider Pauli blocking effects on the nucleons together with self-energy insertions of the $D^{(*)}$ and $\bar{D}^{(*)}$ mesons. The self-energy is obtained self-consistently from the in-medium $D^{(*)}N$ and $\bar{D}^{(*)}N$ effective interaction $t^{\rho,CSIJ}$.

$\chi_{c1}(3872)$ embedded in a nuclear medium: study $D\bar{D}^*$ scattering in presence of nucleons.

for the $I^C = 0^+$ channel, m_0 is the mass of the $\chi_{c1}(3872)$ in the vacuum

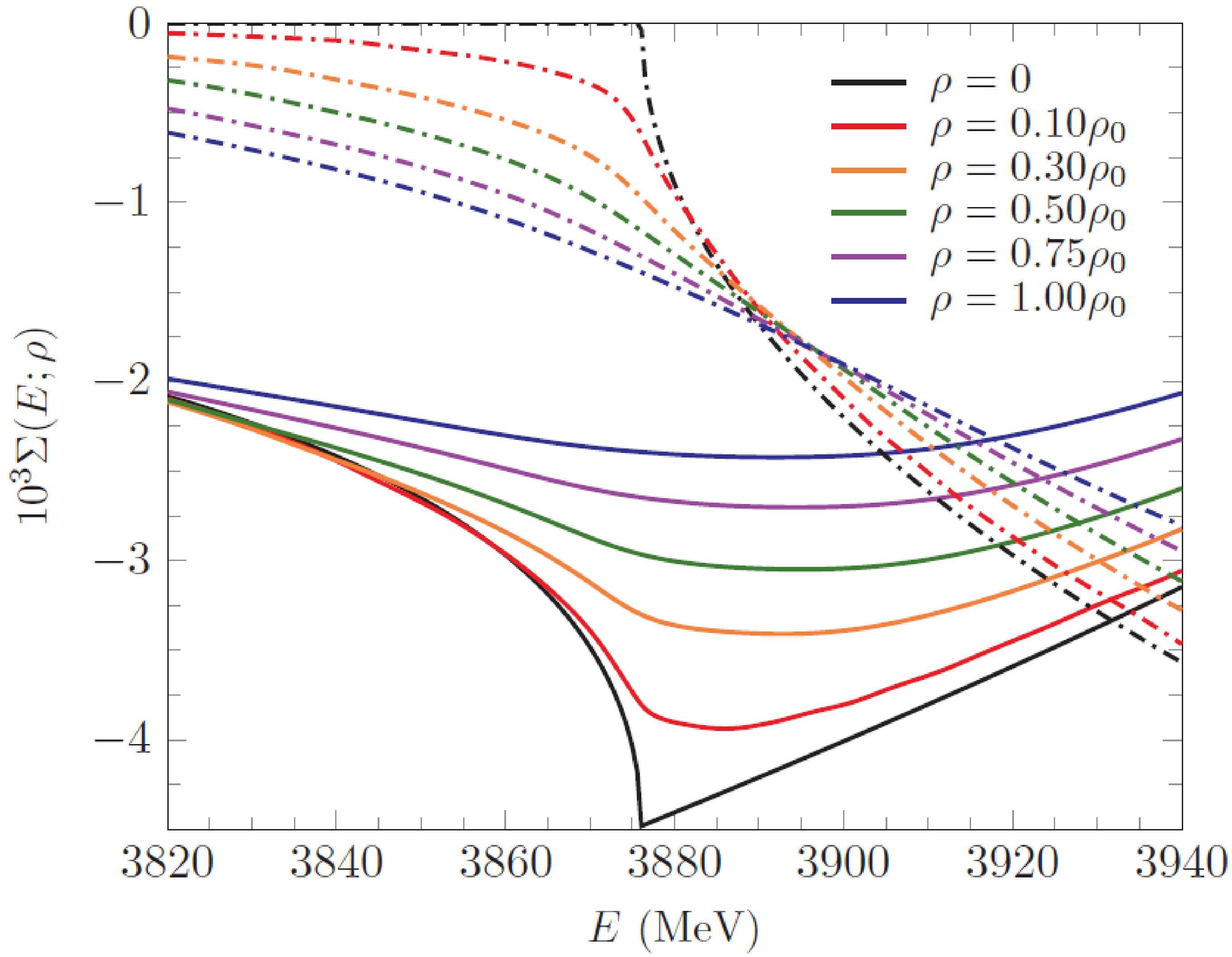
$$T_{0X}^{-1}(s;\rho) = V_{0X}^{-1}(s) - \Sigma(s;\rho).$$

$$V_A(s) = \frac{1}{\Sigma_0(m_0^2)} + \frac{\Sigma_0'(m_0^2)}{[\Sigma_0(m_0^2)]^2}\frac{1-P_0}{P_0}(s-m_0^2)$$

P_0: molecular probability (Weinberg)

$$f_{UW}(\Omega,|\vec{P}|) = \frac{1}{4\pi}\int_0^\Lambda d^3\vec{q}\int_0^\Omega d\omega S_U(\omega,|\vec{P}-\vec{q}|) \times S_W(\Omega-\omega,|\vec{q}|)$$

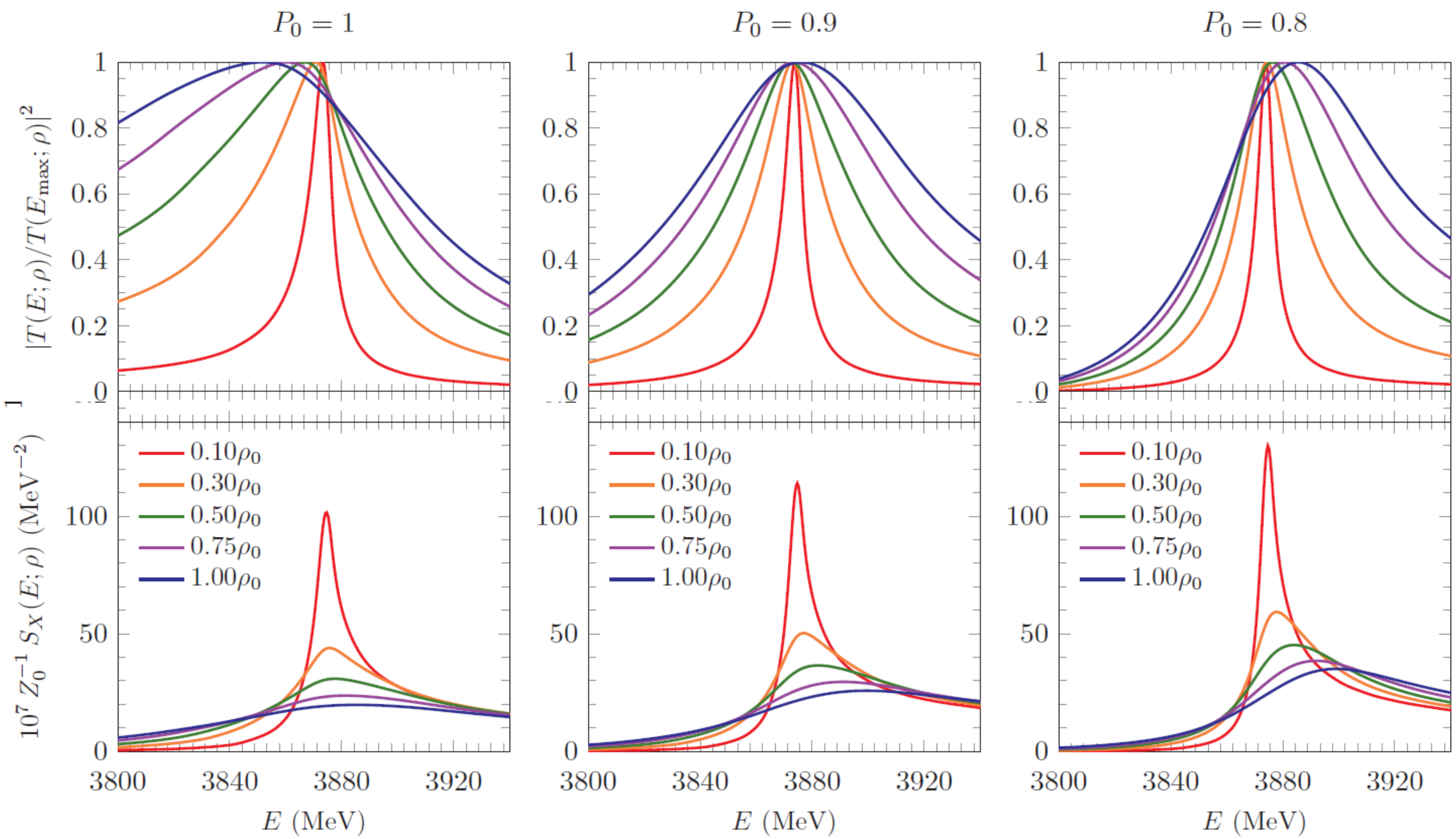
$$\Sigma(P^0,|\vec{P}|;\rho) = \frac{1}{4\pi^2}\int_0^\infty d\Omega\left(\frac{1}{P^0-\Omega+i\varepsilon} - \frac{1}{P^0+\Omega-i\varepsilon}\right) \times (f_{D\bar{D}^*}(\Omega,|\vec{P}|) + f_{D^*\bar{D}}(\Omega,|\vec{P}|)),$$

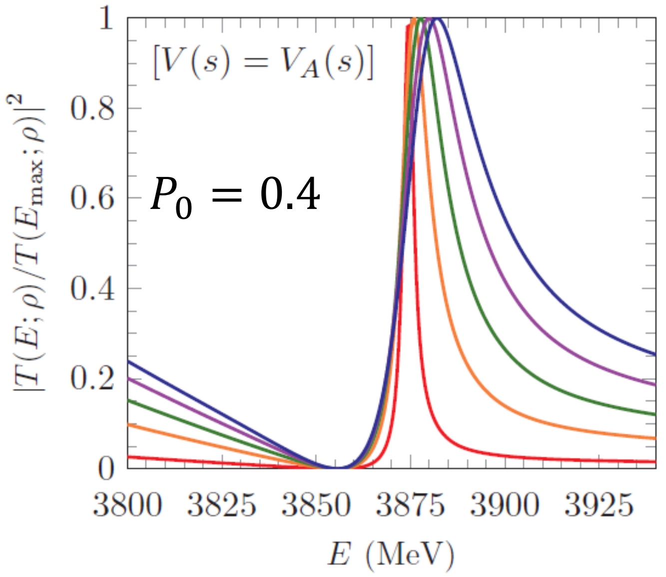


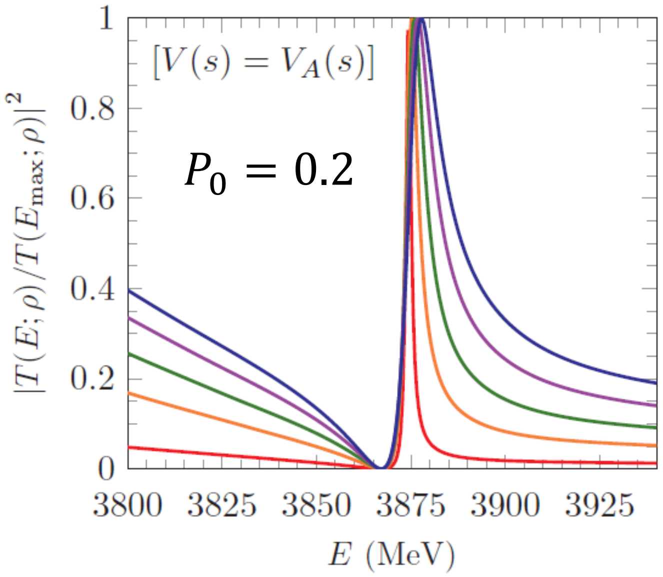
Real and imaginary parts of the $(D\bar{D}^* + \bar{D}\,D^*)[C = +1]$ loop function inside of the nuclear environment, for different nuclear matter densities ρ.

for the $I^C = 0^+$ channel,

$$T_{0X}^{-1}(s;\rho) = V_{0X}^{-1}(s) - \Sigma(s;\rho).$$

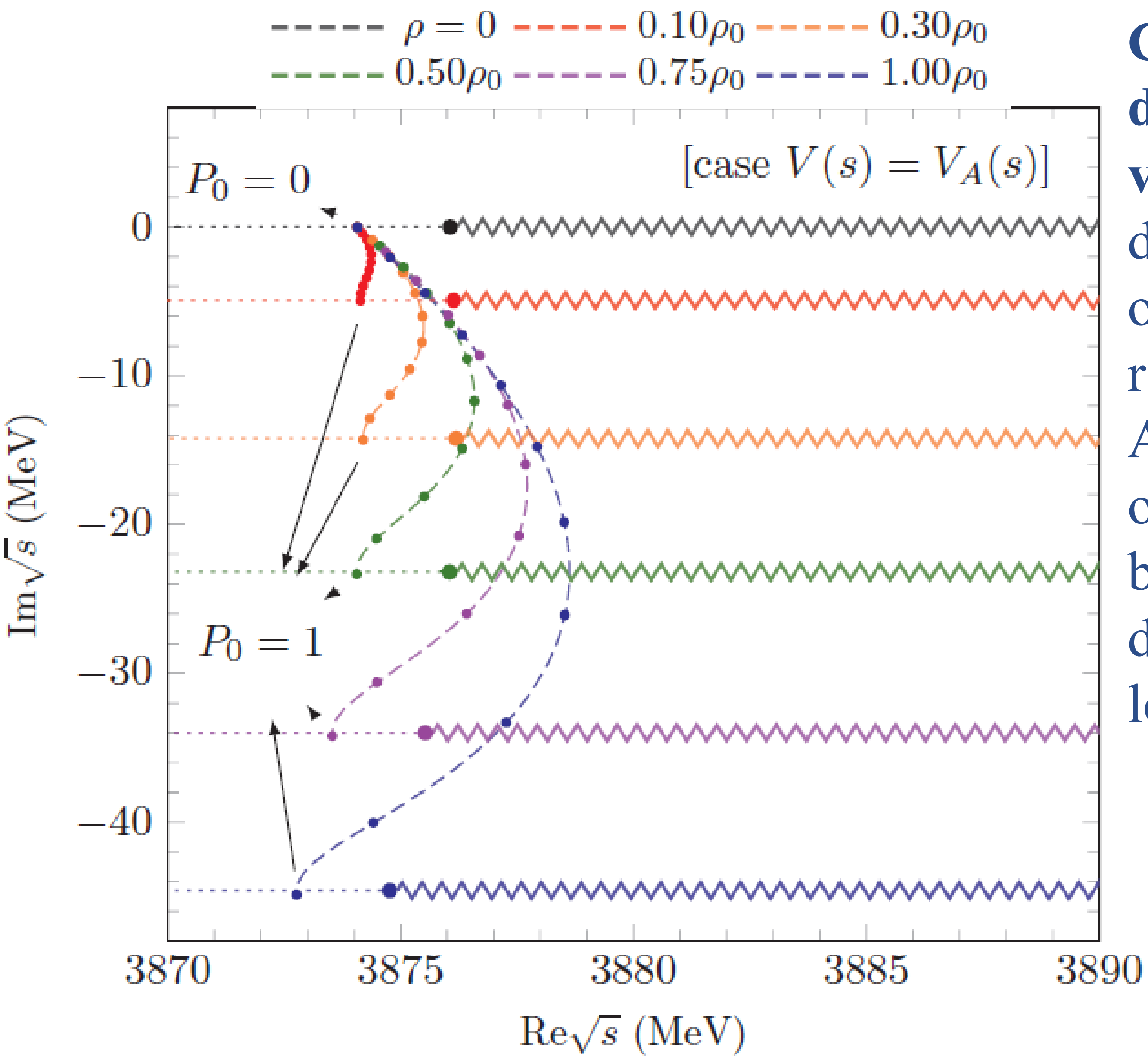






- Squared modulus of the amplitudes $T(E;\rho)$, normalized to be 1 at the maximum as a function of the energy of the $D\bar{D}^*$pair in the c.m. frame

- Spectral function of the *X(3872)* multiplied by $(1 - P_0)^{-1}$



Complex pole position of the $X(3872)$ for different nuclear densities (ρ) and vacuum molecular probabilities (P_0). The dashed curves show the continuous variation of the pole position with P_0, and the points represent steps in the probability $\Delta P_0 = 0.1$. At the endpoints of each curve either $P_0 = 0$ or $P_0 = 1$, and this is indicated in each curve by an arrow. Different colors correspond to different nuclear densities, as detailed in the legend of the plot.

The nuclear environment modifies the spectral function of the $X(3872)$. Note that the $X(3872)$ has a well defined charged-conjugation (C=+). Next we **will study exotic states which do not have well defined C −parity** ⇒ **nuclear medium breaks charge-conjugation symmetry**

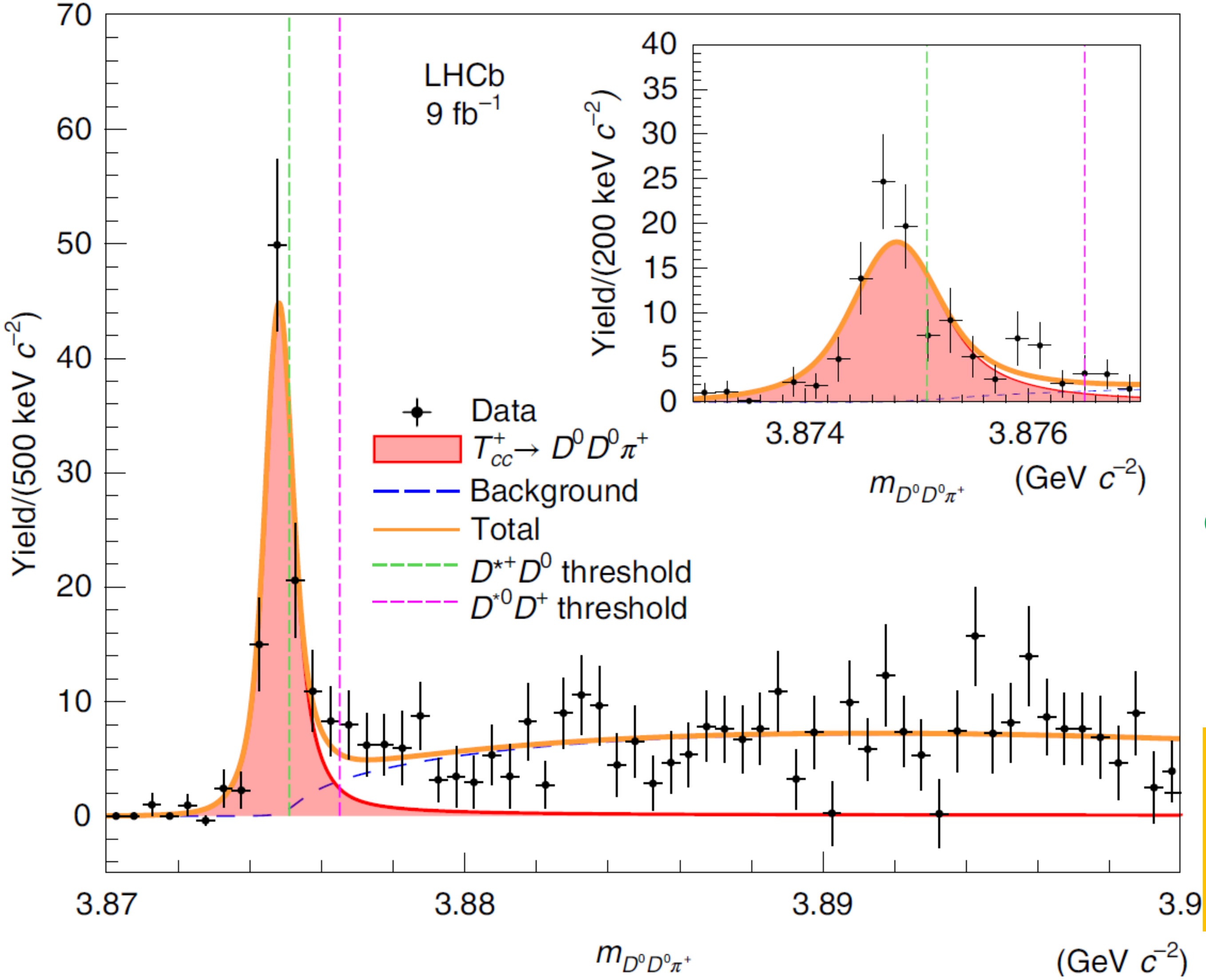


Table 1 | Parameters obtained from the fit to the $D^0D^0\pi^+$ mass spectrum: signal yield, N, BW mass relative to the $D^{*+}D^0$ mass threshold, δm_{BW}, and width, Γ_{BW}. The uncertainties are statistical only

Parameter	Value
N	117 ± 16
δm_{BW}	-273 ± 61 keV c^{-2}
Γ_{BW}	410 ± 165 keV

LHCb: Observation of an exotic narrow doubly charmed Tetraquark, Nature Phys. 18 (2022) 751

∽ 350 cites

$T_{cc}^{+}(3875)$

colorless compact tetraquark structure?
D^*D hadron-molecule?

*Conventional, hadronic matter consists of baryons and mesons made of three quarks and a quark–antiquark pair, respectively. Here, we report the observation of **a hadronic state containing four quarks** in the LHCb experiment. This so-called tetraquark contains **two charm quarks, a $\bar{u}$ and a $\bar{d}$ quark**. This exotic state has a mass of approximately 3875 MeV and manifests as a narrow peak in the mass spectrum of $D^0D^0\pi^+$ mesons just below the $D^{*+}D^0$ mass threshold.*

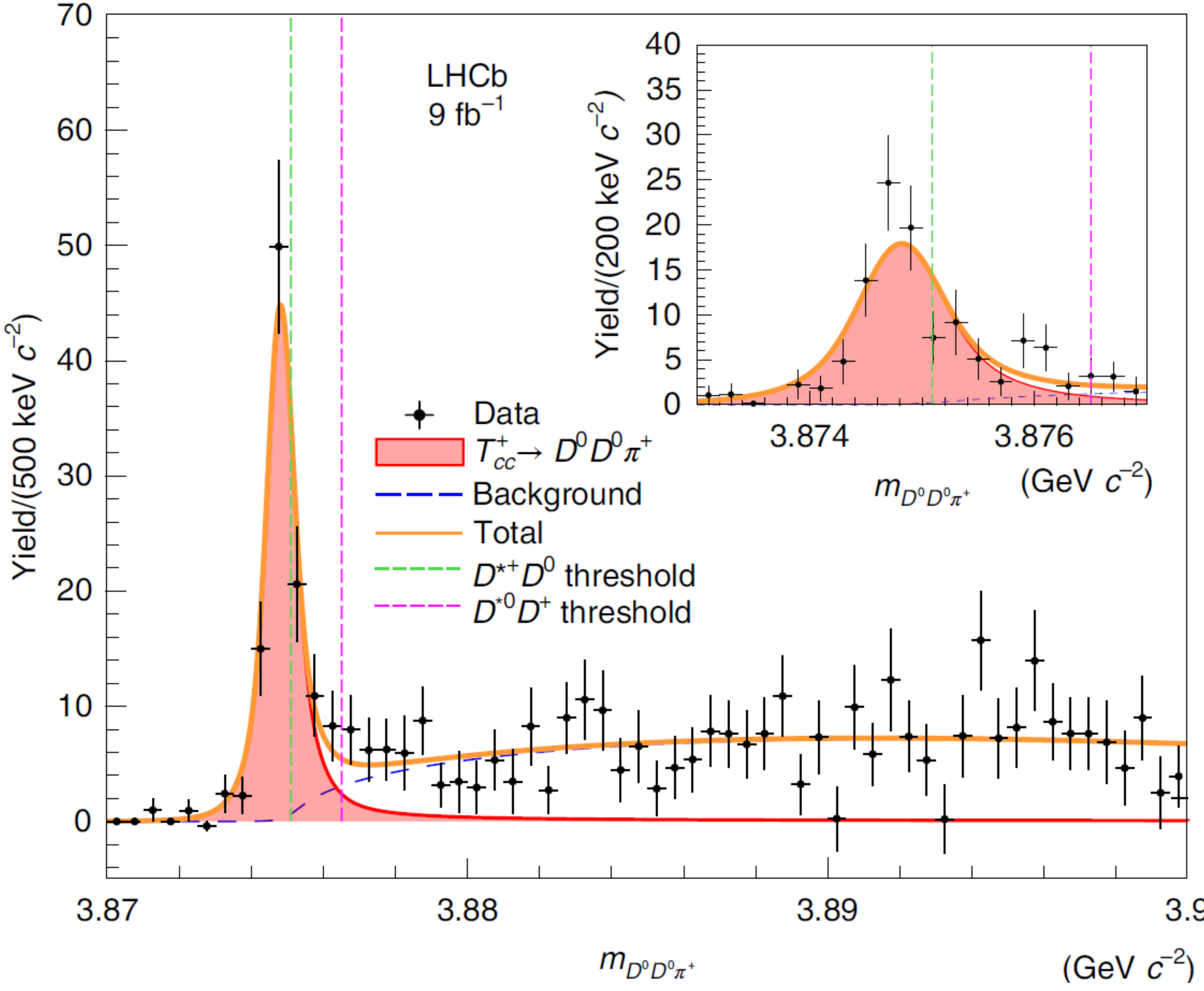


Table 1 | Parameters obtained from the fit to the $D^0D^0\pi^+$ mass spectrum: signal yield, N, BW mass relative to the $D^{*+}D^0$ mass threshold, δm_{BW}, and width, Γ_{BW}. The uncertainties are statistical only

Parameter	Value
N	117 ± 16
δm_{BW}	-273 ± 61 keV c^{-2}
Γ_{BW}	410 ± 165 keV

$T_{cc}^{+}(3875)$ & $T_{\bar{c}\bar{c}}^{-}(3875)$

Line-shapes identical in the free space

colorless compact tetraquark structure?

D^*D hadron-molecule?

Conventional, hadronic matter consists of baryons and mesons made of three quarks and a quark–antiquark pair, respectively. Here, we report the observation of ***a hadronic state containing four quarks*** *in the LHCb experiment. This so-called tetraquark contains* ***two charm quarks, a $\bar{u}$ and a $\bar{d}$ quark****. This exotic state has a mass of approximately 3875 MeV and manifests as a narrow peak in the mass spectrum of $D^0D^0\pi^+$ mesons just below the $D^{*+}D^0$ mass threshold.*

$T_{cc}^{+}(3875)$ & $T_{\bar{c}\bar{c}}^{-}(3875)$ embedded in a nuclear medium which produces a charge-conjugation asymmetry

one might expect that line-shapes are not longer identical...

In the molecular picture,

$T_{cc}^{+}(3875) \Rightarrow D^{*}D$ state

$T_{\bar{c}\bar{c}}^{-}(3875) \Rightarrow \bar{D}^{*}\bar{D}$ state

$D^{(*)} \sim c\bar{\ell}$

$\bar{D}^{(*)} \sim \bar{c}\ell$

the nuclear environment would induce different modifications to charmed $D^{*}D$ than to anti-charmed $\bar{D}^{*}\bar{D}$ pairs of interacting mesons because the **different strength of the $D^{(*)}N$ and $\bar{D}^{(*)}N$ interactions**, which should lead to visible changes among the medium properties of the $T_{cc}^{+}(3875)$ & $T_{\bar{c}\bar{c}}^{-}(3875)$

$$\Delta_Y(q\,;\rho) = \frac{1}{(q^0)^2 - \omega_Y^2(\vec{q}^{\,2}) - \Pi_Y(q^0,\vec{q}\,;\rho)}$$

$$= \int_0^\infty d\omega \left(\frac{S_Y(\omega,|\vec{q}\,|)}{q^0 - \omega + i\varepsilon} - \frac{S_{\bar{Y}}(\omega,|\vec{q}\,|)}{q^0 + \omega - i\varepsilon} \right)$$

meson in the nuclear medium acquires a density-dependent self-energy

Källen-Lehmann representation

with $\omega_Y(\vec{q}^{\,2}) = \sqrt{m_Y^2 + \vec{q}^{\,2}}$. From the above equation, it follows that for $q^0 > 0$

$$S_{D^{(*)},\bar{D}^{(*)}}(q^0,\vec{q}\,;\rho) = -\frac{1}{\pi}\mathrm{Im}\,\Delta_{D^{(*)},\bar{D}^{(*)}}(q^0,\vec{q}\,;\rho)$$
$$= -\mathrm{Im}\Pi_{D^{(*)},\bar{D}^{(*)}}(q^0,\vec{q}\,;\rho) \times \frac{|\Delta_{D^{(*)},\bar{D}^{(*)}}(q^0,\vec{q}\,;\rho)|^2}{\pi}.$$

spectral function is determined by the self-energy

$T = V + V\Sigma T$, Bethe-Salpeter equation:

- restores elastic unitary
- poles FRS & SRS: bound states, resonances

$$\Sigma_{UW}(s;\rho) = i\int \frac{d^4q}{(2\pi)^4} \Delta_U(P-q)\Delta_W(q),$$

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

$$\overline{T}^{-1}(s\,;\,\rho) = V_0^{-1}(s) - \overline{\Sigma}(s\,;\,\rho),$$ $\overline{D}\overline{D}^*$ scattering amplitude

identical DD^* and $\overline{D}\overline{D}^*$ potentials

$$\Sigma(s=E^2\,;\,\rho) = \frac{1}{2\pi^2}\left\{\mathcal{P}\int_0^\infty d\Omega\left(\frac{f_{D^*D}(\Omega\,;\,\rho)}{E-\Omega+i\varepsilon} - \frac{f_{\overline{D}^*\overline{D}}(\Omega\,;\,\rho)}{E+\Omega-i\varepsilon}\right) - i\pi\, f_{D^*D}(E\,;\,\rho)\right\},$$

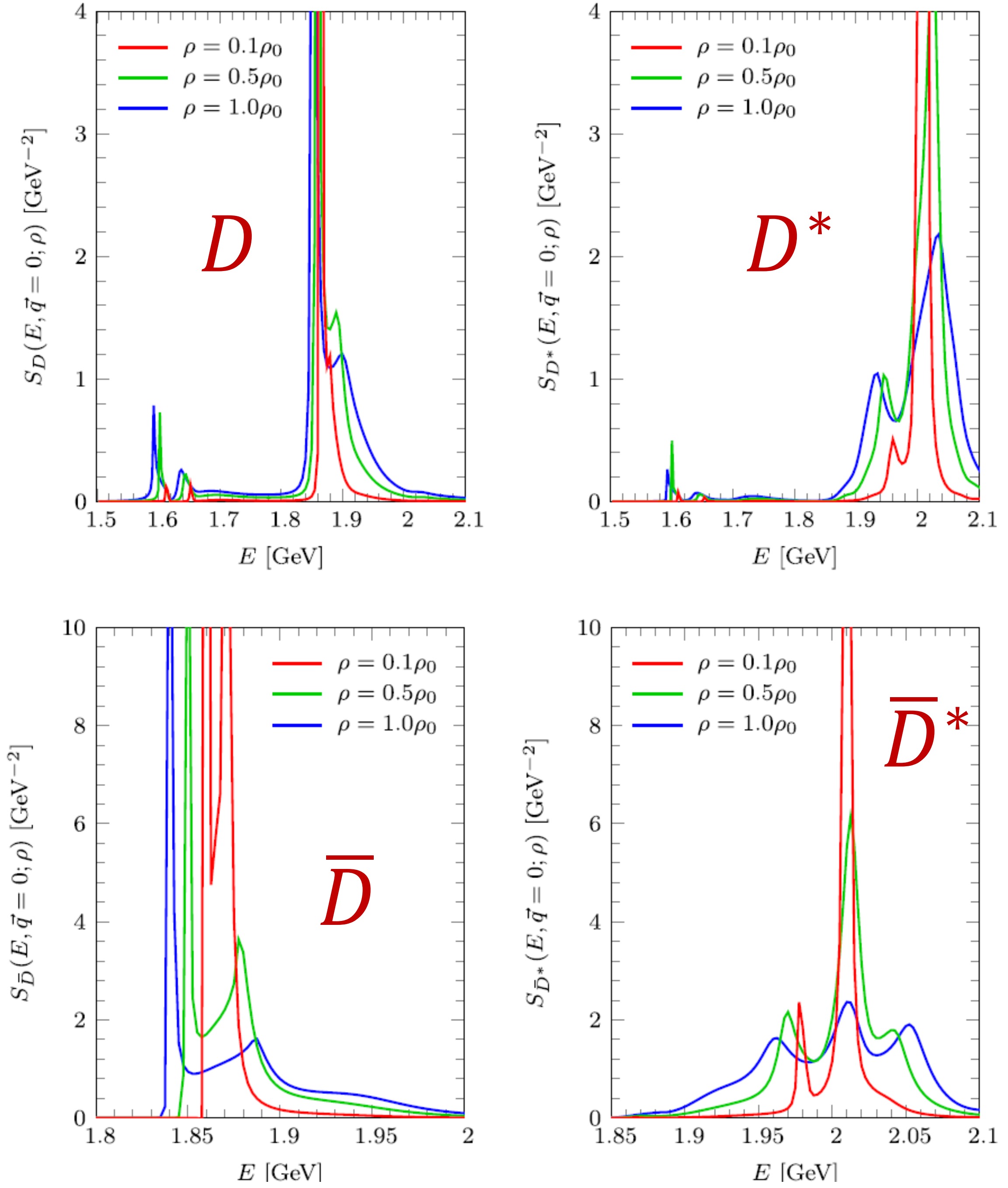
$$\overline{\Sigma}(s=E^2\,;\,\rho) = \frac{1}{2\pi^2}\left\{\mathcal{P}\int_0^\infty d\Omega\left(\frac{f_{\overline{D}^*\overline{D}}(\Omega\,;\,\rho)}{E-\Omega+i\varepsilon} - \frac{f_{D^*D}(\Omega\,;\,\rho)}{E+\Omega-i\varepsilon}\right) - i\pi\, f_{\overline{D}^*\overline{D}}(E\,;\,\rho)\right\},$$

where $\mathcal{P}$ stands for the principal value of the integral and, in addition,

$$f_{UW}(\Omega\,;\,\rho) = \int_0^\Lambda dq\, q^2 \int_0^\Omega d\omega\, S_U(\omega,\, |\vec{q}\,|;\, \rho) S_W(\Omega-\omega,\, |\vec{q}\,|;\, \rho).$$

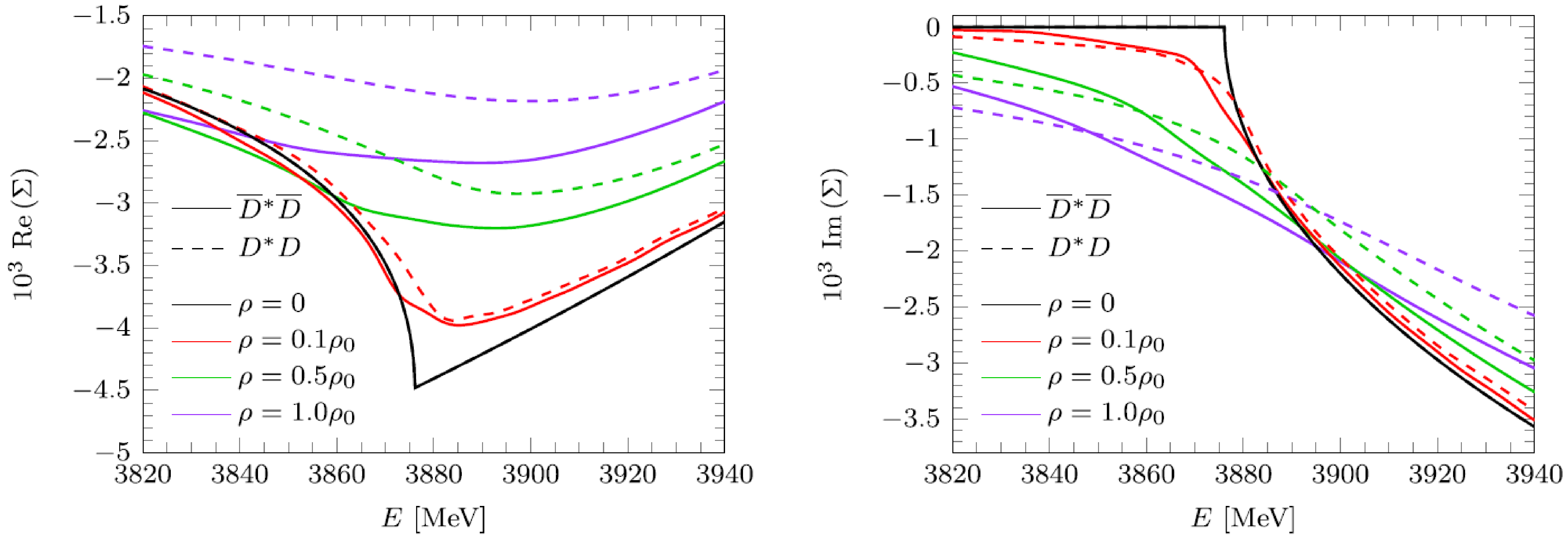
DD^* and $\overline{D}\overline{D}^*$ loop functions inside of the nuclear environment

$\Sigma(s;\,\rho=0) = \overline{\Sigma}(s;\,\rho=0)$ in the vacuum!



Nuclear medium spectral functions:

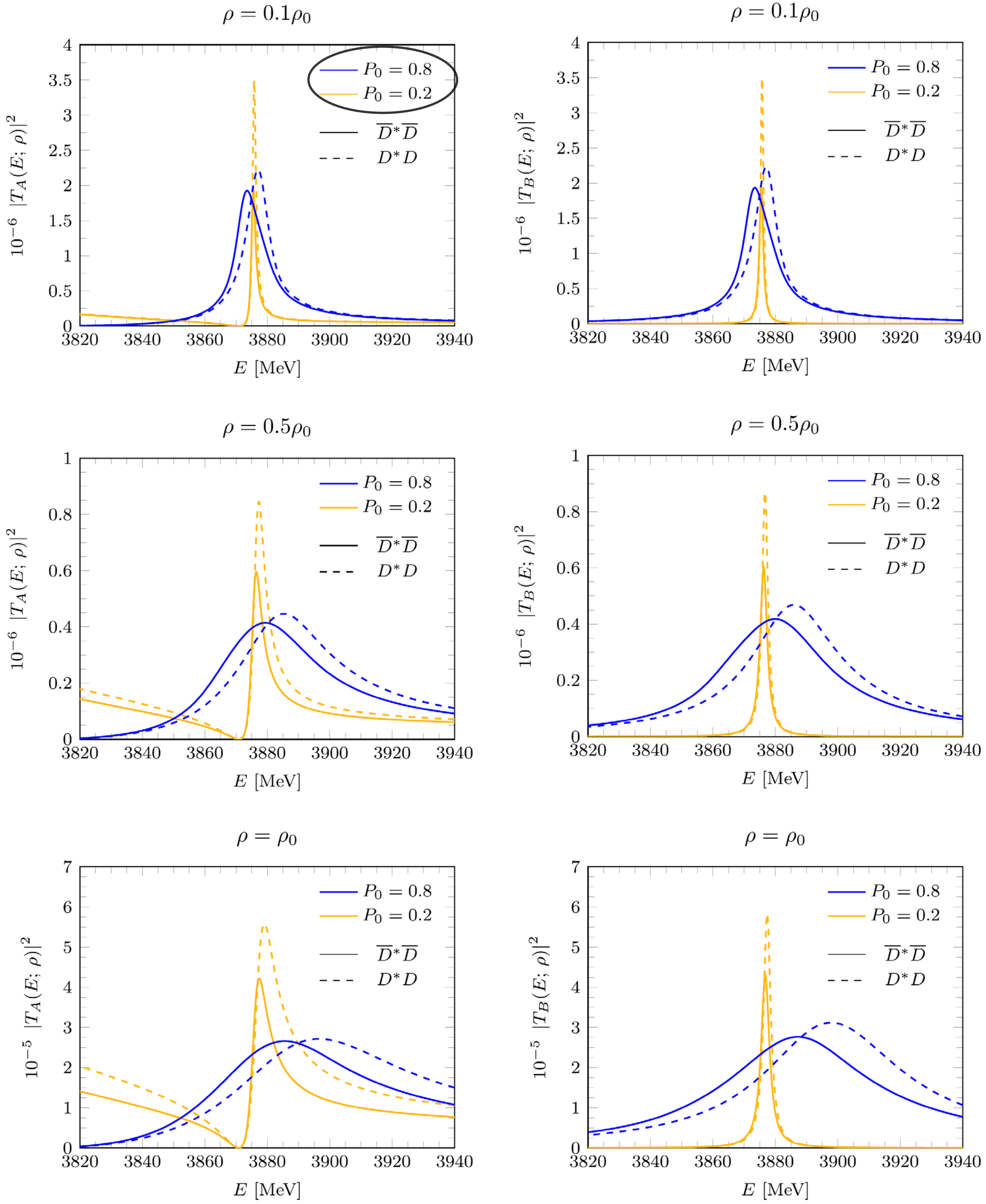
- L. Tolós, C. García-Recio, JN, Phys. Rev. C80 (2009) 065202; Phys. Lett. B690 (2010) 369
- C. García-Recio, JN, L. L. Salcedo, L. Tolos, Phys. Rev. C85 (2012) 025203

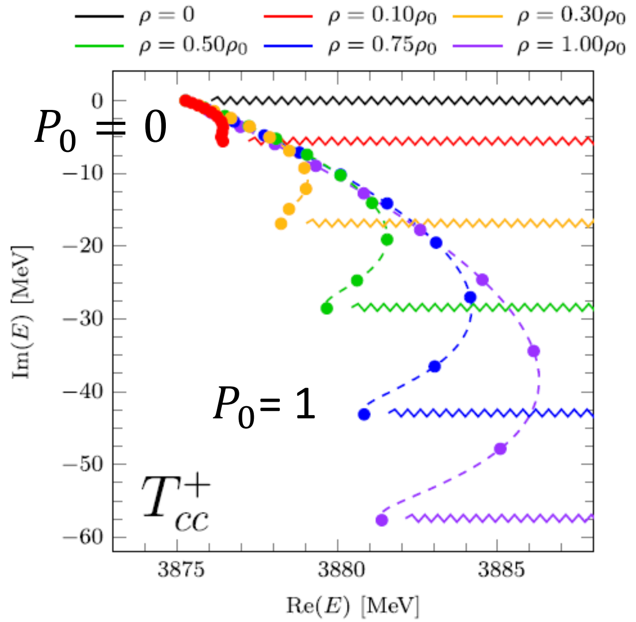


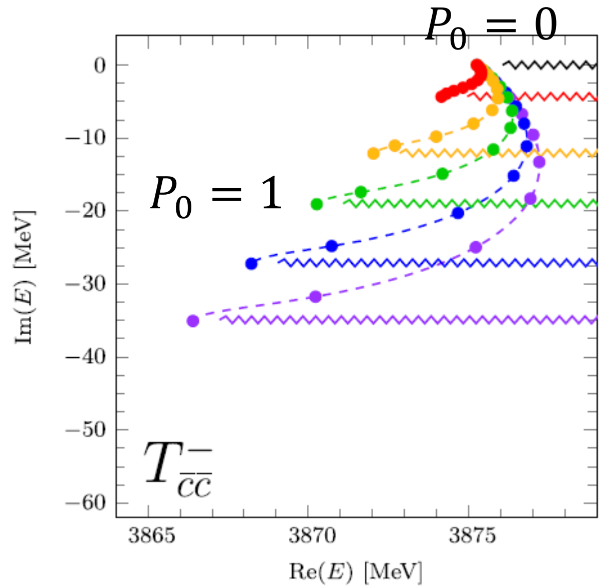
Real and imaginary parts of the DD^* and $\overline{D}\overline{D}^*$ loop functions inside of the nuclear environment

Line-shapes for different densities and molecular probabilities

P_0 : molecular probability (Weinberg)







CHARMED, STRANGE MESONS
($C = \pm1$, $S = \pm1$)
(including possibly non-$q\bar{q}$ states)
$D_s^+ = c\bar{s}$, $D_s^- = \bar{c}s$, similarly for D_s^*'s

PDGID:M172 JSON INSPIRE

$D_{s0}^*(2317)^\pm$

$I(J^P) = 0(0^+)$ J, P need confirmation.

AUBERT 2006P and CHOI 2015A do not observe neutral and doubly charged partners of the $D_{s0}^*(2317)^+$. See the review on "Heavy Non-$q\bar{q}$ Mesons."

$D_{s0}^*(2317)^\pm$ MASS	2317.8 ± 0.5 MeV
$m_{D_{s0}^*(2317)^\pm} - m_{D_s^\pm}$	349.4 ± 0.5 MeV
$D_{s0}^*(2317)^\pm$ WIDTH	< 3.8 MeV CL=95.0%

$D_{s0}^*(2317)^\pm$ DECAY MODES

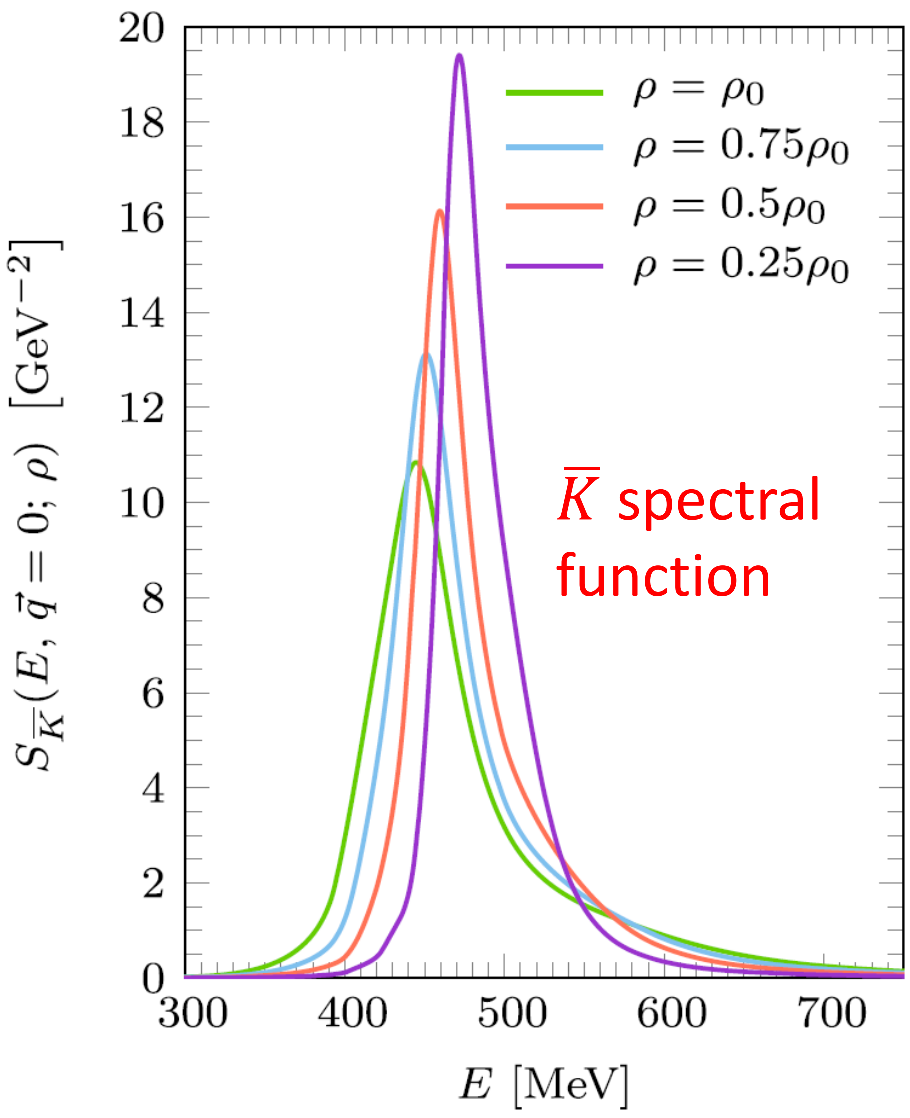
$D_{s0}^*(2317)^-$ modes are charge conjugates of modes below.

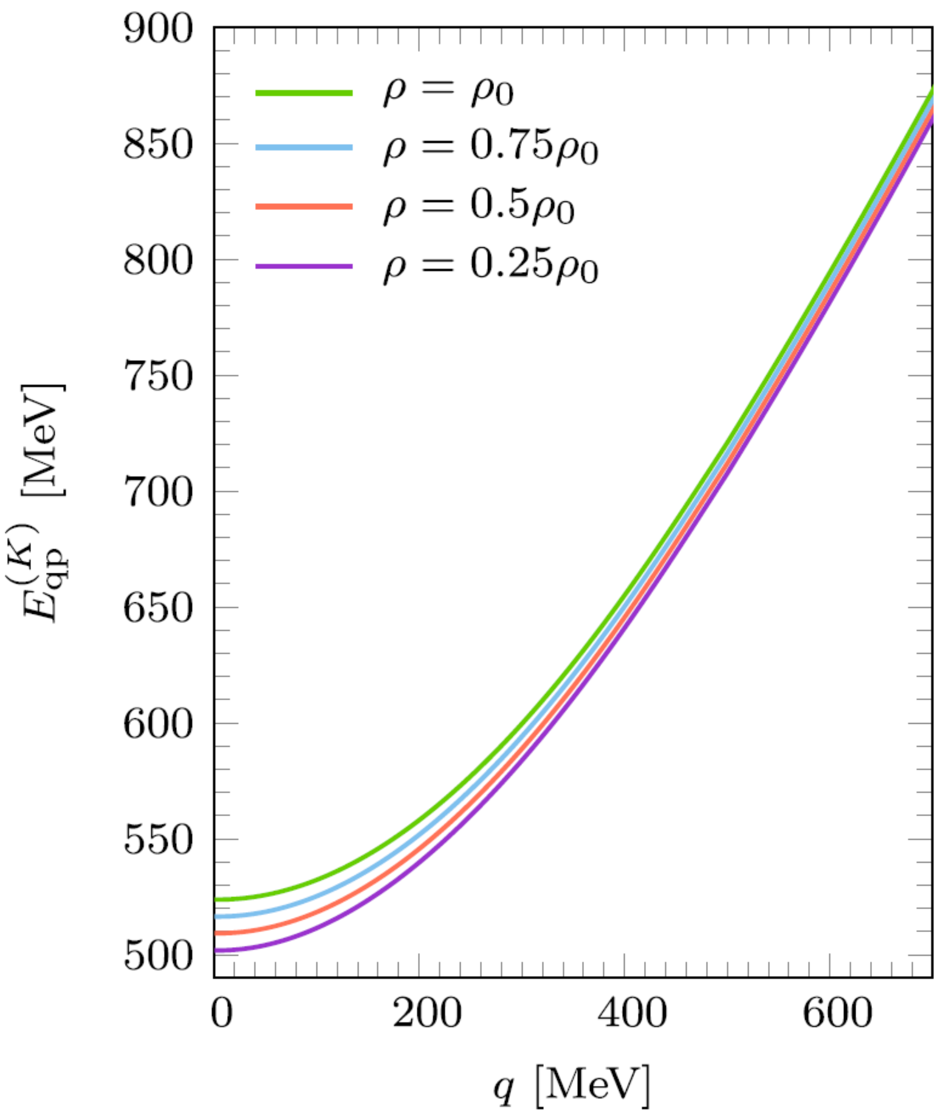
Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^+\pi^0$	$(100^{+0}_{-20})\%$		298
Γ_2	$D_s^+\gamma$	$< 5\%$	CL=90%	323
Γ_3	$D_s^*(2112)^+\gamma$	$< 6\%$	CL=90%	
Γ_4	$D_s^+\gamma\gamma$	$< 18\%$	CL=95%	323
Γ_5	$D_s^*(2112)^+\pi^0$	$< 11\%$	CL=90%	
Γ_6	$D_s^+\pi^+\pi^-$	$< 4 \times 10^{-3}$	CL=90%	194
Γ_7	$D_s^+\pi^0\pi^0$	not seen		205

Now we study the isoscalar $J^P = 0^+$ exotic resonance $D_{s0}^*(2317)^\pm$

- quark content: $c\bar{s}$, $\bar{c}s$
- it cannot be accommodated in CQMs: around 100 MeV lighter than expected
- Molecular picture $D\bar{K}$ and $\bar{D}\,K$

$\bar{K}N$ and KN interactions very different!





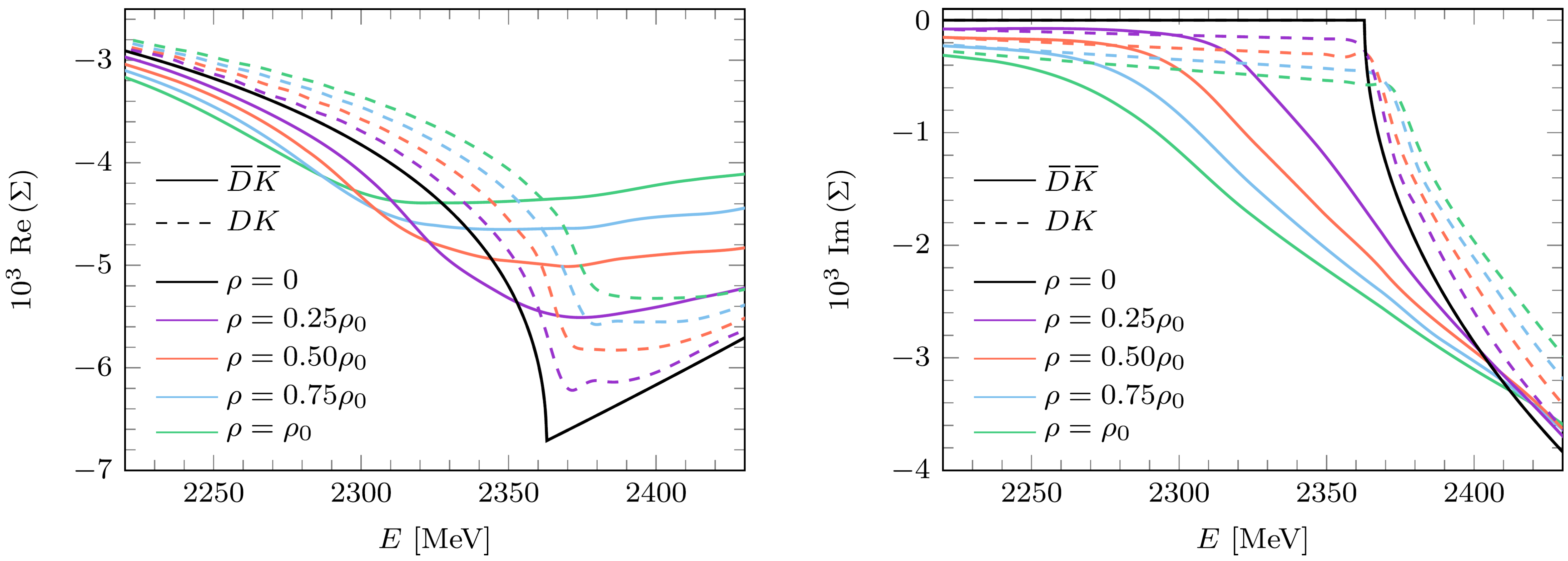
Kaon spectral function in the nuclear medium behaves like a delta function, with a small modification (density-dependent) of the quasi-particle energy $E_{qp}^{(K)}$

$$S_K(E, q; \rho) \approx \frac{\delta\left(E - E_{\rm qp}(q;\rho)\right)}{2E_{\rm qp}(q;\rho)}$$

KN: $\bar{s}\ell_1\ell_2\ell_3\ell_4$ resonance would be a pentaquark. Interaction very weak

$\bar{K}N \to \bar{K}N$: appears strong hyperon resonances like $\Lambda(1405)$, $\Lambda(1670)$, etc..

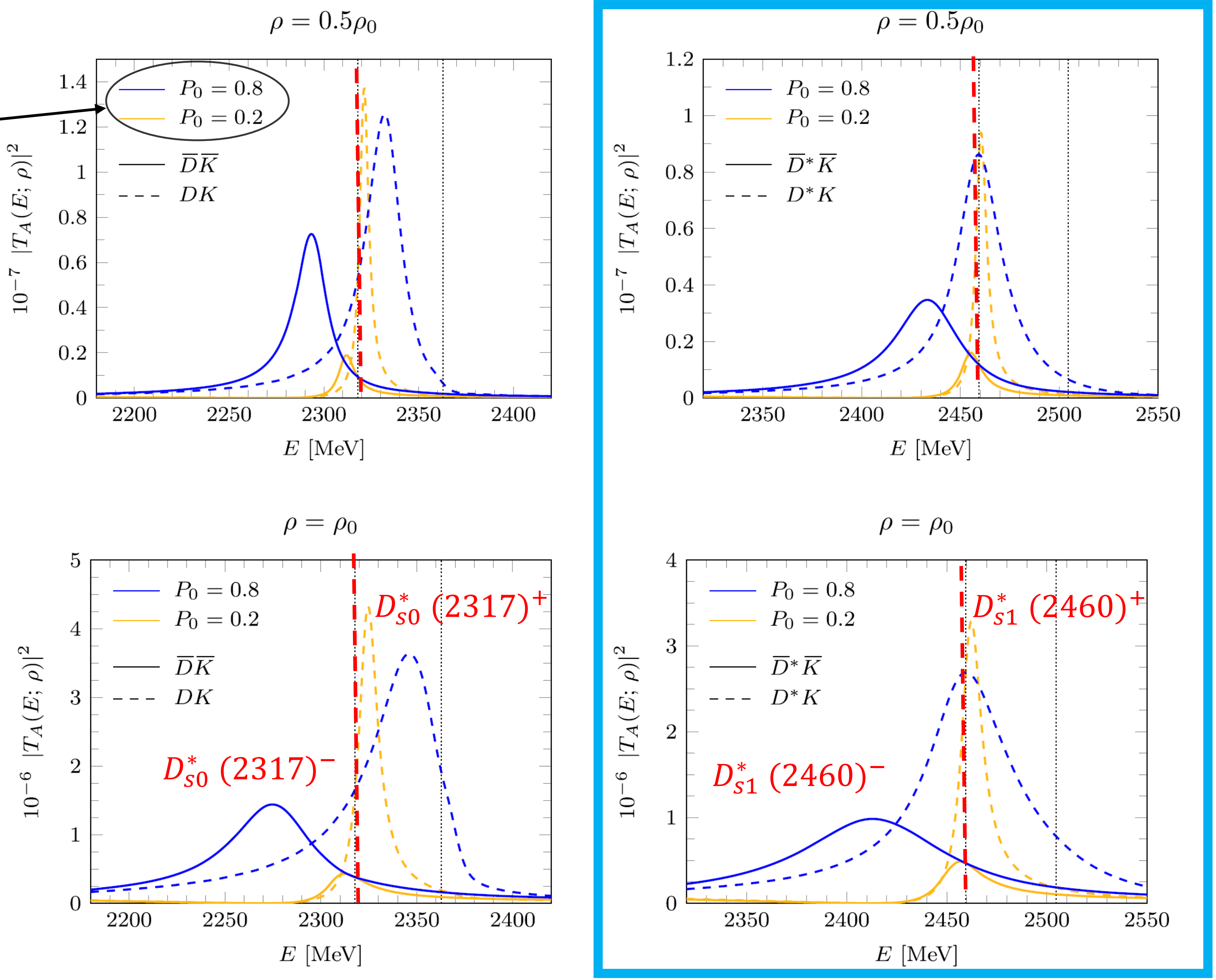
Real and imaginary parts of the DK and $\bar{D}\bar{K}$ loop functions inside of the nuclear environment



we dress in the medium both the (anti-)charmed and the (anti-)kaon mesons. Larger charge-conjugation asymmetry $\Longrightarrow$ different pattern of density corrections to the line-shapes of $D^*_{s0}\,(2317)^+$ and $D^*_{s0}\,(2317)^-$

Line-shapes for different densities and molecular probabilities

two molecular probabilities



HQSS partner
$D_{s1}^*(2460)^{\pm}$
isoscalar $J^P = 1^+$

D^*K and $\overline{D}^*\overline{K}$ molecules

CONCLUSIONS

- Experimental analyses on the in-medium properties of *X(3872)* and comparison of those with the results of the present study can increase our knowledge of this resonance and help us gain useful information on the not-well-known structure of this exotic state

- Particle-antiparticle $[D^*_{s0,s1}(2317,2460)^+ \ \& \ D^*_{s0,s1}(2317,2460)^-]$ line-shapes are necessarily the same in free space, but we have found different density patterns in matter. This large charge-conjugation asymmetry mainly stems from the very different kaon and antikaon interactions with the nucleons of the dense medium. Medium effects strongly depend on the molecular contents

- With increasing densities and molecular probabilities, the $D^*_{s0}(2317)^+$ peak shifts towards higher energies and becomes less broad than its charge-conjugation partner $D^*_{s0}(2317)^-$, whose wider Breit-Wigner-like shape moves more noticeably at lower energies. **At half normal nuclear matter density, the change is already so drastic for high molecular component scenarios that $D^*_{s0}(2317)^+$ and $D^*_{s0}(2317)^-$ line-shapes hardly overlap.**

- Effects violating charge-conjugation symmetry are larger than those found for the $T_{cc}(3875)^+$ & $T_{\bar{c}\bar{c}}(3875)^-$ tetraquarks embedded in a nuclear environment.

In summary:

- The nuclear environment modifies the spectral functions of the exotic states. Moreover, for those states with not well defined C −parity, it breaks charge-conjugation symmetry, and induces different particle-antiparticle line-shapes. If these distinctive density dependencies were experimentally confirmed, it would give support to the presence of important molecular components in these exotic states. This is because if these states were mostly compact four-quark structures, the density behavior of their in-medium lines-shapes, while certainly different, would likely not follow the same patterns found for molecular scenarios