"Present and future perspectives in Hadron Physics"

17–19 de junio de 2024 Laboratori Nazionali di Frascati INFN

Charge-conjugation asymmetry and molecular content: the $T_{cc}(3875)$ and $D^*_{s0}(2317)$ in nuclear matter

PHYSICAL REVIEW C 108 (2023) 035205 & Phys. Lett. B 853 (2024) 138656

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

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

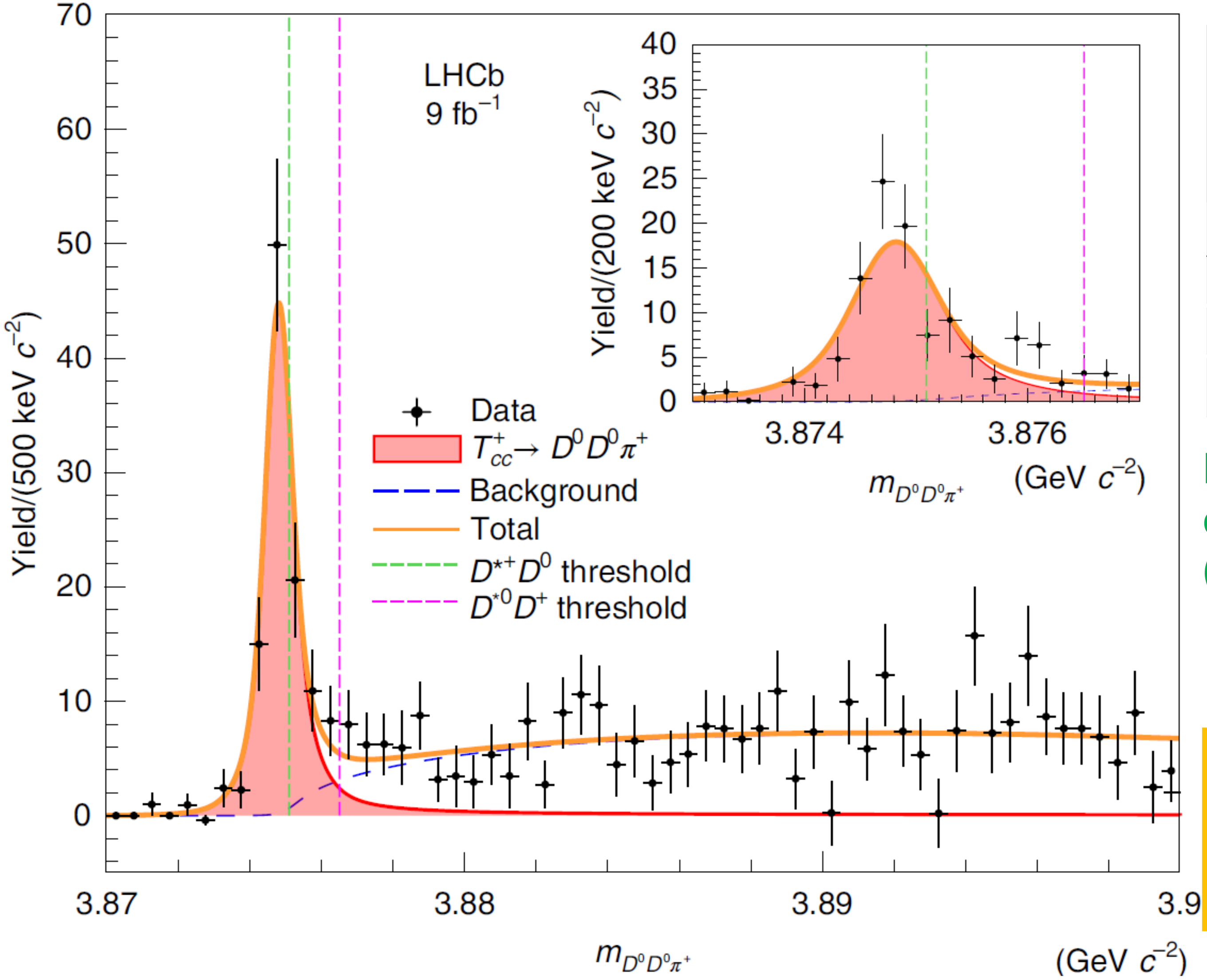


Table 1 | Parameters obtained from the fit to the $D^0D^0\pi^+$ mass spectrum: signal yield, N, BW mass relative to the $D^{*+}D^0$ mass threshold, δm_{BW}, and width, Γ_{BW}. The uncertainties are statistical only

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.*

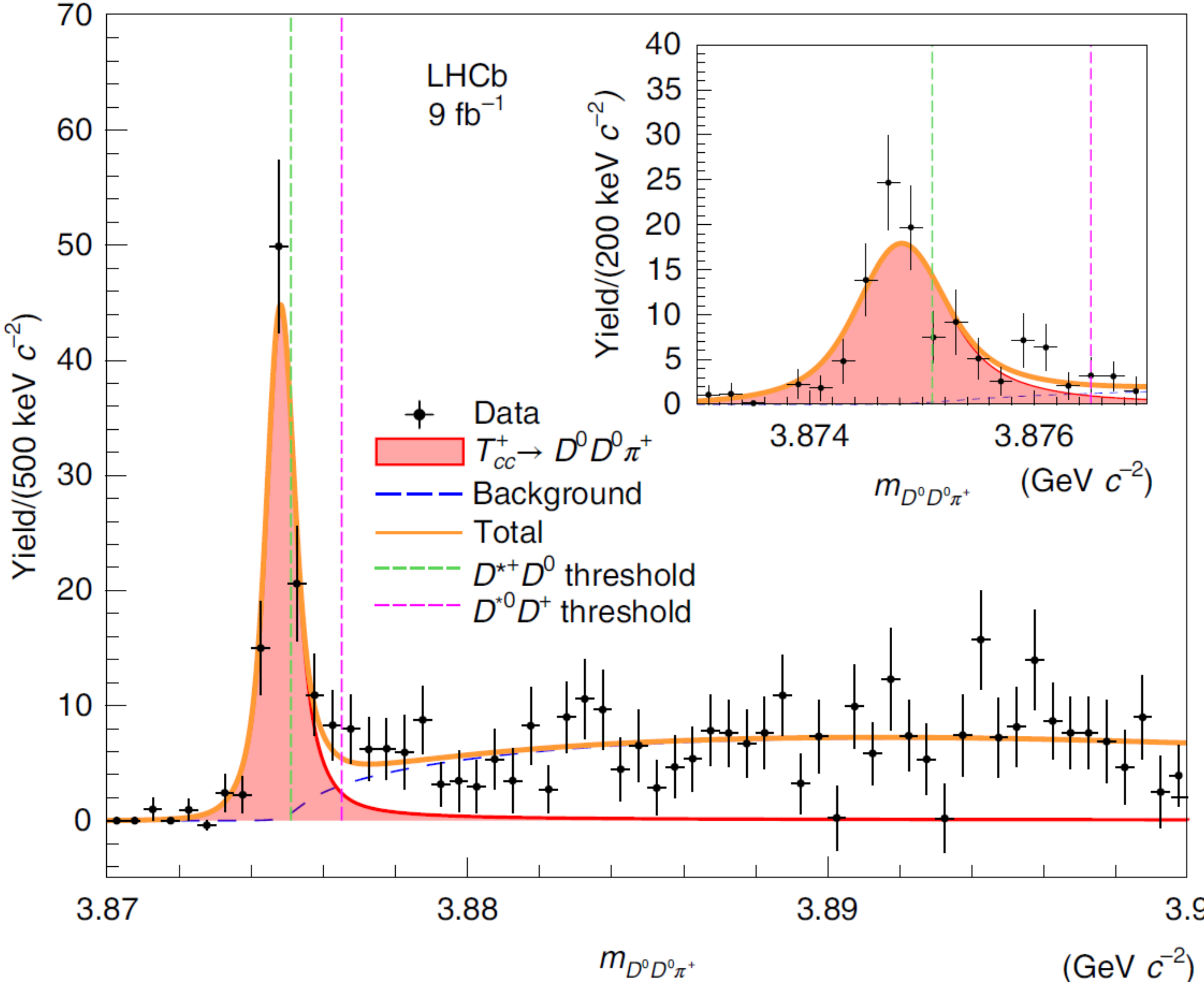


Table 1 | Parameters obtained from the fit to the $D^0D^0\pi^+$ mass spectrum: signal yield, N, BW mass relative to the $D^{*+}D^0$ mass threshold, δm_{BW}, and width, Γ_{BW}. The uncertainties are statistical only

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 $q^0 > 0$

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

spectral function is determined by the self-energy

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

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

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

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

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

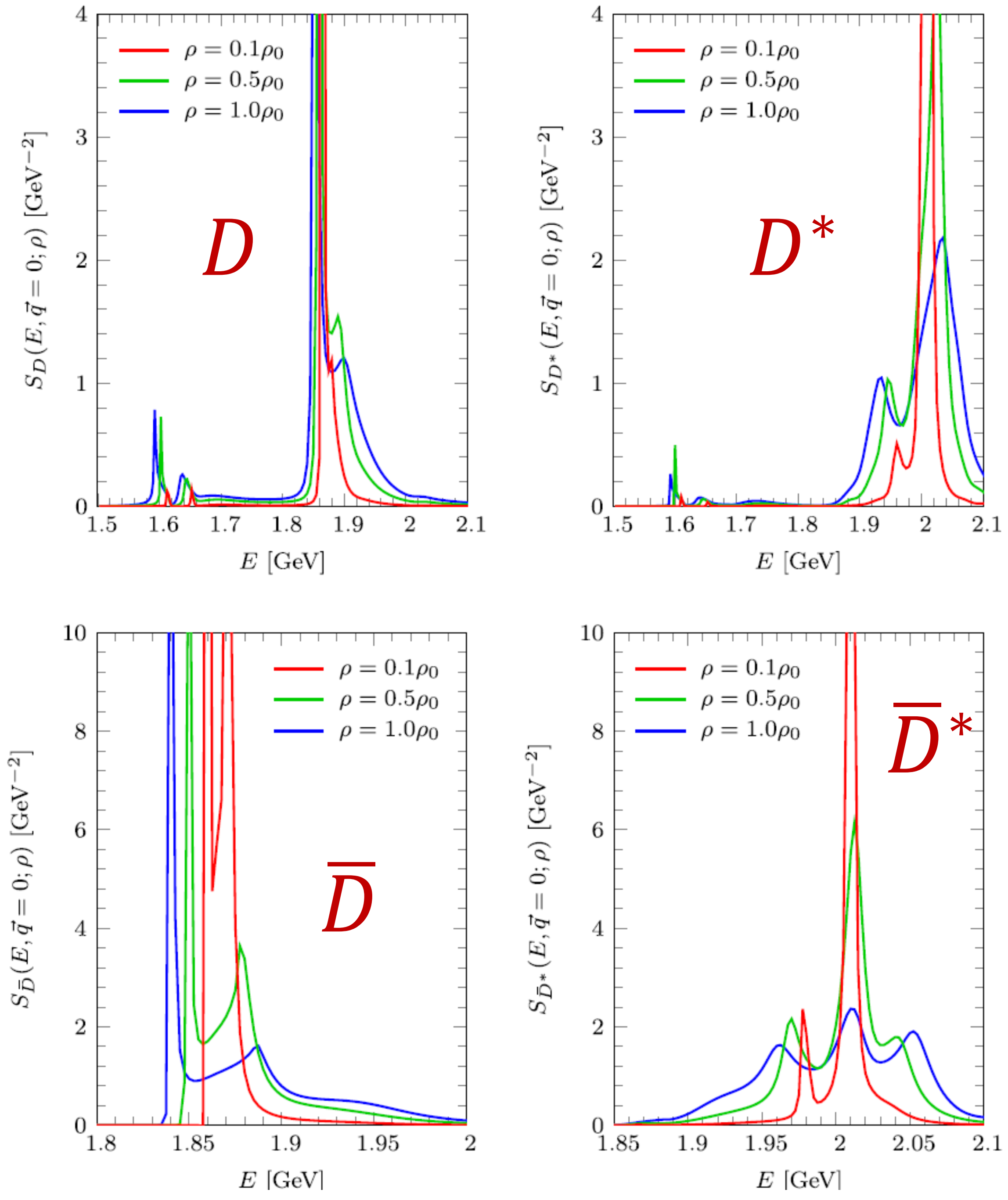
$$\overline{\Sigma}(s=E^2\,;\,\rho) = \frac{1}{2\pi^2}\left\{\mathcal{P}\int_0^\infty d\Omega\left(\frac{f_{\overline{D}^*\overline{D}}(\Omega\,;\,\rho)}{E-\Omega+i\varepsilon} - \frac{f_{D^*D}(\Omega\,;\,\rho)}{E+\Omega-i\varepsilon}\right) - i\pi\, f_{\overline{D}^*\overline{D}}(E\,;\,\rho)\right\},$$

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

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

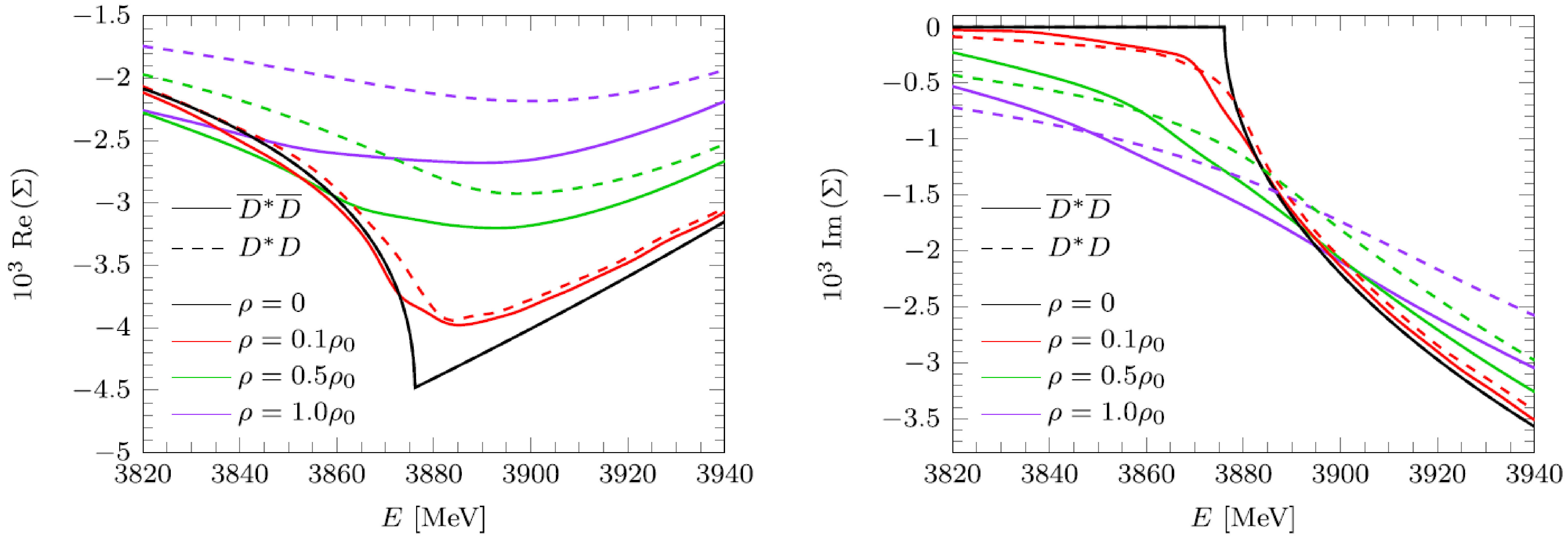
DD^* and $\overline{D}\overline{D}^*$ loop functions inside of the nuclear environment

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



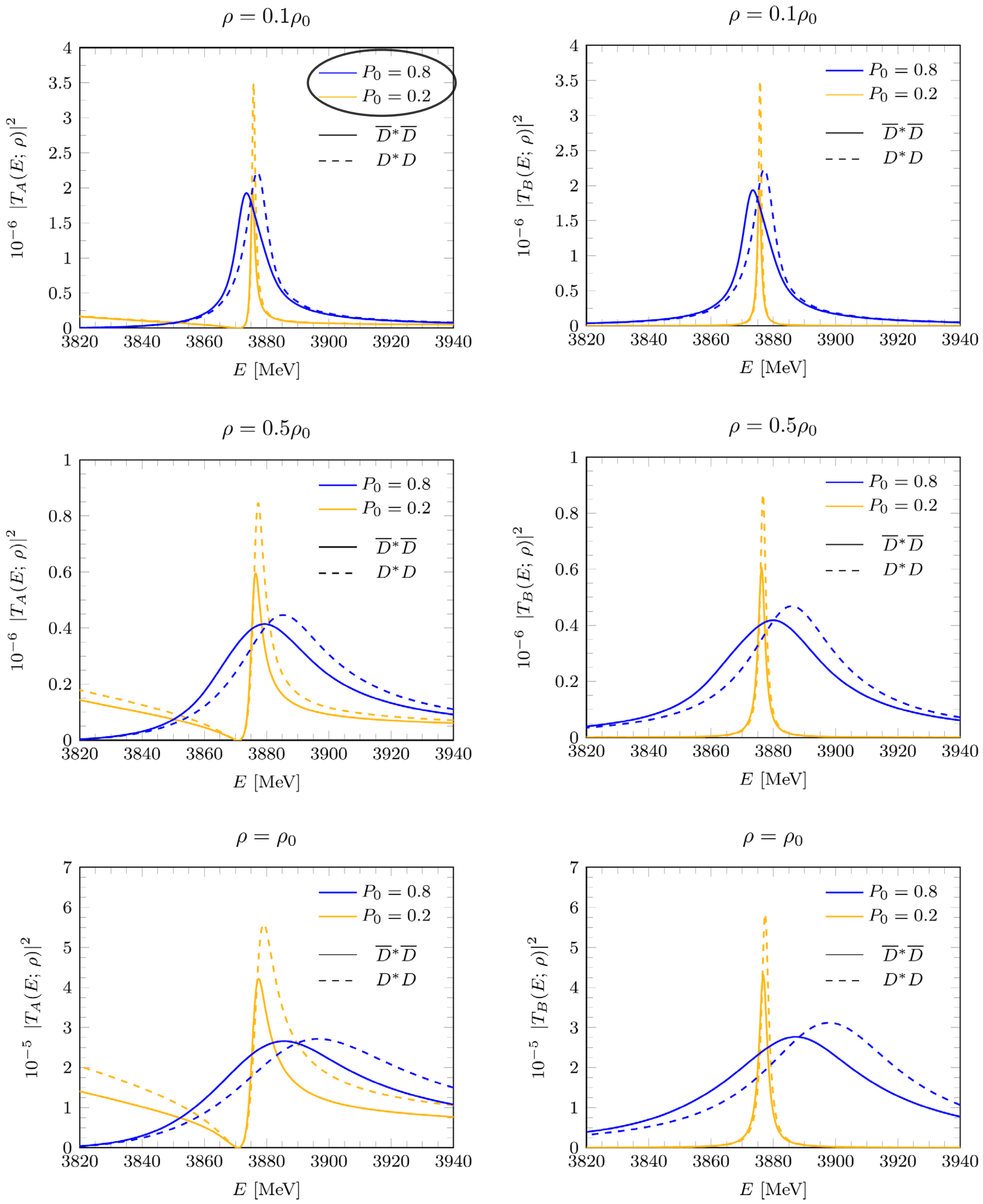
Nuclear medium spectral functions:

- 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

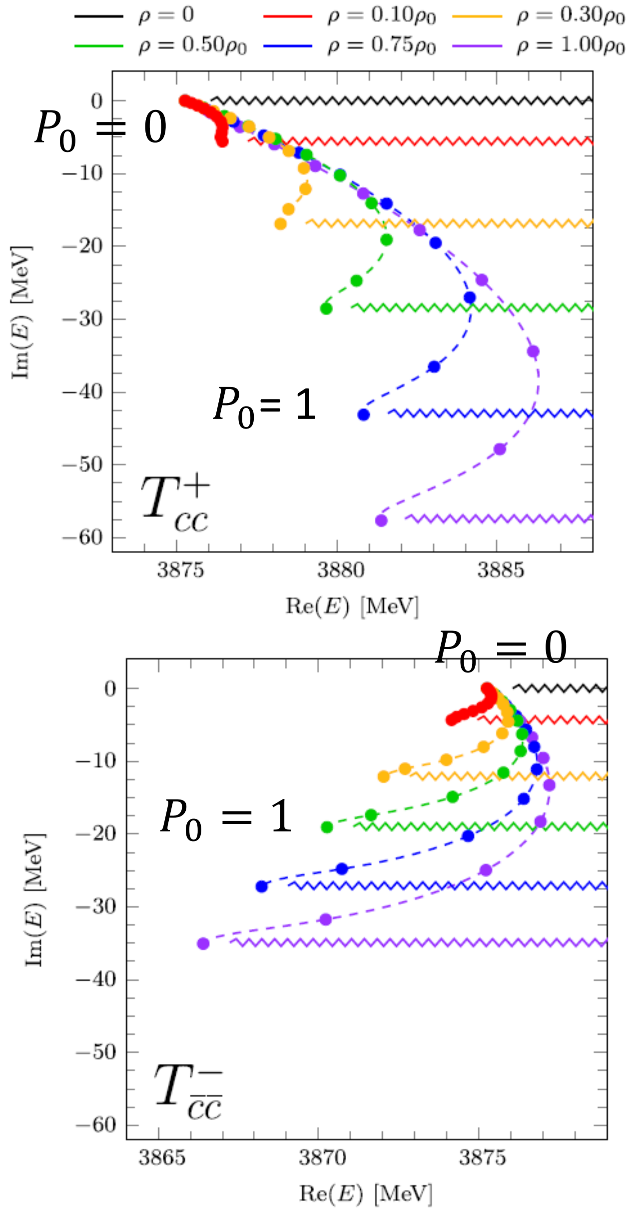


Real and imaginary parts of the DD^* and $\overline{D}\overline{D}^*$ loop functions inside of the nuclear environment

Line-shapes for different densities and molecular probabilities



P_0 : molecular probability (Weinberg)



CHARMED, STRANGE MESONS
($C = \pm 1$, $S = \pm 1$)
(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

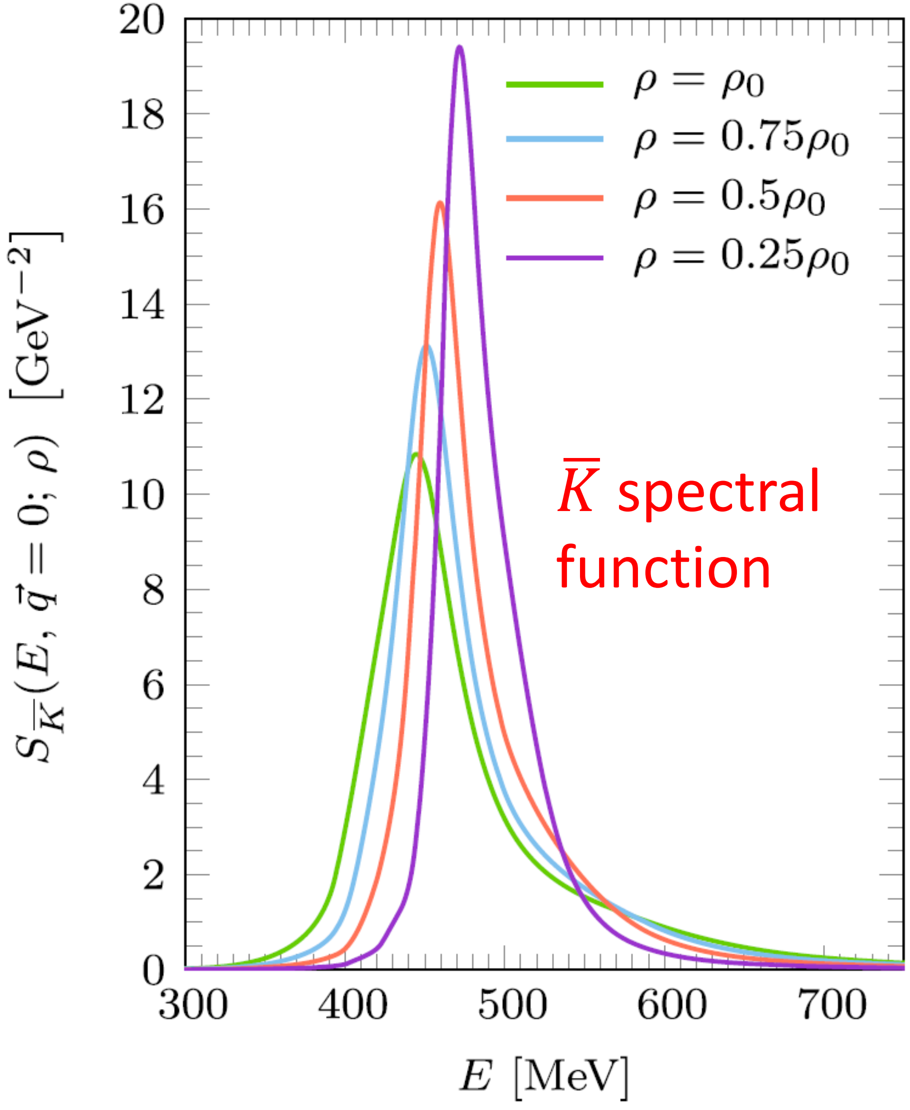
$D_{s0}^*(2317)^-$ modes are charge conjugates of modes below.

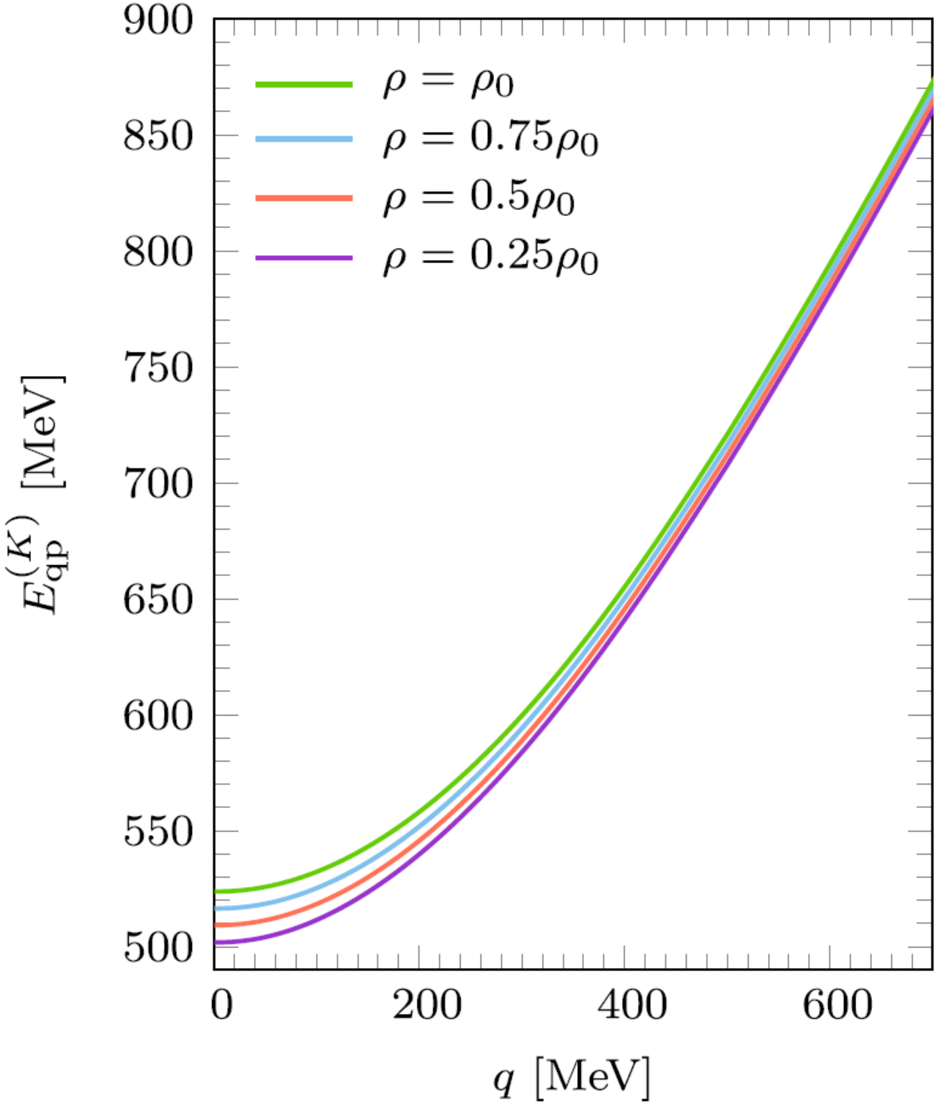
Mode		Fraction (Γ_i/Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_1	$D_s^+\pi^0$	$(100^{+0}_{-20})\%$		298
Γ_2	$D_s^+\gamma$	$< 5\%$	CL=90%	323
Γ_3	$D_s^*(2112)^+\gamma$	$< 6\%$	CL=90%	
Γ_4	$D_s^+\gamma\gamma$	$< 18\%$	CL=95%	323
Γ_5	$D_s^*(2112)^+\pi^0$	$< 11\%$	CL=90%	
Γ_6	$D_s^+\pi^+\pi^-$	$< 4 \times 10^{-3}$	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 $\bar{D}K$

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





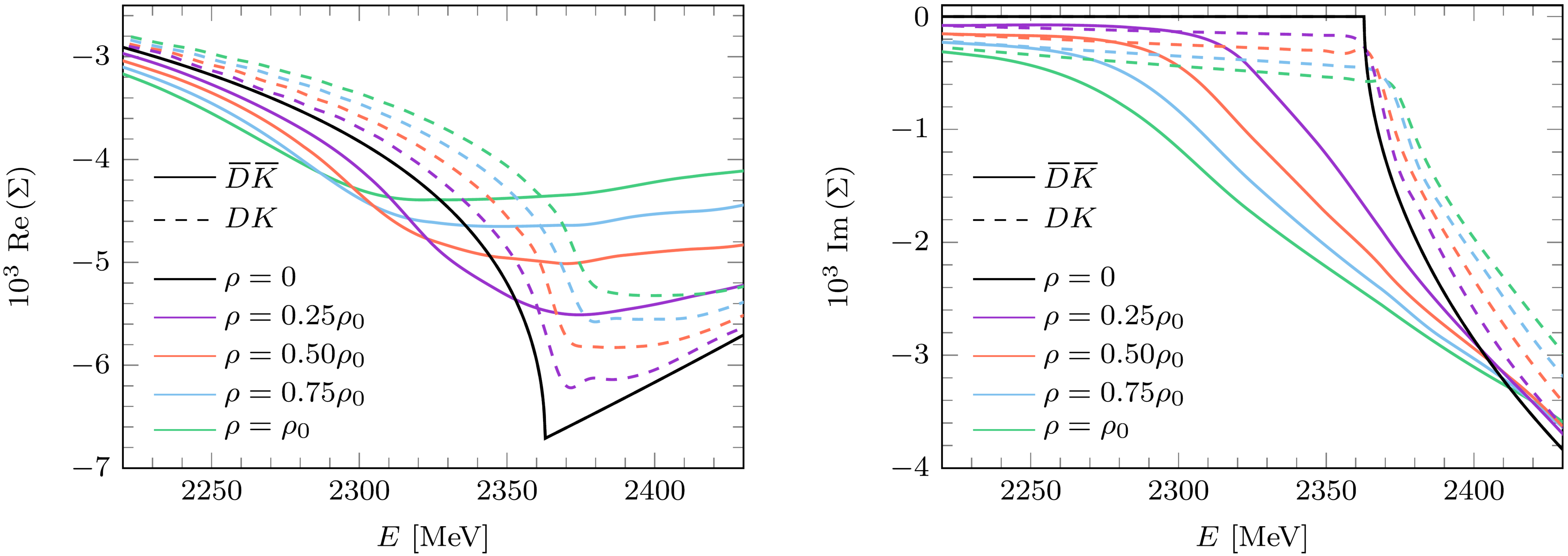
Kaon spectral function in the nuclear medium behaves like a delta function, with a small modification (density-dependent) of the quasi-particle energy $E_{qp}^{(K)}$

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

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

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

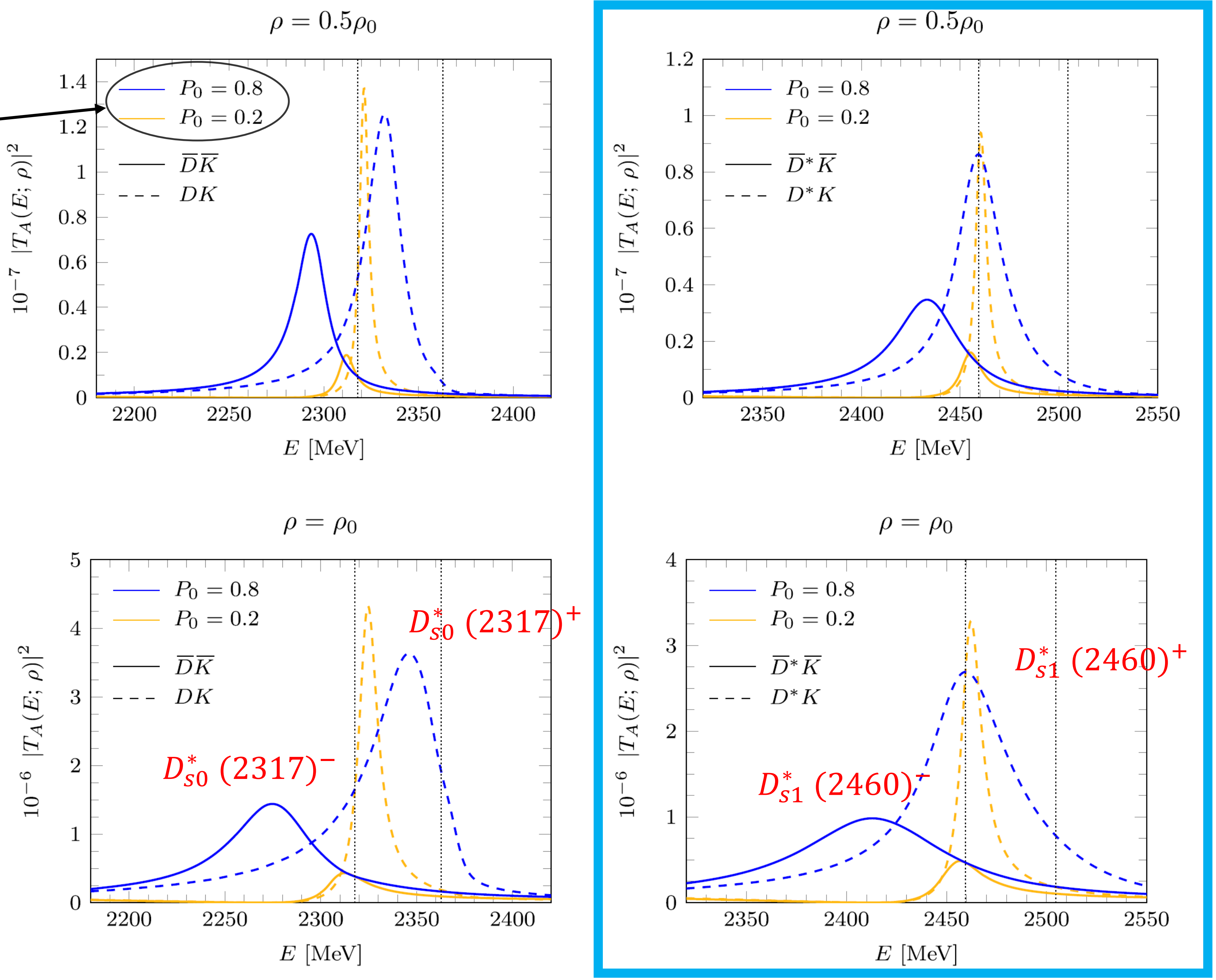
Real and imaginary parts of the DK and $\overline{D}\overline{K}$ loop functions inside of the nuclear environment



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 $D_{s0}^{*}\,(2317)^{-}$

two molecular probabilities

Line-shapes for different densities and molecular probabilities



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

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

CONCLUSIONS

- 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 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

Back up