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$T_{cc}(3875)$ AT FINITE DENSITY AND FINITE TEMPERATURE

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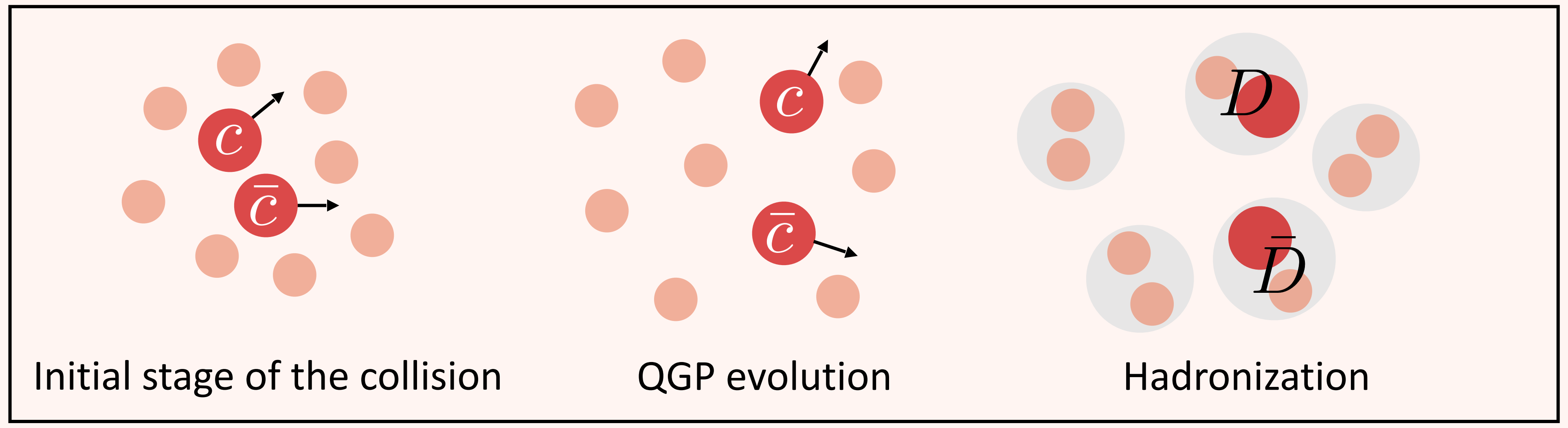
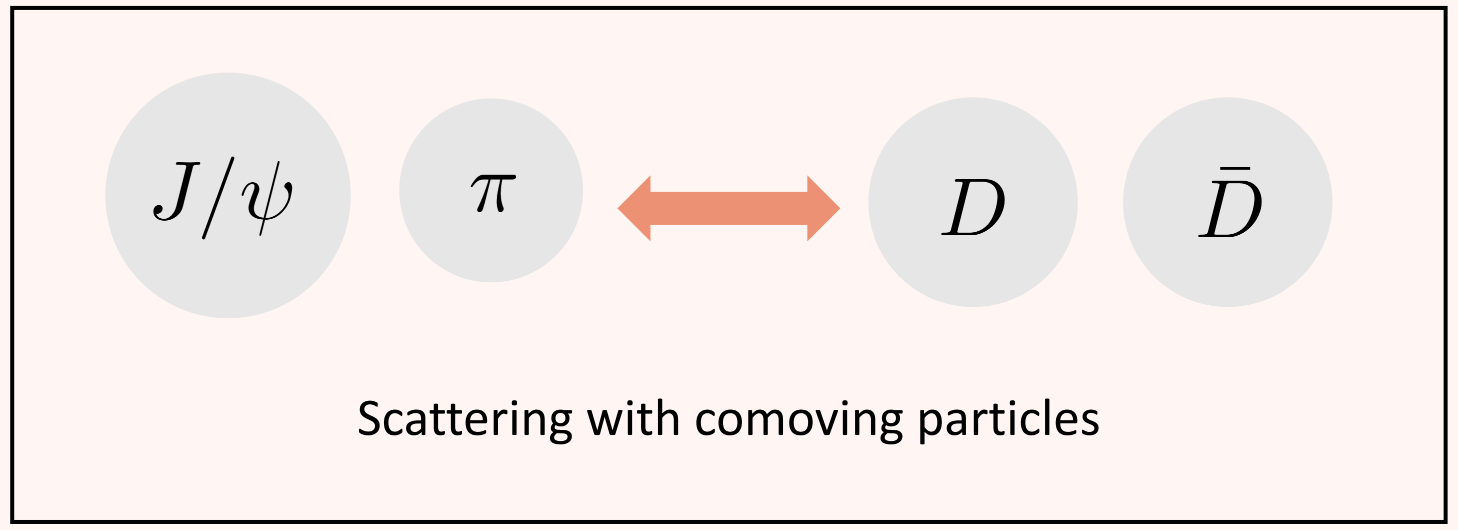
WHY HEAVY FLAVOR IN MATTER?

- **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

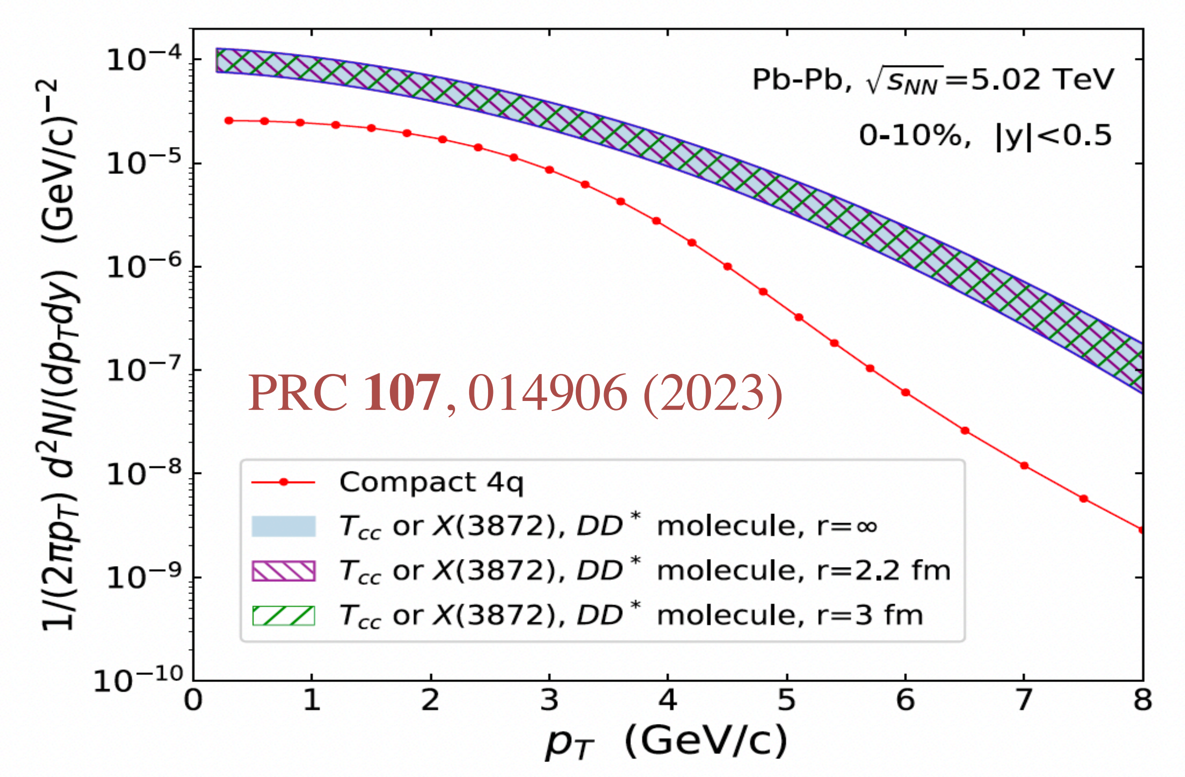


comover scattering



Credit: G. Montaña

- **Interesting by itself, to understand their nature**
  - **Pure (compact) quark states**
  - **Meson molecules**
  - **Combination of both**



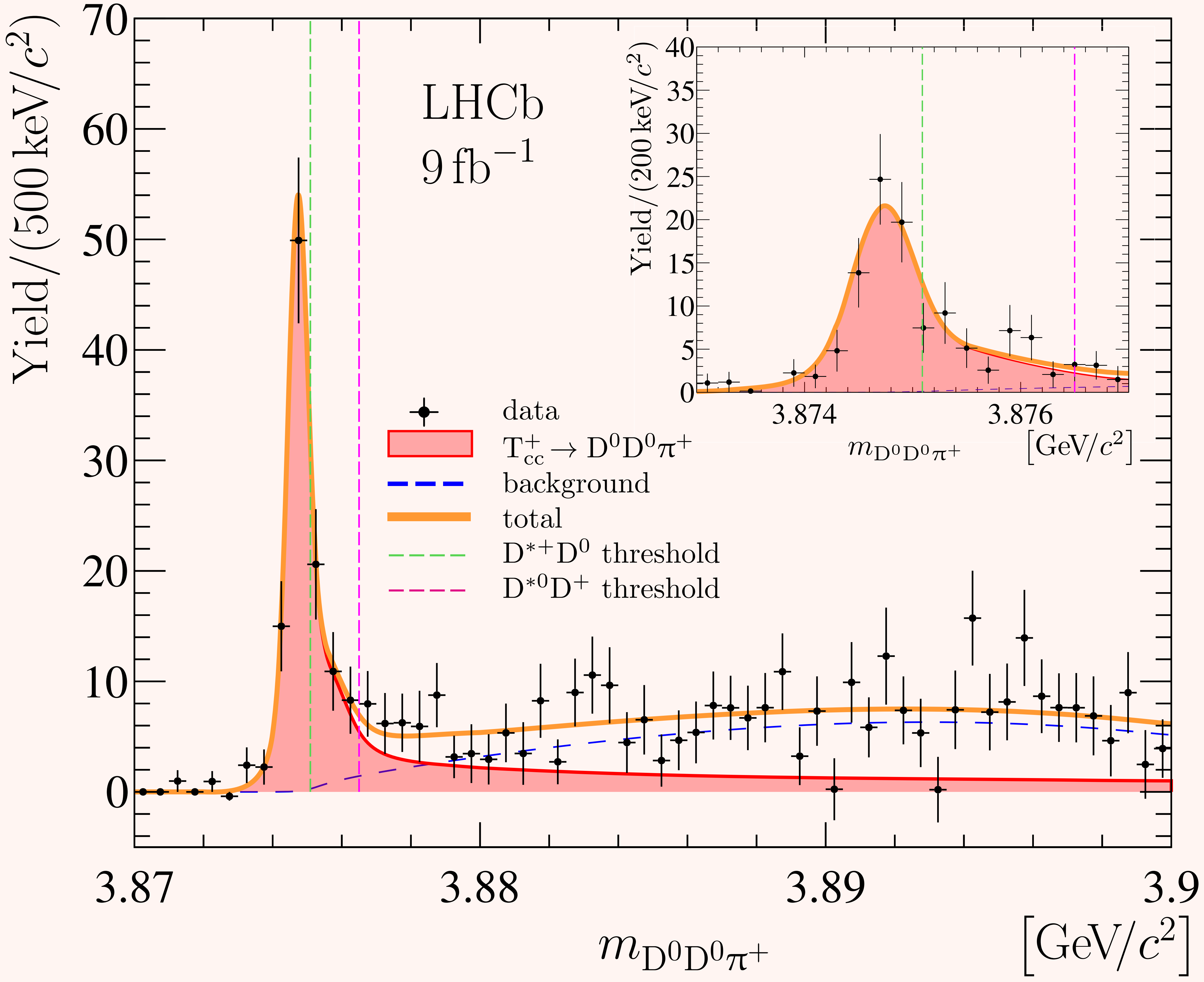
$T_{cc}(3875)$: EXPERIMENTAL DISCOVERY

- **$T_{cc}(3875)$ measured by LHCb**
  [Nat. Phys. 18 (2022) 751,
  Nat. Comm. 13 (2022) 3351]

  - $\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0}$ keV
    $(\delta m \equiv m_{T_{cc}} - m_{D*^+} - m_{D^0})$
  - $\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14}$ keV

- **Extremely close to DD^* threshold:**

→ Strongly favours DD^* molecular interpretation in $I(J^P) = 0(1^+)$ channel

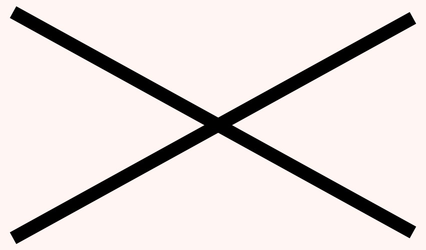


The distribution of the $D^0D^0\pi^+$mass

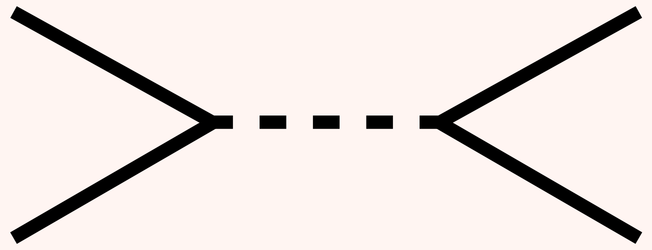
MESON-MESON SCATTERING IN VACUUM

- **We start by considering a molecular state modelled as a pole in the two-meson scattering amplitude in S-wave in vacuum**

- **We use two parameterizations for a single-channel contact potential [PRC 104 (2021) 035203]**

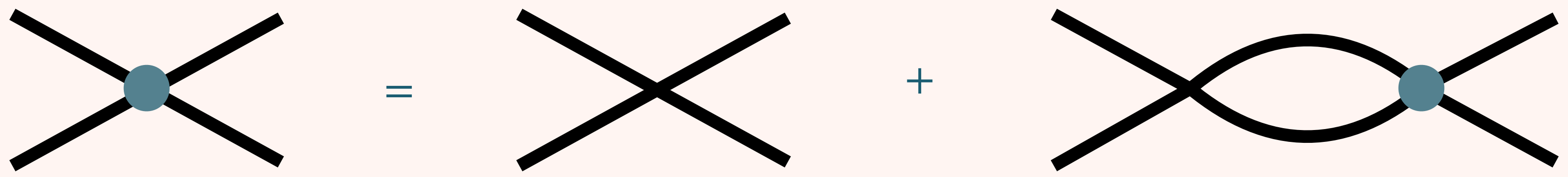


$$V_A(s) = C + Ds \qquad \text{or} \qquad V_B(s) = \frac{1}{C' + D's}$$



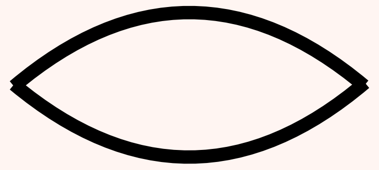
- **Then we use the on-shell Bethe-Salpeter equation to unitarize the resulting amplitudes**

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



- **$\Sigma_0(s)$ is the two-meson loop function in vacuum**

$$\Sigma_0(s = P^2) = \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_1^2 + i\varepsilon} \frac{1}{(P-q)^2 - m_2^2 + i\varepsilon}$$



EXPLICIT FORM OF THE POTENTIALS

- $C^{(\prime)}$ and $D^{(\prime)}$ parameters fix the pole position (m_0) and molecular probability (P_0) of the bound state

- Impose $T^{-1}(m_0^2) = 0$ and $\dfrac{dT^{-1}(m_0^2)}{ds} = \dfrac{1}{g_0^2}$

- Weinberg compositeness (rediscussed in PRD 81 (2010) 014029)

$$P_0 = -g_0^2 \frac{d\Sigma_0(m_0^2)}{ds}$$

- The compositeness P_0 can be interpreted as the probability that the bound state appears as a two-meson state

$$P_0 = \left| \langle MM' | \Psi \rangle \right|^2$$

- Other contributions to the total probability may arise from:
  - Other two-meson channels
  - Energy dependence on the interaction

$$1 = g_0^2 \frac{dV^{-1}}{ds} - g_0^2 \frac{d\Sigma_0}{ds} = Z_0 + P_0$$

- We will vary P_0 from 0 to 1

NUCLEAR MATTER

- **What is nuclear matter?**
  - **No Coulomb interaction.**
  - **Equal number of protons and neutrons (isospin symmetric).**
  - **Very large in size (boundary effects neglected).**

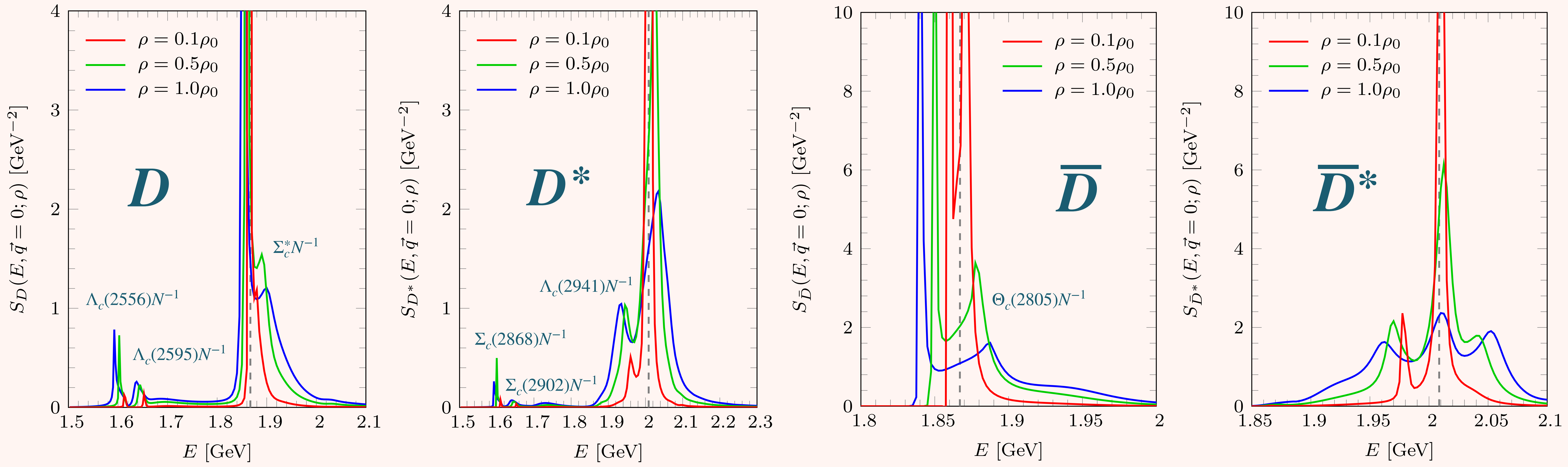
- **What happens when inserting a particle into such a system?**
  - **Particle undergoes scattering with the nucleons.**
  - **Its energy dispersion formula changes ($E^2 \neq m^2 + p^2$) due to interactions.**
  - **Develops a finite lifetime.**

- **This information is contained in the self-energy Π, or alternatively, the spectral function S**

$$\frac{1}{q^2 - m^2} \to \frac{1}{q^2 - m^2 - \Pi(q)} = \int_0^\infty d\omega \left(\frac{S_M(\omega, |\vec{q}\,|)}{q^0 - \omega + i\varepsilon} - \frac{S_{\overline{M}}(\omega, |\vec{q}\,|)}{q^0 + \omega - i\varepsilon} \right).$$

D AND D^* SPECTRAL FUNCTIONS

D and D^*: [PRC 80 (2009) 065202] $\bar{D}$: [PRC 85 (2012) 025203] $\bar{D}^*$: [PRD 81 (2010) 094016]



- T_{cc} as a DD^* molecule, we consider the $D^{(*)}$ spectral functions
- For zero density $\rightarrow S \propto \delta(E - m)$
- Rich structure due to particle-hole excitations
- Distinct $D^{(*)}$ vs $\bar{D}^{(*)}$ spectral functions due to different interactions with the nucleons of the sea

DD^* SCATTERING IN NUCLEAR MATTER

- With the D and D^* self energies, we can compute the two-meson propagator in nuclear matter ($\Lambda = 0.7$ GeV)

$$\Sigma(E,\overrightarrow{P};\rho) = \int \frac{d^4q}{(2\pi)^4} \frac{1}{q^2 - m_D^2 + \Pi_D(q;\rho)} \frac{1}{(P-q)^2 - m_{D^*}^2 + \Pi_{D^*}(P-q;\rho)}$$

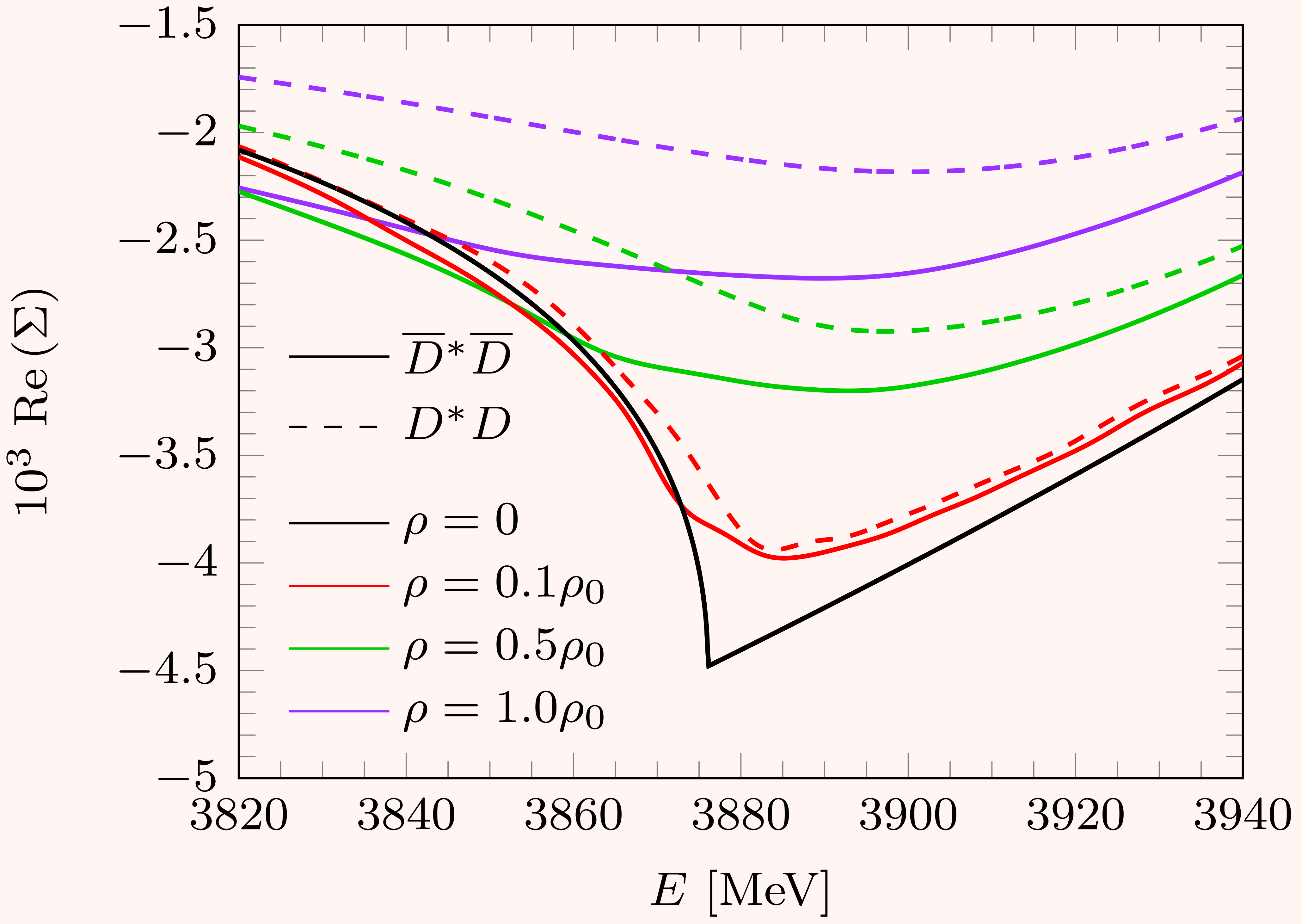
- In terms of the spectral functions

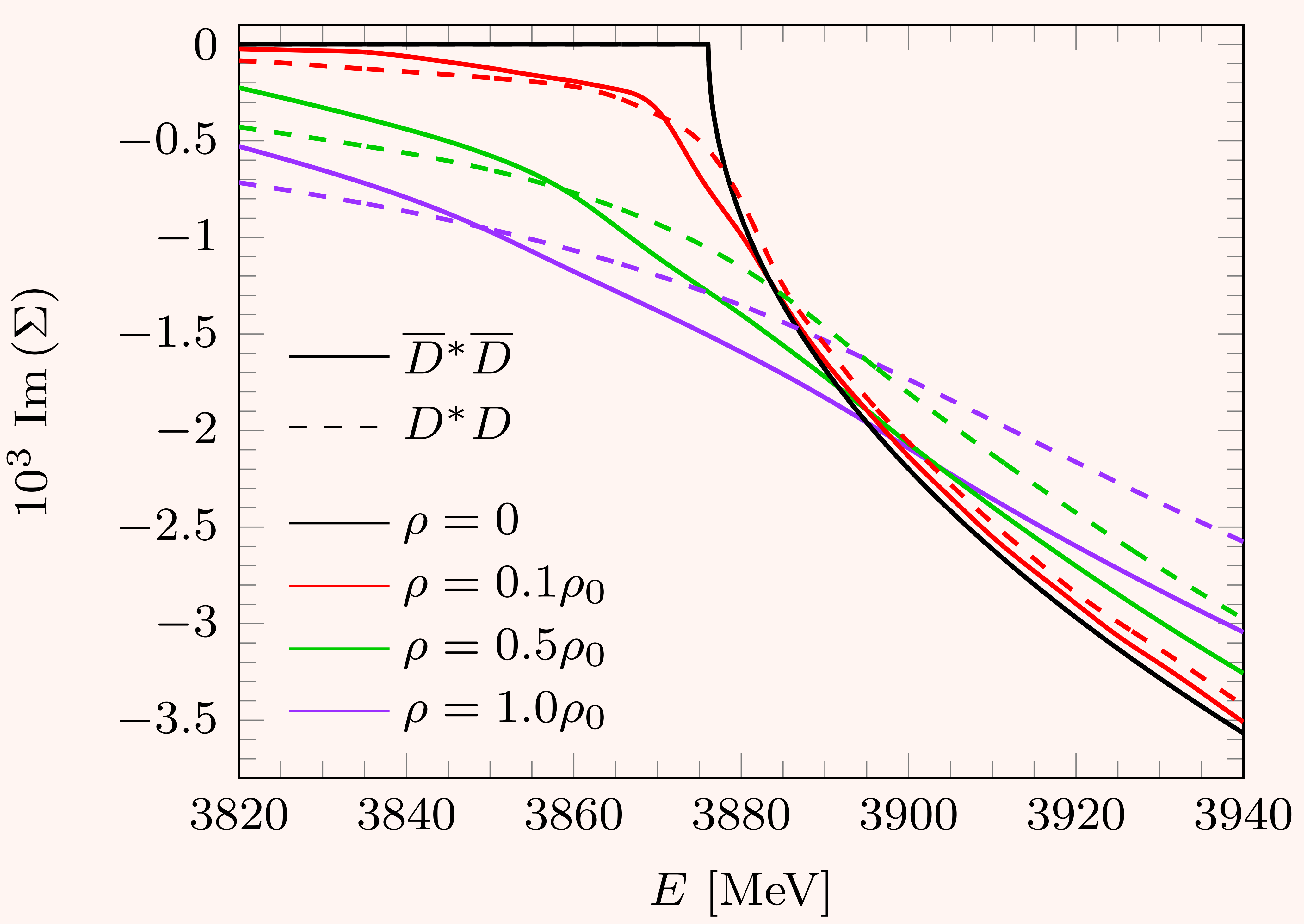
$$\Sigma(E,\vec{0};\rho) = \frac{1}{(2\pi)^3}\int_0^\Lambda d^3q \int_0^\infty d\omega \int_0^\infty d\omega' \left(\frac{S_D(\omega,|\vec{q}\,|;\rho)S_{D*}(\omega',|\vec{q}\,|;\rho)}{E-\omega-\omega'+i\varepsilon} - \frac{S_{\overline{D}}(\omega,|\vec{q}\,|;\rho)S_{\overline{D}*}(\omega',|\vec{q}\,|;\rho)}{E+\omega+\omega'-i\varepsilon} \right)$$

Computed in the medium rest-frame

- $\Sigma_{\overline{D}\overline{D}^*}$ different from Σ_{DD^*} → Different in-medium amplitudes!

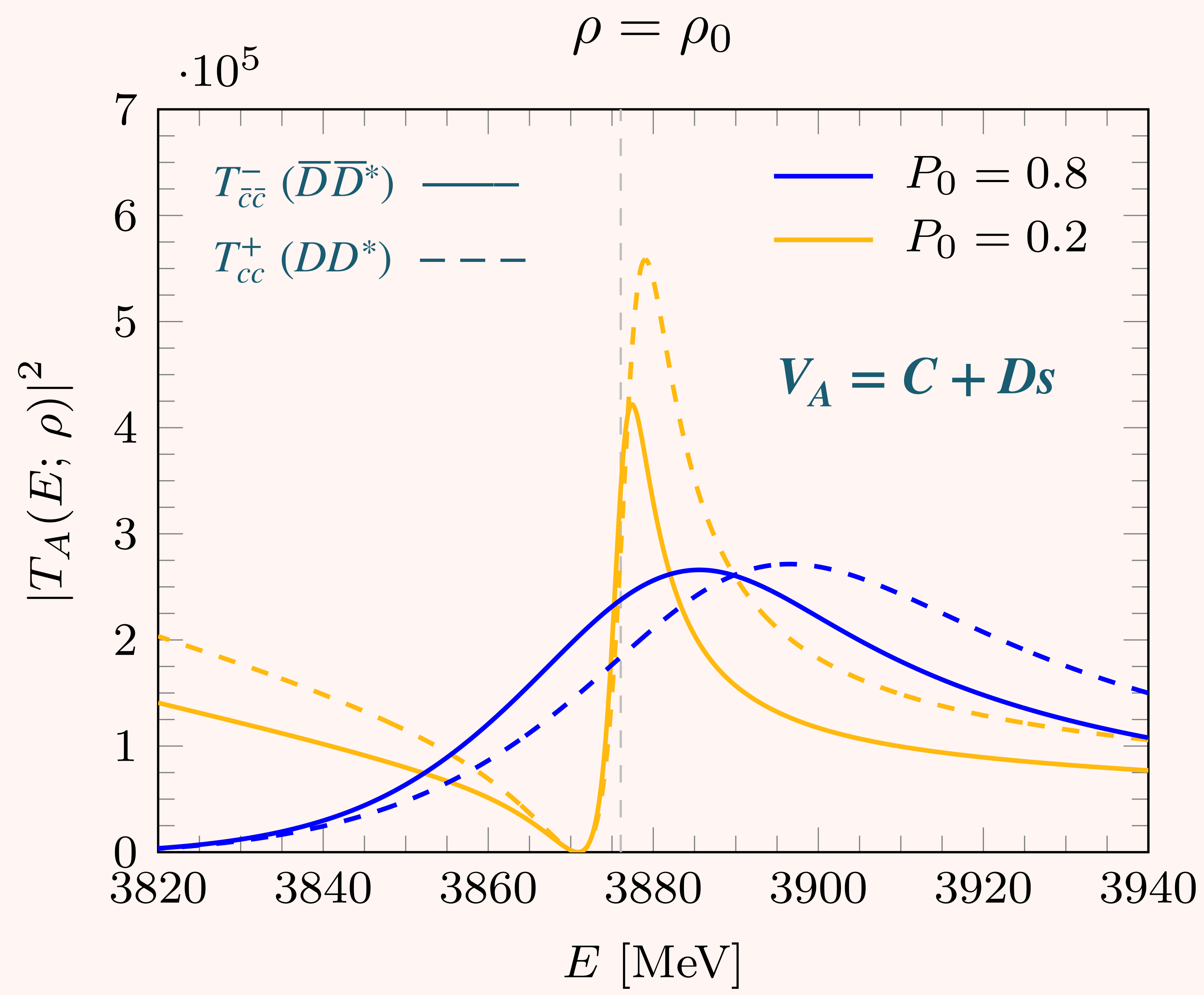
DD^* AND $\overline{D}\overline{D}^*$ LOOP FUNCTIONS

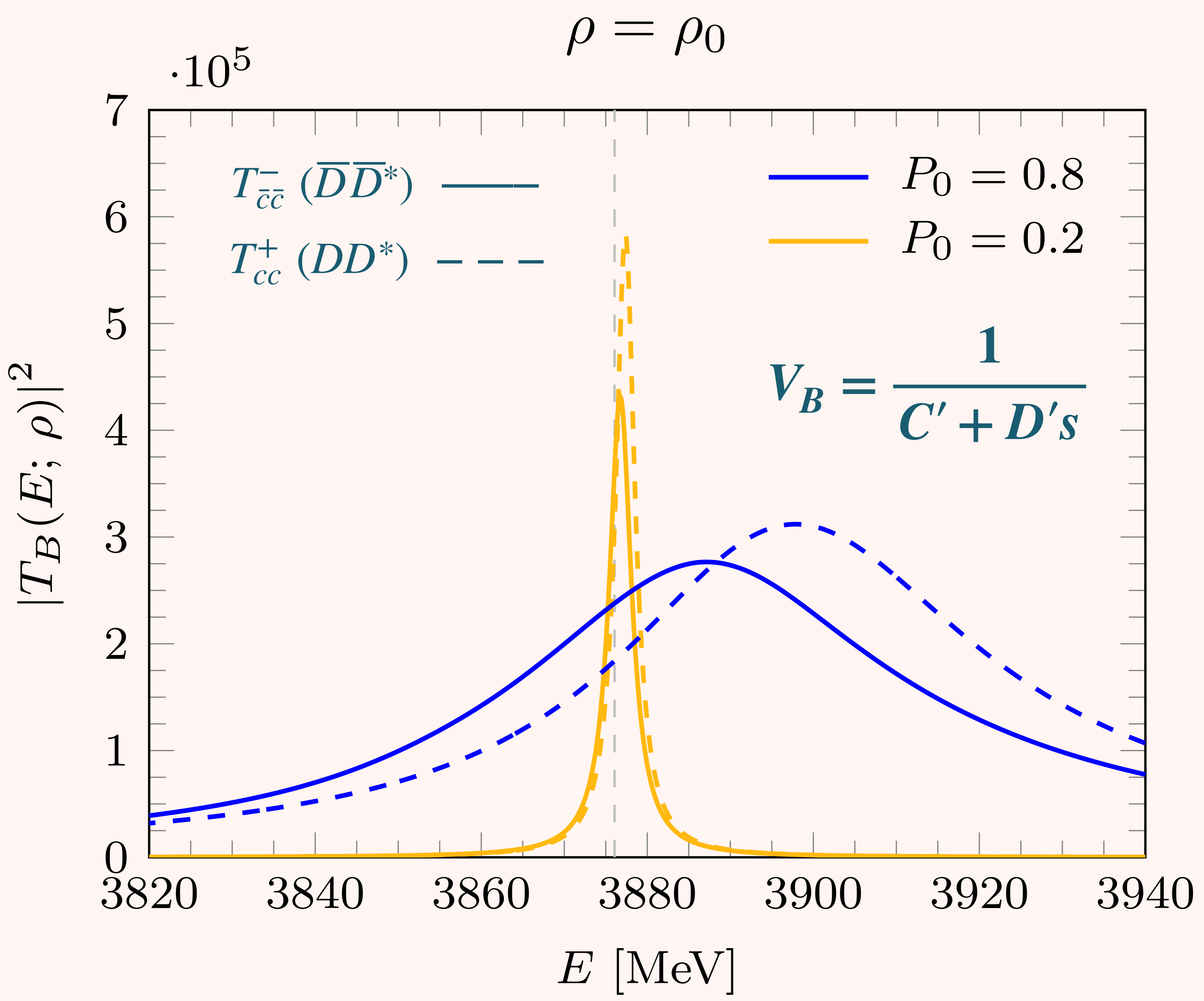




- **The sharp threshold smoothes out with increasing density**
- **Imaginary part below vacuum threshold (due to charmed mesons acquiring width)**

DD^* AND $\overline{D}\overline{D}^*$ SCATTERING AMPLITUDES





- T^+_{cc} and $T^-_{\bar{c}\bar{c}}$ behave differently in nuclear matter, but equal in vacuum (charge conjugation symmetry)
- Widths of T^+_{cc} and $T^-_{\bar{c}\bar{c}}$ grow with density, specially for high P_0 (due to their coupling to charmed mesons)
- Differences between positions and widths of T^+_{cc} and $T^-_{\bar{c}\bar{c}}$ arise with molecular content and density
  - $T^-_{\bar{c}\bar{c}}$ less massive than T^+_{cc}
  - $T^-_{\bar{c}\bar{c}}$ and T^+_{cc} develop comparable widths

MESONS AT FINITE TEMPERATURE

- **Similar formalism as in finite density case.**
- **Before: modification due to interactions with nucleons in the medium.**
- **Now, modifications…**
  1. **due to the Bose-Einstein distributions at finite temperature,**
  2. **due to the interaction with other species in the hot bath (mainly light mesons - pions).**

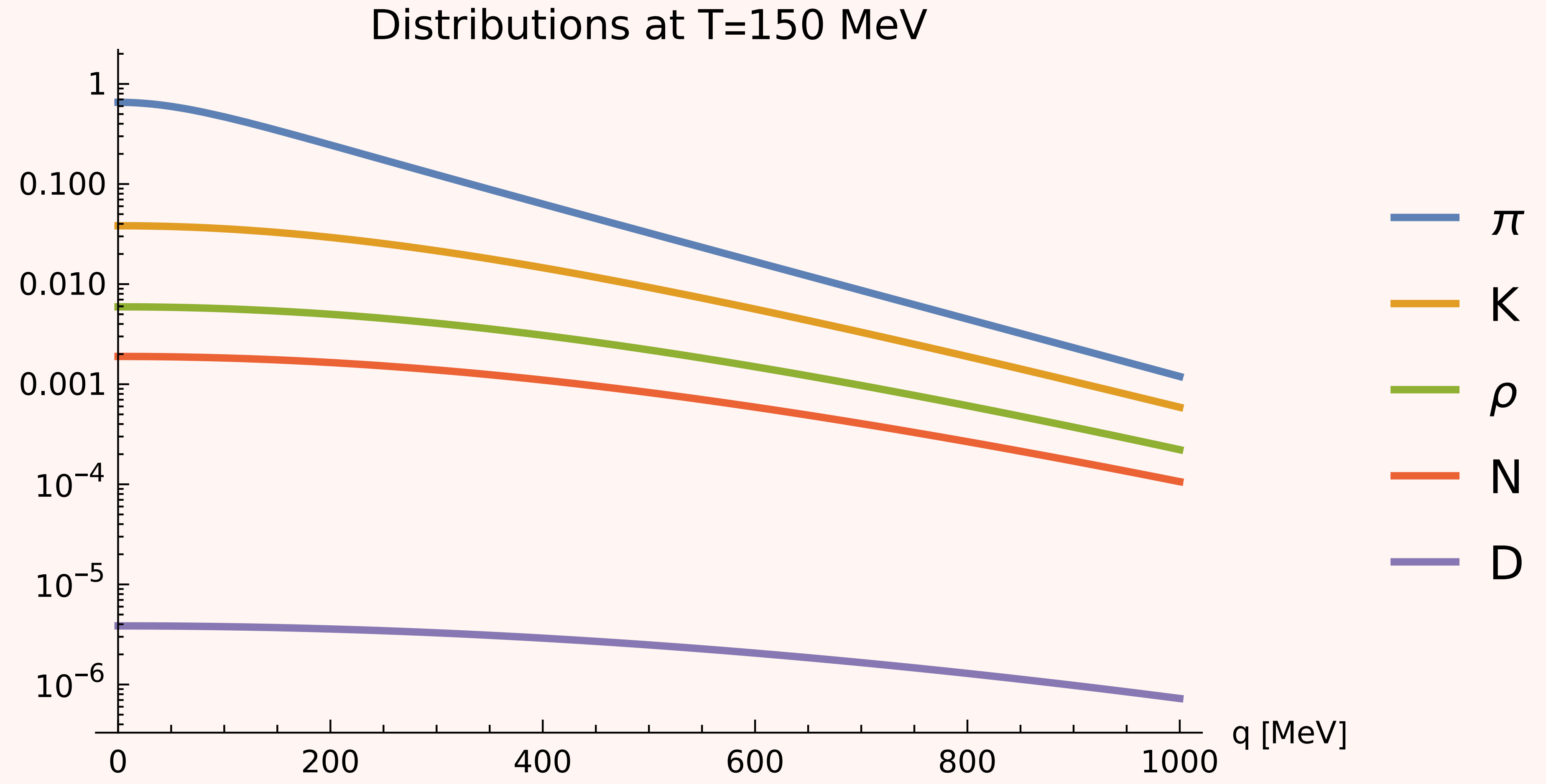


Figure: Plot of distributions for different particles. Heavy particle distribution strongly suppressed.

$$f_{\mathrm{B-E}}[\omega(q), T] = \frac{1}{e^{\omega(q)/T} - 1}$$

$$f_{\mathrm{F-D}}[\omega(q), T] = \frac{1}{e^{\omega(q)/T} + 1}$$

DD^* SCATTERING AT FINITE TEMPERATURE

- **The DD^* and $\overline{D}\overline{D}^*$ propagators at finite temperature computed in Imaginary Time Formalism:**

$$\Sigma_{DD^*}(E,\vec{p}=0;T) = \Sigma_{\overline{D}\overline{D}^*}(E,\vec{p}=0;T) = \int \frac{d^3q}{(2\pi)^3} \int_0^\infty d\omega \int_0^\infty d\omega' \, S_D(\omega,|\vec{q}\,|) S_{D^*}(\omega',|\vec{q}\,|)$$

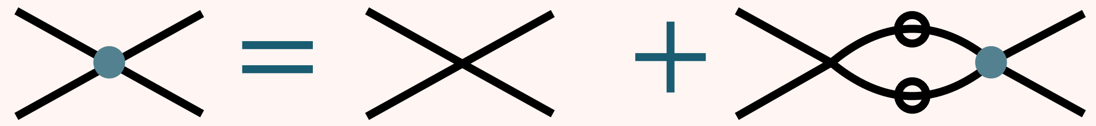
$$\times \left\{ \left[1 + b(\omega,T) + b(\omega',T)\right] \left(\frac{1}{E-\omega-\omega'+i\varepsilon} - \frac{1}{E+\omega+\omega'+i\varepsilon} \right) \right.$$

$$\left. + \left[b(\omega,T) - b(\omega',T)\right] \left(\frac{1}{E+\omega-\omega'+i\varepsilon} - \frac{1}{E-\omega+\omega'+i\varepsilon} \right) \right\}$$

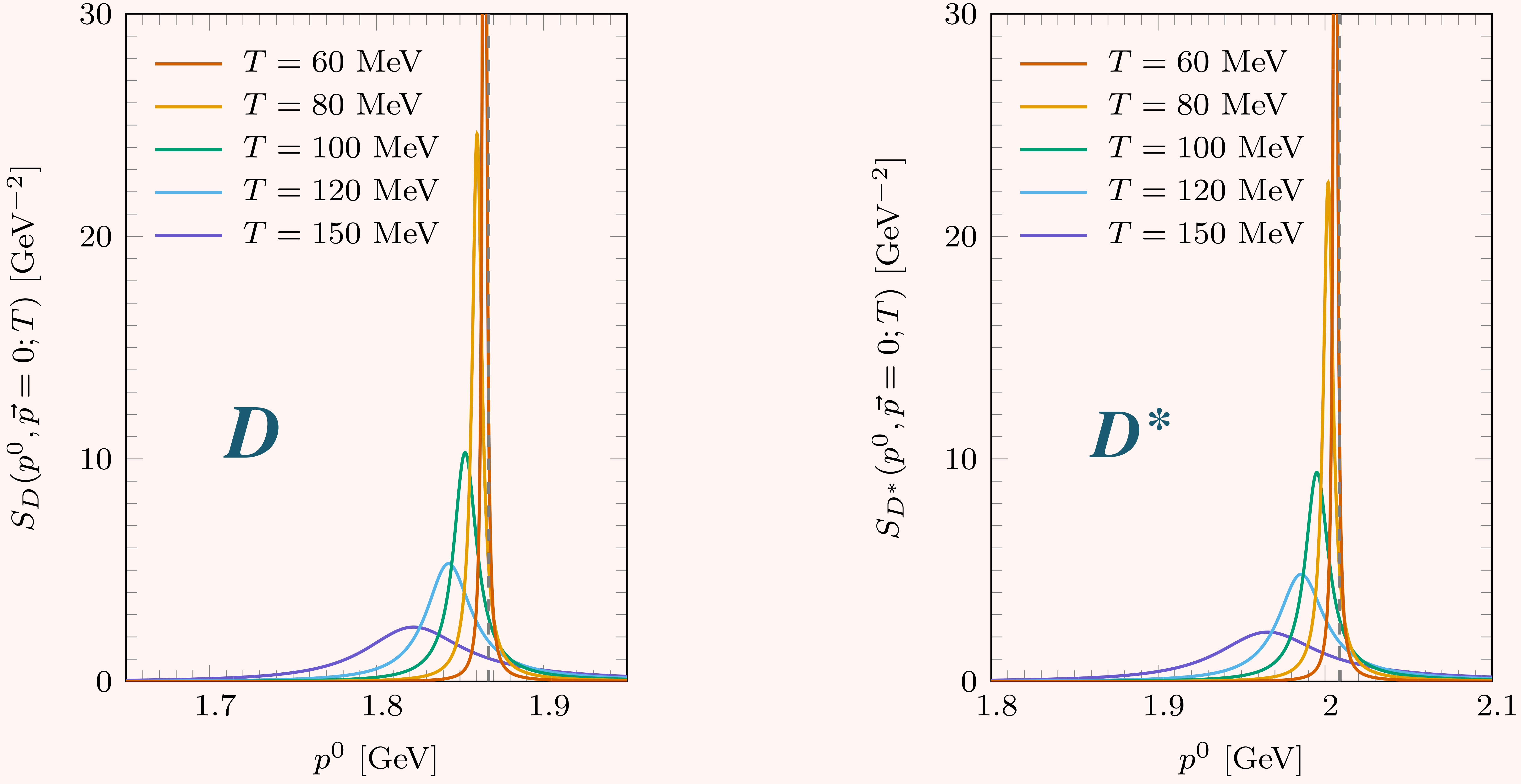
- **It depends on**
  - **Bose-Einstein distributions** $\quad b[\omega,T] = \dfrac{1}{e^{\omega/T}-1}$
  - **D and D^* self-energy due to the interaction with pions**
- **Potential families same as the ones used in the finite density study**

The on-shell BS amplitude:

$$\mathcal{T}^{-1}_{A,B}(s;T) = V^{-1}_{A,B}(s) - \Sigma(s;T)$$

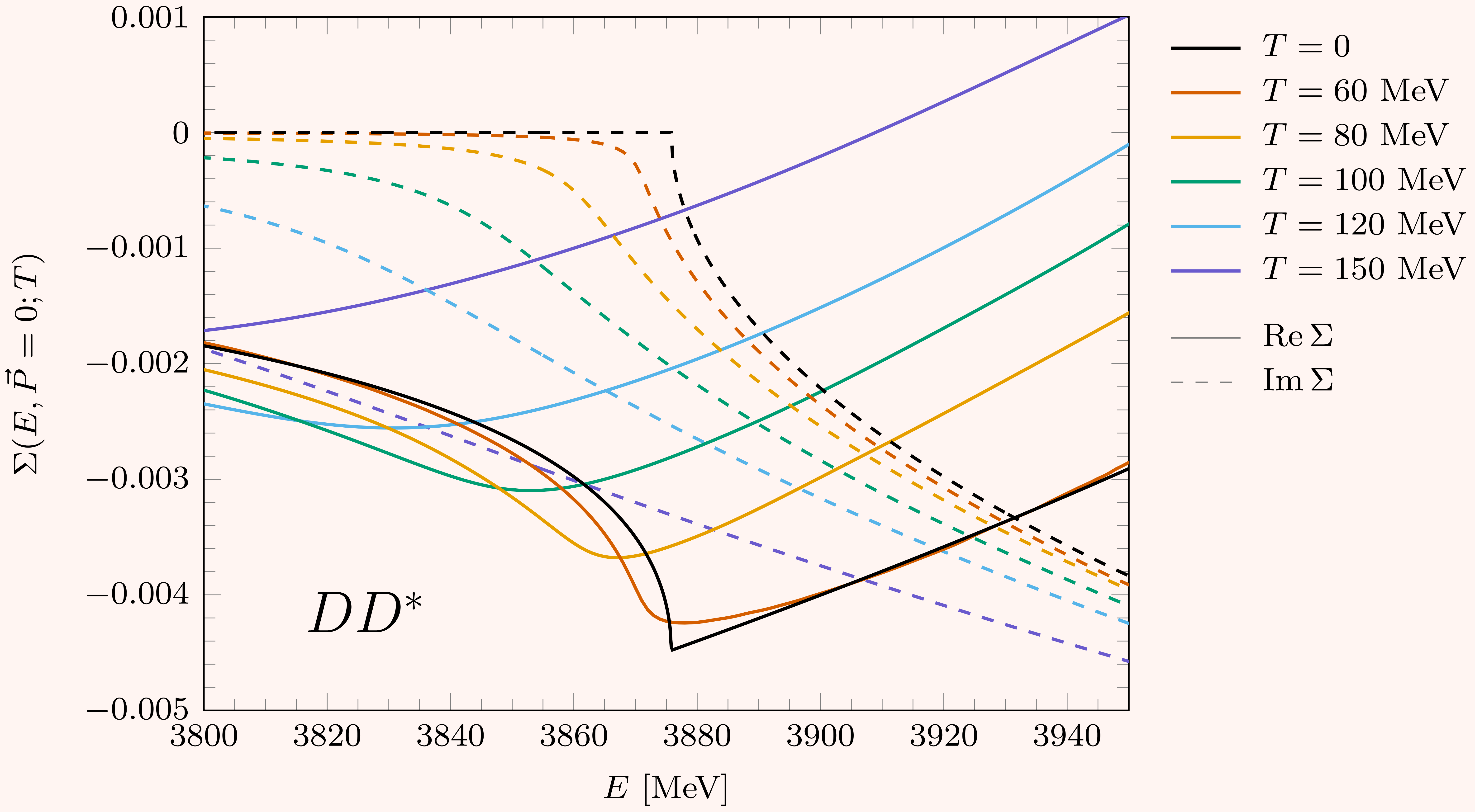


$D^{(*)}$ SPECTRAL FUNCTIONS AT FINITE TEMPERATURE



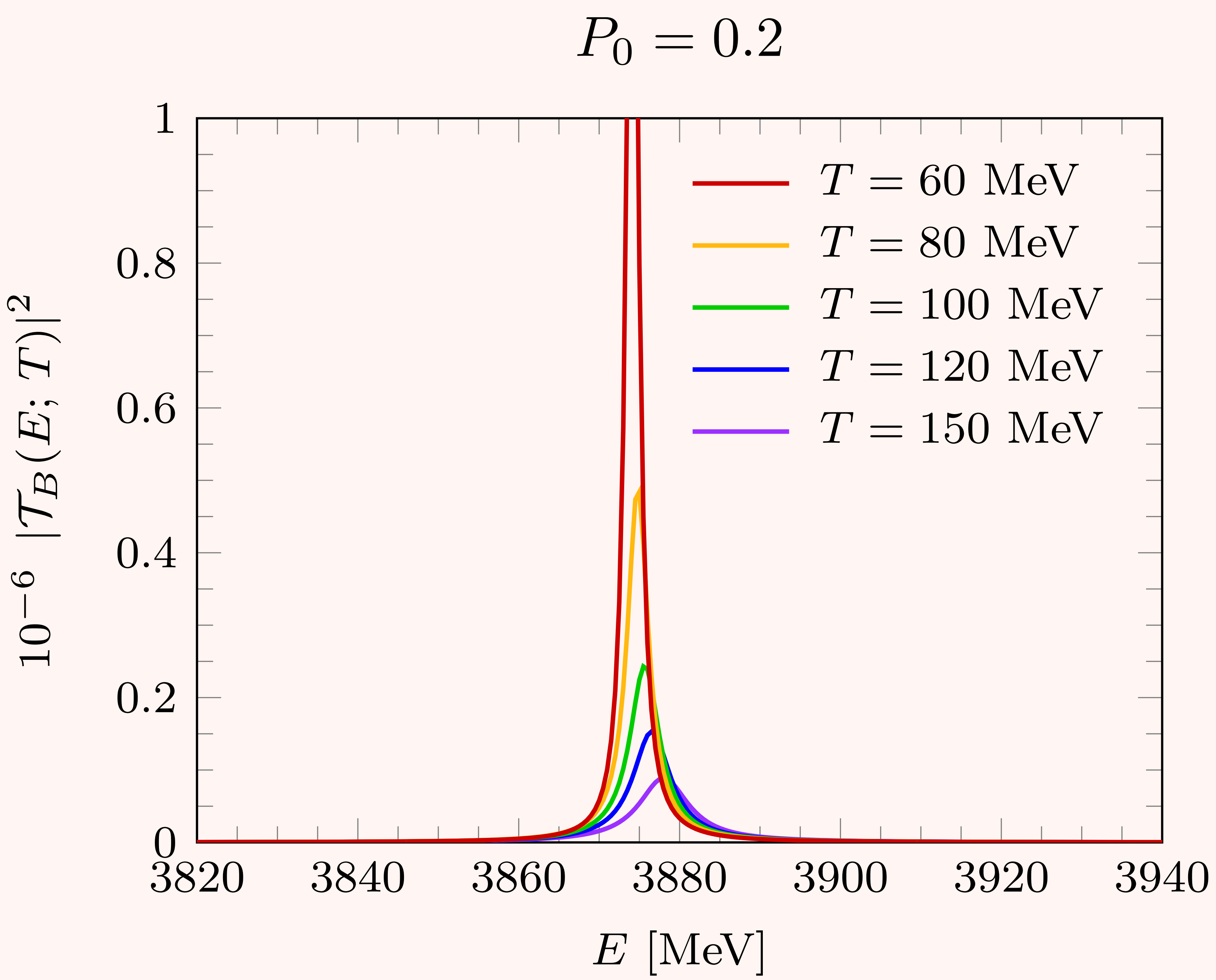
- **Spectral functions show little structure**
- **D and D^* widths increase importantly**
- **The quasi-particle peak shifts towards lower energies**

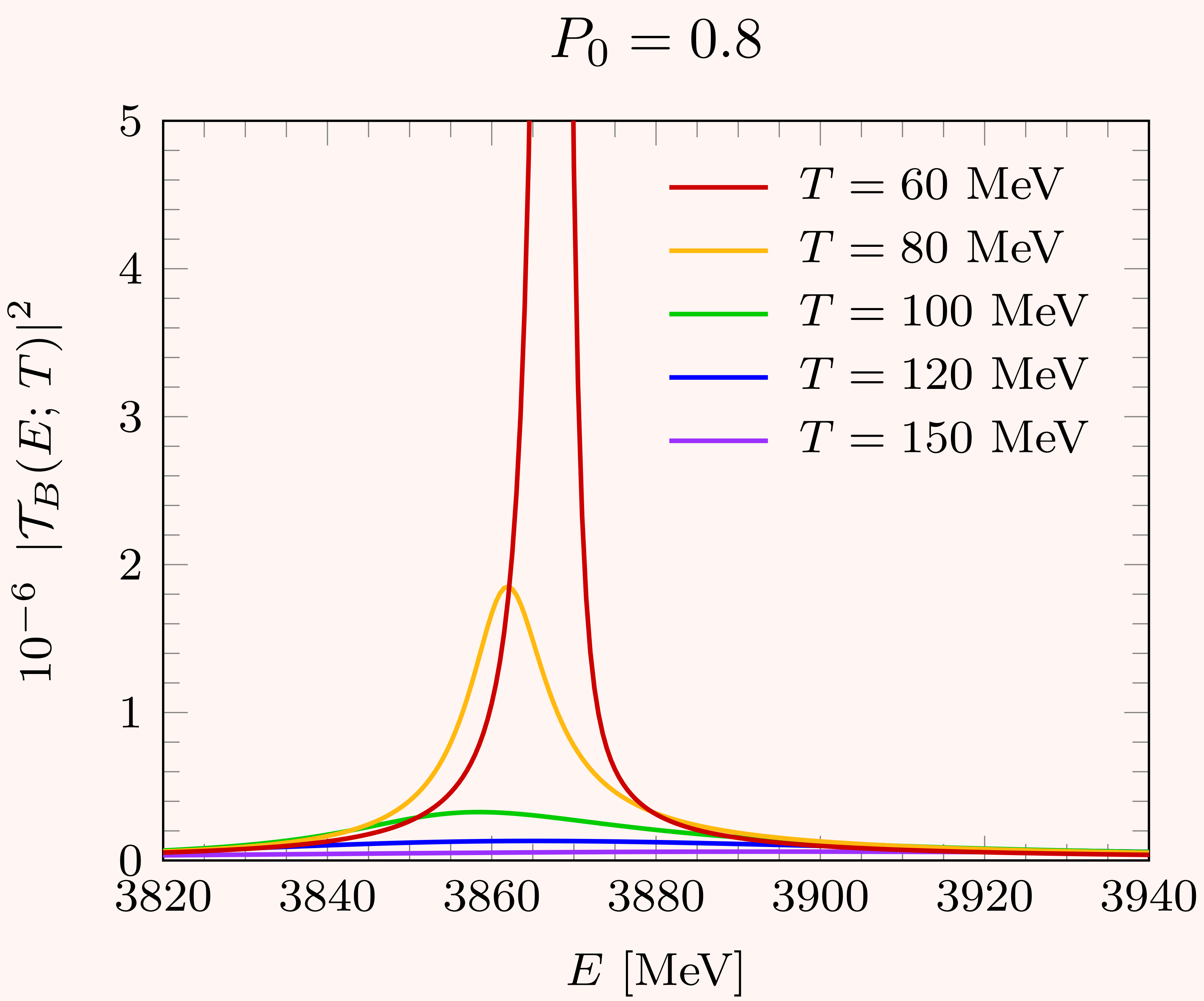
DD^* LOOP FUNCTION AT FINITE TEMPERATURE



- **Very notable effects for high temperature**
- **Important growth of the imaginary part**
- **Shift of the threshold towards lower energies**
- **DD^* and $\overline{D}\overline{D}^*$ loop functions equal due to their interactions with pions being the same**

DD^* SCATTERING AMPLITUDE AT FINITE TEMPERATURE





- T_{cc}^{+} and $T_{\bar{c}\bar{c}}^{-}$ behave identically with increasing temperature
- Width of T_{cc} grows with temperature, much more so for high P_0 (due to its coupling to DD^*)

- Differences between the two P_0 scenarios
  - $P_0 = 0.2 \rightarrow$ slightly repulsive behavior and moderate width increase
  - $P_0 = 0.8 \rightarrow$ extreme increase in width, dissolution of T_{cc} around $T \sim 120$ MeV

CONCLUSIONS

- T_{cc} in nuclear matter
  - Particle-antiparticle are necessarily the same in free space (charge conjugation symmetry), but they are different in nuclear matter $\rightarrow$ very different D and $\bar{D}$ 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
- T_{cc} at finite temperature
  - Thermal modification to T_{cc} strongly dependent on the molecular probability, since the meson properties are largely affected by the pion bath
  - Large molecular component $\rightarrow$ T_{cc} melts down at $T \sim 100$ MeV
- Measurement of these lineshapes in dense matter at CBM (FAIR) or in heavy-ion collisions at RHIC or LHC would provide a powerful tool for constraining the molecular compositeness of these states