$D_{s0}^*(2317)^+$ AND $D_{s0}^*(2317)^-$ IN NUCLEAR MATTER

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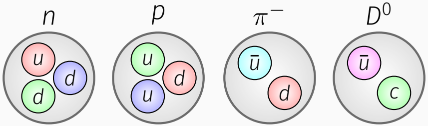
Hadron spectroscopy: Conventional and exotic



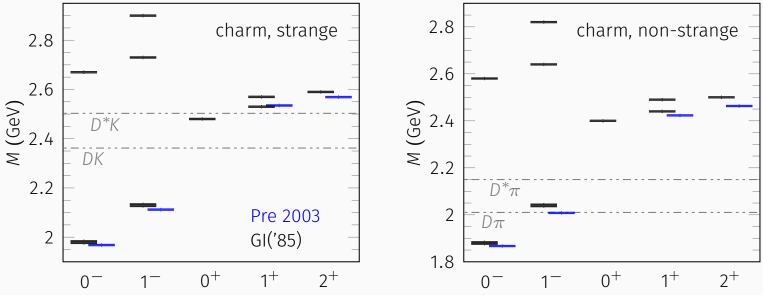
- Conventional hadrons:
  - Mesons: $q\bar{q}'$: $\pi^+ = u\bar{d}$, $D^0 = c\bar{u}$, ...
  - Baryons: $q_1q_2q_3$: $p = uud$, $n = udd$, ...
- Constituent quark models have successfully described most of (but not all!) the hadrons discovered so far.

- Only possibilities? No, the only requirement is to be color singlets. There can be tetraquarks ($q_1\bar{q}_2q_3\bar{q}_4$), pentaquarks ($\bar{q}_1q_2q_3q_4q_5$), hybrids ($\bar{q}_1q_2g$), glueballs (gg), hadronic molecules (MM', MB, BB'), ...
- QCD cannot be used perturbatively at the low energies required in spectroscopy. Non perturbatively, some numerical calculations can be done with LQCD. However, there are problems at finite density.
- Use effective field theories together with non-perturbative methods.

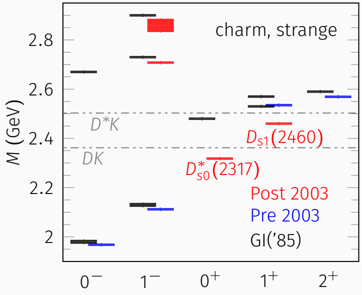
QUARK MODEL IN THE OPEN-CHARM SECTOR

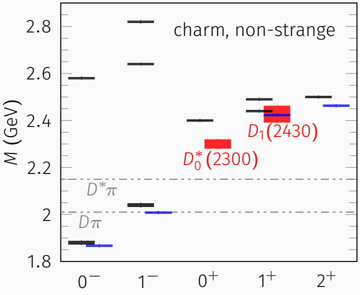
- Quark model $c\bar{n}$ is still our baseline:

  «In this paper we present the results of a study of light and heavy mesons in soft QCD. We have found that all mesons–from the pion to the upsilon–can be described in a unified framework.» [Godfrey, Isgur, PR,D32,189('85)]



- Quark model $c\bar{n}$ is still our baseline:



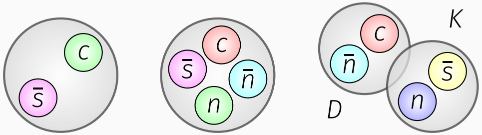


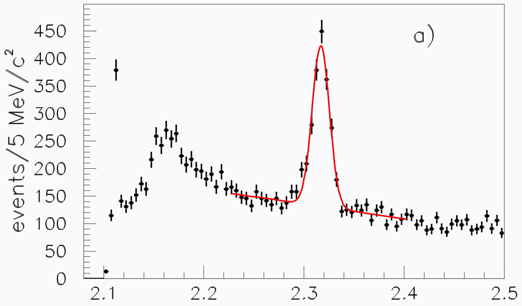
- The discovery of $D^*_{s0}(2317)$ in 2003 (and $D_{s1}(2460)$ later on) is "equivalent" to the discovery of $X(3872)$ in charmonium-like system.

BABAR, PRL,90,242001('03)
CLEO, PR,D68,032002('03)

Generalities about the $D_{s0}^{*}(2317)^{+}$

- First reported by BABAR in 2003.
- Very narrow state, close to the DK threshold.
  - $m_D + m_K - m_{D_{s0}^{*+}} \simeq 45$ MeV.
  - $\Gamma_{D_{s0}^{*+}} < 3.8$ MeV CL= 95%.
- Well established as an isoscalar state.
- $J^P = 0^+$.
- Quark content?

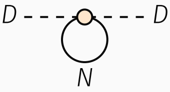


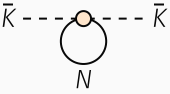


$D_s^+\pi^0$ mass distribution for the decay $D_s^+ \to K^+K^-\pi^0$ showing the $D_{s0}^{*}(2317)^+$ signal from BABAR [BABAR, PRL,90,242001('03)].

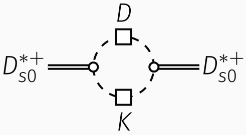
$D_{s0}^*(2317)^+$ AND $D_{s0}^*(2317)^-$ IN NUCLEAR MATTER: OVERVIEW

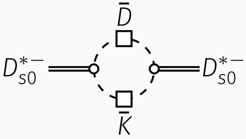
1. The nuclear medium changes the properties of D, K, $\bar{D}$ and $\bar{K}$ mesons. They develop a self-energy.





2. The D_{s0}^{*+} couples to the DK pair, and the D_{s0}^{*-} to the $\bar{D}\bar{K}$ one.
3. The dressed DK and $\bar{D}\bar{K}$ mesons renormalize the D_{s0}^{*+} and D_{s0}^{*-} propagators.

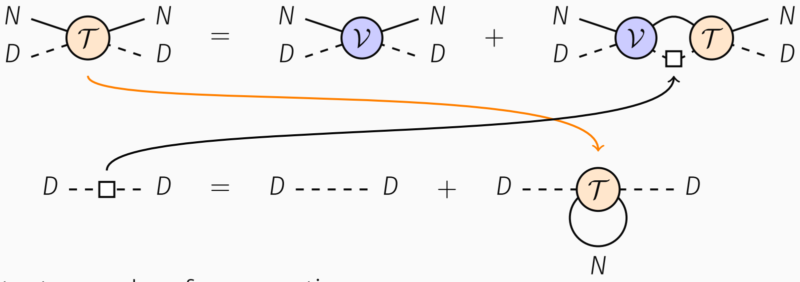




4. Owing to the different DN and KN vs $\bar{D}N$ and $\bar{K}N$ interactions, the D_{s0}^{*+} and D_{s0}^{*-} will behave very differently in the medium.

D MESONS IN NUCLEAR MATTER

More details on the DN interaction: L. Tolos, C. Garcia-Recio, J. Nieves, PRC 80, 065202 ('09)

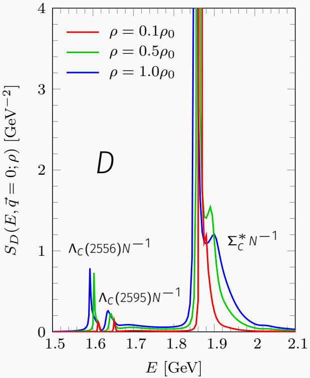


- Self-consistent procedure for computing the D and $\bar{D}$ self-energies
- In the isospin limit, $\Pi_{D^0} = \Pi_{D^+} \equiv \Pi_D$
- However $\Pi_D \neq \Pi_{\bar{D}}$

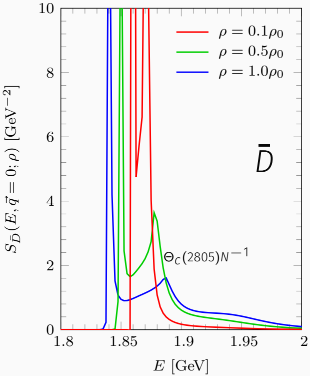
$$\Delta_D(q;\,\rho) = \frac{1}{q^2 - m_D^2 - \Pi_D(q;\,\rho)}$$

D and $\bar{D}$ spectral functions

L. Tolos, C. Garcia-Recio, J. Nieves, PRC 80, 065202 ('09)



C. Garcia-Recio, J. Nieves, L.L. Salcedo, L. Tolos, PRC 85, 025203 ('12)

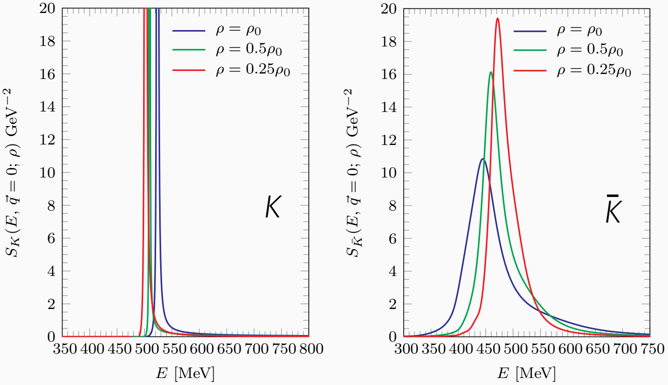


$$\Delta_D(q;\,\rho) = \frac{1}{q^2 - m_D^2 - \Pi_D(q;\,\rho)} = \int_0^\infty d\omega \left(\frac{S_D(\omega, |\vec{q}\,|;\,\rho)}{q^0 - \omega + i\varepsilon} - \frac{S_{\bar{D}}(\omega, |\vec{q}\,|;\,\rho)}{q^0 + \omega - i\varepsilon} \right)$$

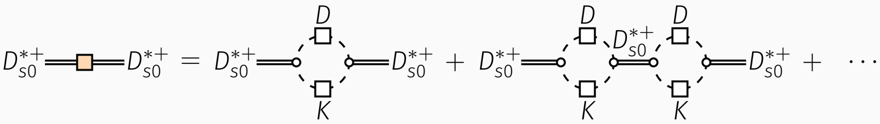
K and $\bar{K}$ mesons in nuclear matter

L. Tolos, D. Cabrera, A. Ramos, PRC 78, 045205 ('08)

- K and $\bar{K}$ self-energies are computed analogously to the D and $\bar{D}$ ones.
- KN and $\bar{K}N$ interactions radically different!
  - KN interaction is very weak $\rightarrow$ K spectral function almost a Dirac delta.
  - In $\bar{K}N$ the two-pole $\Lambda(1405)$ state appears.



$D_{s0}^*(2317)^+$ SELF-ENERGY IN NUCLEAR MATTER



- Renormalized D_{s0}^{*+} propagator in terms of the bare mass ($\hat{m}$) and coupling ($\hat{g}$):

$$\Delta^{-1}_{D_{s0}^{*+}}(p;\,\rho) = p^2 - \hat{m}^2 - \hat{g}^2\Sigma(p;\,\rho) \quad \leftarrow \quad \Sigma(p;\,\rho) = i\int \frac{d^4q}{(2\pi)^4} \underbrace{\Delta_D(p-q;\,\rho)\Delta_K(q;\,\rho)}_{\Delta_D \text{ and } \Delta_K \text{ in nuclear medium}}$$

- We introduce a sharp cutoff Λ in the d^3q integral to regularize $\Sigma(p;\,\rho)$.
- The D_{s0}^{*+} mass for finite density in terms of the vacuum mass (m_0) and coupling (g_0) is

$$m^2(\rho) = m_0^2 + \frac{g_0^2}{1 + g_0^2\Sigma'(m_0;\,0)}\left\{\Sigma[m(\rho);\,\rho] - \Sigma(m_0;\,0)\right\}$$

- $\Sigma(p;\,\rho)$ develops an imaginary part, and so does $m^2(\rho)$.

DK scattering in nuclear matter

- We solve the Bethe-Salpeter Equation in the on-shell approximation to obtain the $I = 0$ DK $T-$matrix.

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

- We consider two families of potentials.

$$\begin{cases} V_A(s) = C_1 + C_2 s \\ V_B(s) = (C_1' + C_2' s)^{-1} \end{cases}$$

- $C_1^{(\prime)}$ and $C_2^{(\prime)}$ constants fixed by imposing

$$\begin{cases} T^{-1}(m_0^2;\,0) = 0 \\ \left.\dfrac{dT^{-1}(s\,;0)}{ds}\right|_{s=m_0^2} = \dfrac{1}{g_0^2} \end{cases}$$

- The loop function contains the medium effects.
- Weinberg compositeness condition:

$$P_0 = -g_0^2 \Sigma'(m_0;\,0).$$

S. Weinberg, Phys.Rev. 137, B672 ('65)
D. Gamermann, J. Nieves, E. Oset, E. Ruiz Arriola, PRD 81, 014029 ('10)

- P_0 is interpreted as the DK molecular component in the D_{s0}^{*+} wavefunction.

Preliminary results: in-medium *DK* Loop Function

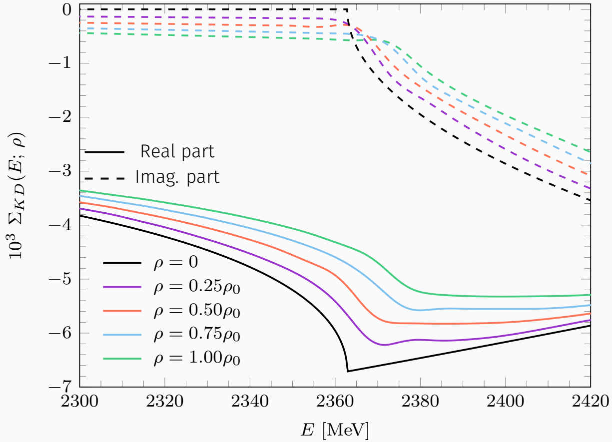


Figure: *DK* loop function for different values of ρ.

- The sharp threshold is smoothed out at finite density.
- Σ develops some imaginary part below threshold.
- Ignoring the effects of the imaginary part, the shift in the real part of Σ can be naively related to a more repulsive interaction.

Preliminary results: $D^*_{s0}(2317)^+$ propagator

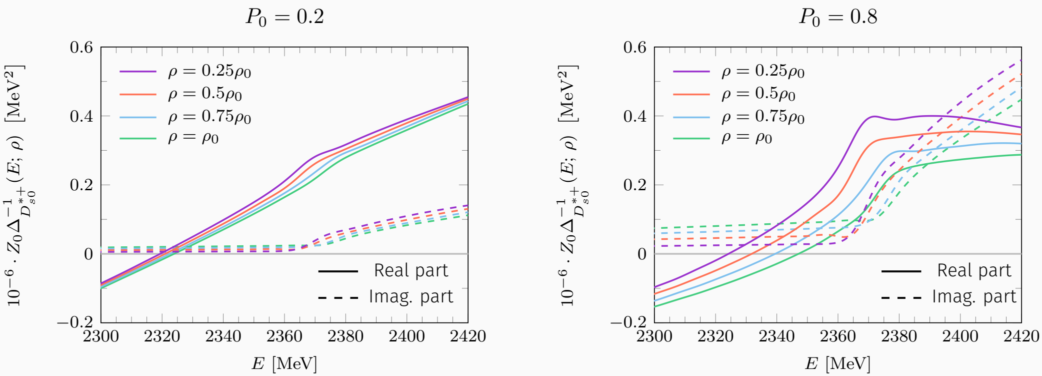


Figure: $D^*_{s0}(2317)^+$ renormalized propagator for different values of ρ.

- Imaginary part below threshold.

- Quasi-particle energy: $\mathrm{Re}\, \Delta^{-1}_{D^{*+}_{s0}}(E_{\rm qp}, |\vec{q}|;\, \rho) = 0$.
- $E_{\rm qp}$ shifts towards higher energies for growing ρ.

Preliminary results: in-medium DK amplitude

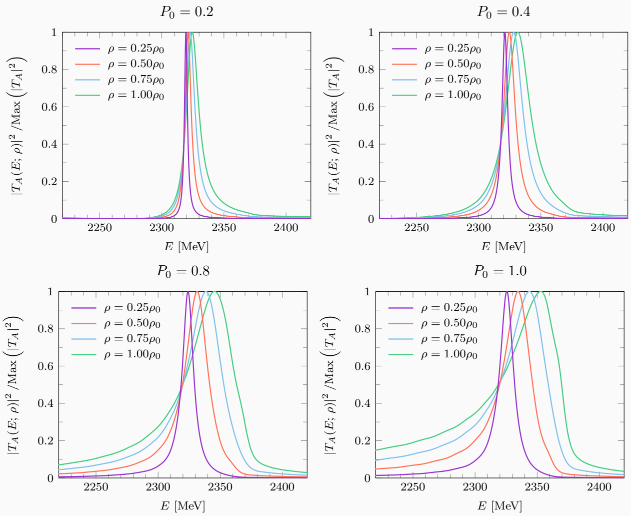


Figure: DK scattering $T-$matrix for different values of P_0 and ρ.

- What was a bound state is now a resonance with some width.
- Its width increases with growing ρ and P_0.
- The position of its maximum shifts to the right with growing ρ.

Preliminary results: $\bar{D}\bar{K}$ vs DK, loop functions

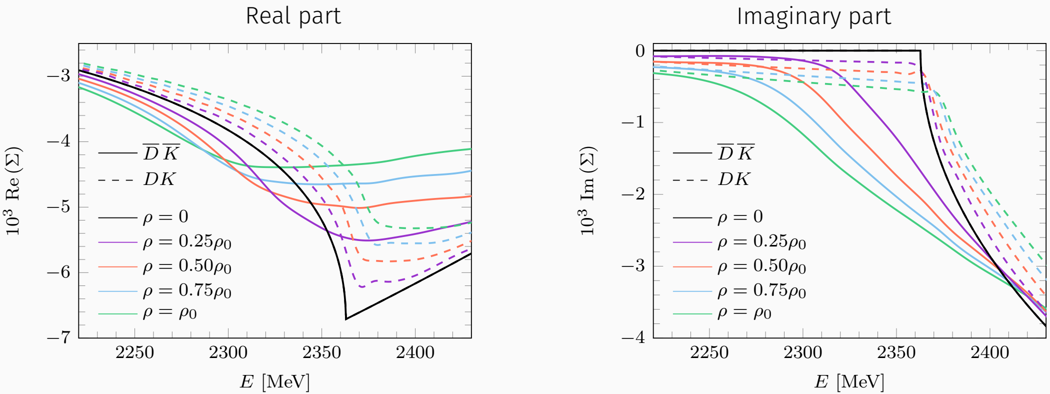


Figure: $\bar{D}\bar{K}$ and DK scattering loop functions for different values of ρ.

- Very different density pattern!
- Shift in $\mathrm{Re}\,(\Sigma)$ now points to more attraction.

Preliminary results: $D^*_{s0}(2317)^-$ propagator

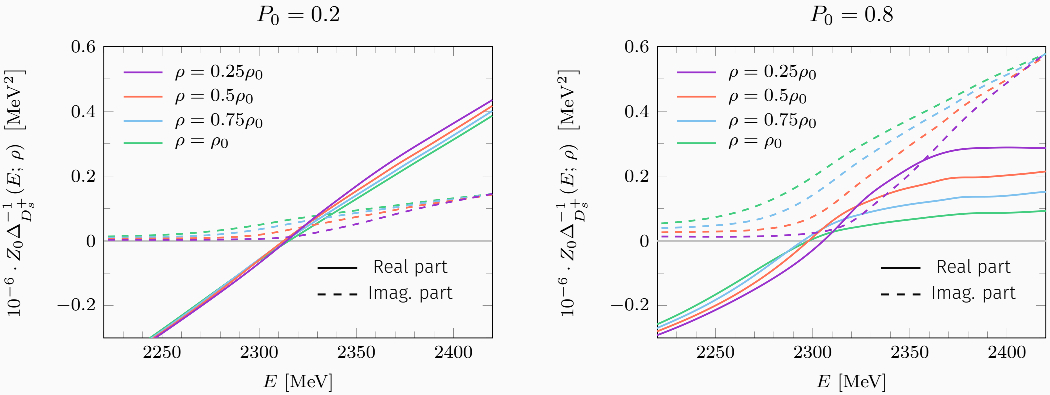


Figure: $D^*_{s0}(2317)^-$ renormalized propagator for different values of ρ.

- Notable imaginary part growth below threshold.
- E_{qp} shifts to lower energies (not so clear).

Preliminary results: $\bar{D}\bar{K}$ vs DK, amplitudes

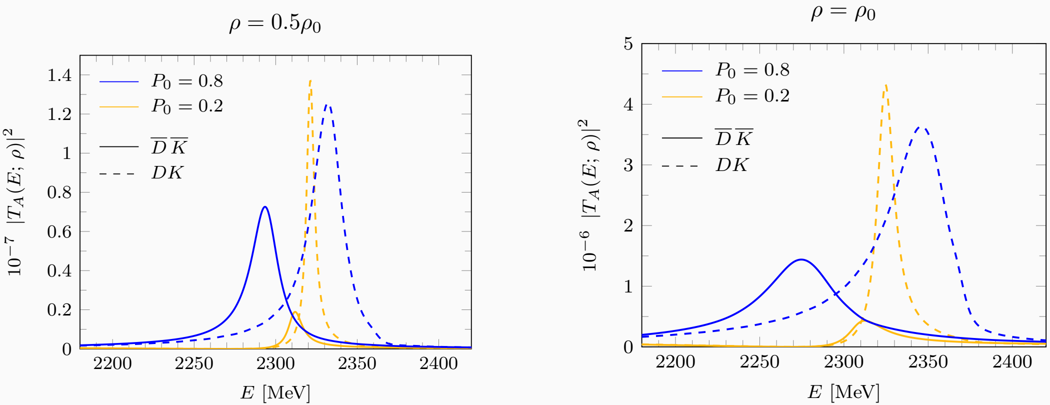


Figure: $\bar{D}\bar{K}$ and DK amplitudes for different values of P_0 and ρ.

- D_{s0}^{*-} wider than D_{s0}^{*+}.
- D_{s0}^{*-} peak shifts to lower energies.
- More notable effects for a large value of P_0.

Summary

- The nuclear medium induces modifications on the properties of the $D_{s0}^*(2317)^+$ and $D_{s0}^*(2317)^-$.
- Due to the different interactions of $\bar{K}$ and K in nuclear matter, the $D_{s0}^*(2317)^-$ and the $D_{s0}^*(2317)^+$ behave very differently in a dense medium.
- The changes in nuclear matter of $D_{s0}^*(2317)^+$ and $D_{s0}^*(2317)^-$ depend strongly on the molecular probability. Hence, the medium modifications could help us to disentagle the nature of these two states.

Backup slides

Some details on the calculation of Σ (part 1)

- The DK (or $\bar{D}\bar{K}$) loop function, Σ, is the object that encodes the nuclear medium effects.
  - $\Delta_{D^*_{s0}}(p;\rho) = p^2 - \hat{m}^2 - \hat{g}^2\Sigma(p;\,\rho)$
  - $T^{-1}(s;\,\rho) = V^{-1}(s) - \Sigma(s;\,\rho)$
- In a previous slide we have shown

$$\Sigma_{MN}(p;\,\rho) = i\int \frac{d^4q}{(2\pi)^4}\Delta_M(p-q;\,\rho)\Delta_N(q;\,\rho)$$

1. We use the Källen-Lehmann representation for the meson propagators

$$\Delta_M(q\,;\rho) = \int_0^\infty d\omega\left(\frac{S_M(\omega,\,|\vec{q}|;\,\rho)}{q^0-\omega+i\varepsilon} - \frac{S_{\bar{M}}(\omega,\,|\vec{q}|;\,\rho)}{q^0+\omega-i\varepsilon}\right)$$

2. We define the auxiliary function

$$f_{MN}(\Omega;\,\rho) = \int_0^\Lambda dq\,q^2\int_0^\Omega d\omega\,S_M\left(\omega,\,|\vec{q}|;\,\rho\right)S_N\left(\Omega-\omega,\,|\vec{q}|;\,\rho\right)$$

Some details on the calculation of Σ (part 2)

3. One can show that the loop function can be written as

$$\Sigma_{MN}(E\,;\,\rho) = \frac{1}{2\pi^2}\left\{\int_0^\infty d\Omega \left(\frac{f_{MN}(\Omega\,;\,\rho)}{E-\Omega+i\varepsilon} - \frac{f_{\bar{M}\bar{N}}(\Omega\,;\,\rho)}{E+\Omega-i\varepsilon}\right) - i\pi f_{MN}(E\,;\,\rho)\right\}$$

- When computing f_{DK} we make a simplification:

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

- The quasi-particle energy ($E_{\rm qp}$) is defined from the condition

$$\mathrm{Re}\ \Delta_K^{-1}(E_{\rm qp},\,|\vec{q}|;\,\rho) = 0$$

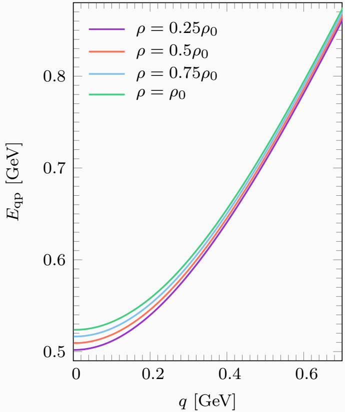


Figure: $E_{\rm qp}$ as a function of the magnitude of three-momentum q for different densities.