$D\bar{D}^*$ and $\chi_{c1}(3872)$ in nuclear matter

[arXiv:2102.08589]

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Experimental and theoretical status of and perspectives for XYZ states, Darmstadt, Apr 12-15, 2020

In collaboration with:
J. Nieves, L. Tolos

Outline

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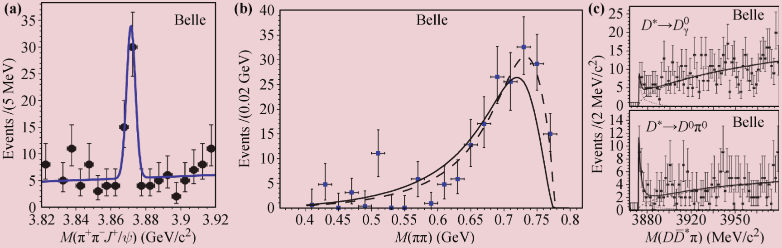
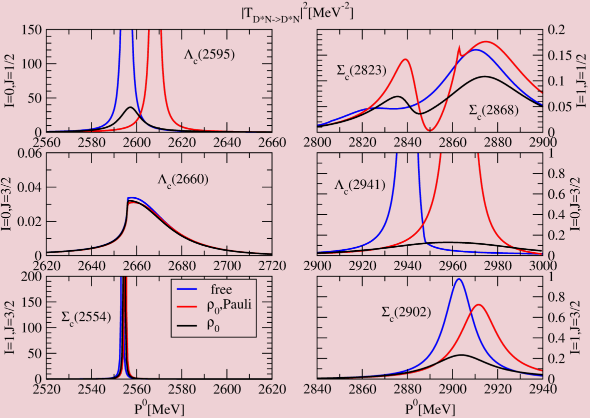
- $X(3872)$ discovered by Belle [PRL,91,262001('03)].
- First XYZ state. $J^{PC} = 1^{++}$.
  CDF,PRL,93,072001('04); D0,PRL,93,162002('04); BaBar,PR,D71,071003('05); LHCb,EPJ,C72,1972('12).
- PDG: $m_{D^0} + m_{D^{*0}} - m_X = 0.01 \pm 0.18$ MeV.
- See recent reviews:
  Olsen, Front. Phys.,10,121('15), Chen *et al.*, Phys. Rept., 639,1('16), Hosaka *et al.*, PTEP,16,062C01('16), Guo *et al.*, RMP,90,015004('18).



Interpretations

- **Quark model**: $\chi_{c1}(2P)$ around 3.93 GeV. Difficult assignment.
  Barnes, PR,D69,054008('04), Suzuki, PR,D72,114013('05).
- **Molecular** interpretation quite appealing.
  Swanson, PL,B588,189('04); Voloshin, PL,B604,69('04); Braaten, Kusunoki, PR,D72,054022('05); Gamerman, Oset, EPJ,A33,119('07). . .
- **Compact tetraquark:** Maiani *et al.*, PRD,71,014028('05), Ebert *et al.*, PLB,634,214('06), Matheus, PRD,75,014005('07),. . .
- Many **LQCD** simulations performed.
  Chiu *et al.*, PL,B646('07), . . . Bali *et al.*, PR,D84,094506('11), . . . , Cheung *et al.*,JHEP,1612,089('16).
- First one to find evidence of $X(3872)$: Prelovsek *et al.*,PRL,111,192001('13).
  Key to this evidence was the **inclusion of $D\bar{D}^*$ interpolators**.

Why nuclear matter?



- Amplitudes $\leftrightarrow$ resonances **modify their behaviour** in the presence of nuclear matter.
- Experimental facilities could **detect** final states with charmonium(-like) content: $D\bar{D}^*$, $X(3872)$.

Outline

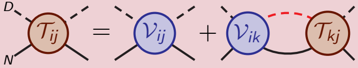
Formalism:

- Particle basis: $\{D^0\bar{D}^{*0}, D^{*0}\bar{D}^0, D^+\bar{D}^{*-}, D^{*+}D^-\}$
- T-matrix: $T^{-1}(s) = V^{-1}(s) - G(s)$ (matrices)
- **Interaction kernels**: $V(s) = AV_d(s)A$
  - $V_d(s) = \mathrm{diag}(V_{0Z}(s), V_{0X}(s), V_{1Z}(s), V_{1X}(s))$
  - A transforms particle basis $\Longleftrightarrow$ $I^{\mathcal{C}}$ basis
- **Loop functions**: $G_i(s) = i\int \frac{d^4q}{(2\pi)^4} D_{Y_i}(P-q)D_{Y_i'}(q)$.

$$D_Y(q) = \frac{1}{q_0^2 - \vec{q}^2 - m_Y^2 - \Pi_Y(q^0,\vec{q})} = \int_0^\infty d\omega \left(\frac{S_Y(\omega,|\vec{q}|)}{q^0 - \omega + i\varepsilon} - \frac{S_{\bar{Y}}(\omega,|\vec{q}|)}{q^0 + \omega - i\varepsilon} \right) .$$

- D_{Y_i} are **propagators**, S_{Y_i} are **spectral functions**, $Y_i Y_i'$ =particle basis.

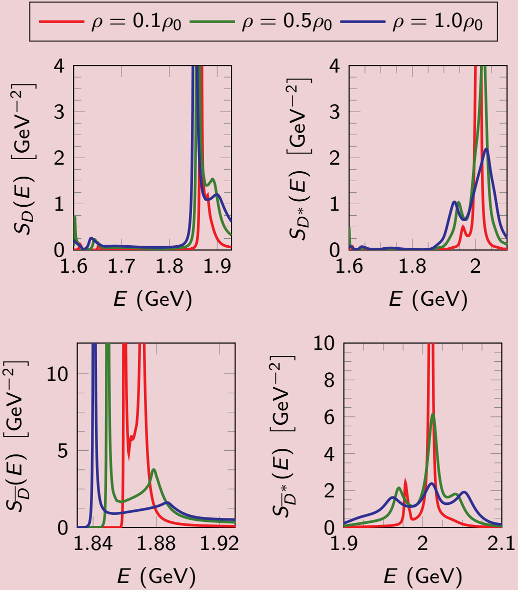
$D^{(*)}$ and $\overline{D}^{(*)}$ in nuclear matter



- $D^{(*)}$, $\bar{D}^{(*)}$ propagators in nuclear matter:

$$D_Y^{-1}(q) = q_0^2 - \vec{q}^{\,2} - m_Y^2 - \Pi_Y(q^0, \vec{q})$$

- Self-consistent calculation:
    - $D^{(*)}$: Tolos *et al.*, PR,C80,065202('09)
    - $\bar{D}^{(*)}$: Garcia-Recio *et al.*, PR,C85,025203('12)



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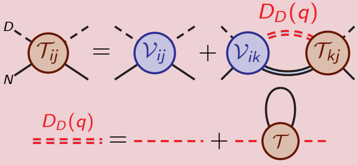

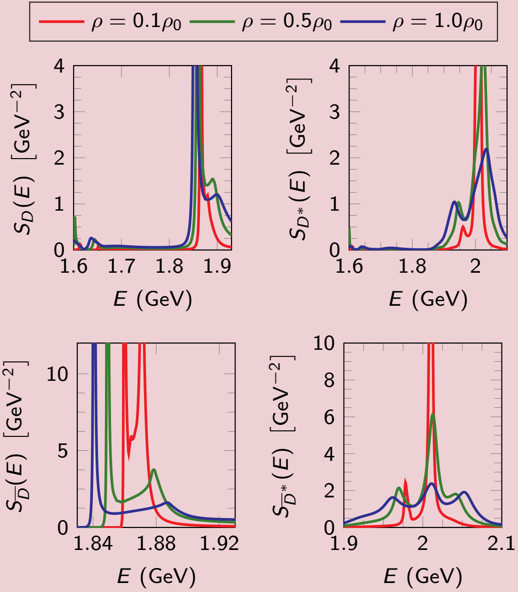

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Formalism: Vaccuum *vs* Medium

Vaccuum

- We assume isospin symmetry, $m_{D^+} = m_{D^0}$.
- All loop functions G_i equal, $G(s) = \Sigma_0(s)\mathbb{I}_4$.
- The T-matrix diagonalizes as $V(s)$: $\langle I'\mathbb{C}'|\hat{T}|I\mathbb{C}\rangle = \delta_{I,I'}\delta_{\mathbb{C},\mathbb{C}'}T_{I\mathbb{C}}(s)$

$$T(s) = AT_d(s)A, \quad T_d(s) = \mathrm{diag}\left(T_{0Z}(s), T_{0X}(s), T_{1Z}(s), T_{1X}(s)\right)$$

Formalism: Vaccuum *vs* Medium

Medium

- We assume the potentials $V_d(s)$ do not change in nuclear matter.
- We still assume isospin symmetry: $S_{D^+} = S_{D^0} \equiv S_D$, $S_{D^-} = S_{\bar{D}^0} \equiv S_{\bar{D}}$, but **in general** $S_D \neq S_{\bar{D}}$.
- T-matrix only block diagonalized, $G(s;\rho)$ is not $\propto \mathbb{I}_4$

$$T^{-1}(s;\rho) = A\left(V_d^{-1}(s) - AG(s;\rho)A\right)A\,, \quad AG(s;\rho)A = \begin{bmatrix} \widetilde{G}(s;\rho) & 0 \\ 0 & \widetilde{G}(s;\rho) \end{bmatrix}$$

$$\widetilde{G}(s;\rho) = \begin{bmatrix} \Sigma(s;\rho) & \delta G(s;\rho) \\ \delta G(s;\rho) & \Sigma(s;\rho) \end{bmatrix}\,, \qquad \begin{aligned} \Sigma(s;\rho) &= \frac{G_{D\bar{D}^*}(s;\rho) + G_{\bar{D}D^*}(s;\rho)}{2} \\ \delta G(s;\rho) &= \frac{G_{D\bar{D}^*}(s;\rho) - G_{\bar{D}D^*}(s;\rho)}{2} \end{aligned}$$

- $\langle I'\mathbb{C}'|\hat{T}|I\mathbb{C}\rangle = \delta_{I,I'}\, T^{(I)}_{\mathbb{C},\mathbb{C}'}(s)$, but no C-parity violation (of course): actual scattering is $D\bar{D}^*N \to D\bar{D}^*N$
- , everything gets back to fully diagonal.

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- $\langle I'\mathbb{C}'|\hat{T}|I\mathbb{C}\rangle = \delta_{I,I'}\delta_{\mathbb{C},\mathbb{C}'}T_{I\mathbb{C}}(s)$
- $T_{0X}^{-1}(s;\rho) = V_{0X}^{-1}(s) - \Sigma(s;\rho)$

Interaction kernel $V(s)$

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

- Simplest option: $V(s) = C_{0X} = 1/\Sigma_0(m_0^2)$
- $D\bar{D}^*$ (molecular) probability P_0:

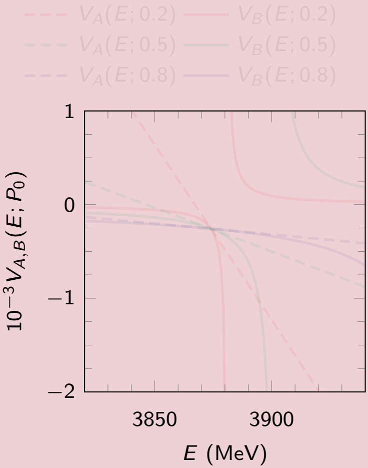
$$\boxed{P_0 = -g_0^2 \Sigma_0'(m_0^2)}$$

- Two easy generalizations:

$$V_A(s) = a + b(s - m_0^2)$$

$$V_B^{-1}(s) = a' + b'(s - m_0^2)$$

- Study both V_A, V_B.
- Fix $a^{(')}$, $b^{(')}$ in terms of m_0^2, P_0:
  - Take $m_0 = m_D + m_{D^*} - 2$ MeV
  - "Play" varying P_0



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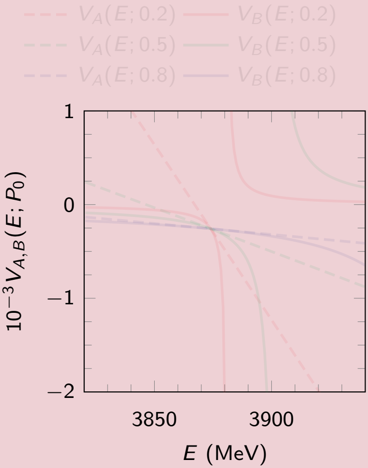

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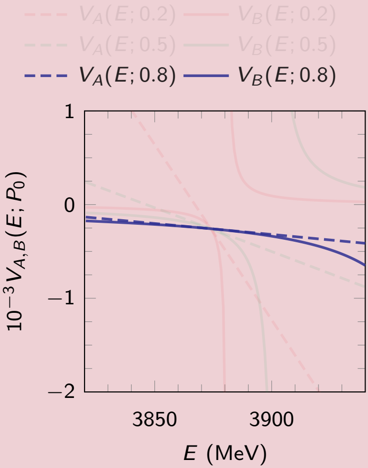

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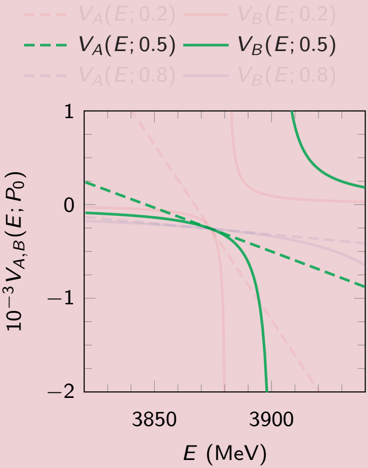

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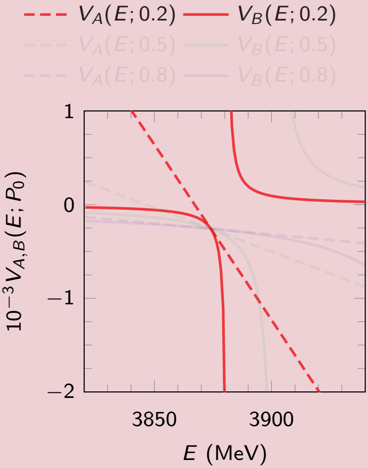

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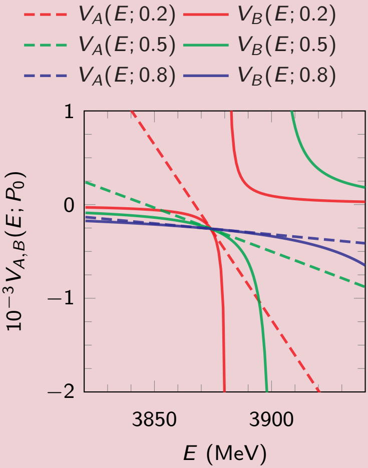
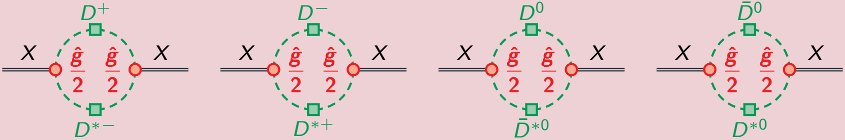


$X(3872)$ Self-energy

- Consider a "pre-existing" state with bare mass $\hat{m}$ and coupling $\hat{g}/2$.
  Bare propagator: $\hat{\Delta}^{-1}(q^2) = q^2 - \hat{m}^2 + i\epsilon$.
- Renormalization: $\Delta^{-1}(q^2;\rho) = \hat{\Delta}^{-1}(q^2) - \hat{g}^2\Sigma(q^2;\rho) \equiv \hat{\Delta}^{-1}(q^2) - \Pi_X(q^2;\rho)$.



- $X(3872)$ self-energy:

$$S_X(q^2;\rho) = -\frac{1}{\pi}\mathrm{Im}\Delta(q^2;\rho) = -\frac{1}{\pi}\frac{\mathrm{Im}\Pi_X(q^2;\rho)}{[q^2 - m_0^2 - \mathrm{Re}\Pi_X(q^2;\rho)]^2 + [\mathrm{Im}\Pi_X(q^2;\rho)]^2}$$

- Depends on m_0^2, P_0 (but not on "potential" V_A or V_B)

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- Mass of $X(3872)$ in vaccuum and in medium from $\Delta^{-1}(m^2(\rho);\rho) = 0$.
- In particular, one can write $m(\rho)$ and $\hat{m}$ in terms of m_0:

Bare

$$\hat{m}^2 = m_0^2 - \frac{g_0^2\Sigma_0(m_0^2)}{1 + g_0^2\Sigma_0'(m_0^2)}$$

$$\hat{g}^2 = \frac{g_0^2}{1 + g_0^2\Sigma_0'(m_0^2)}$$

ρ

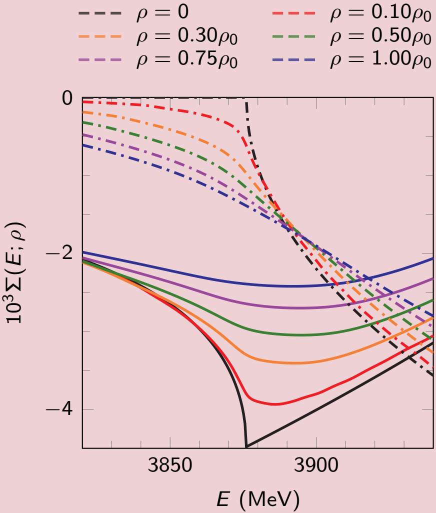
$$m^2(\rho) = m_0^2 + \frac{g_0^2\left(\Sigma[m^2(\rho);\rho] - \Sigma_0(m_0^2)\right)}{1 + g_0^2\Sigma_0'(m_0^2)}$$

$$g^2(\rho) = \frac{g_0^2}{1 - g_0^2\left(\Sigma'[m^2(\rho);\rho] - \Sigma_0'(m_0^2)\right)}$$

Outline

1.
2.
3. **Results**
4.

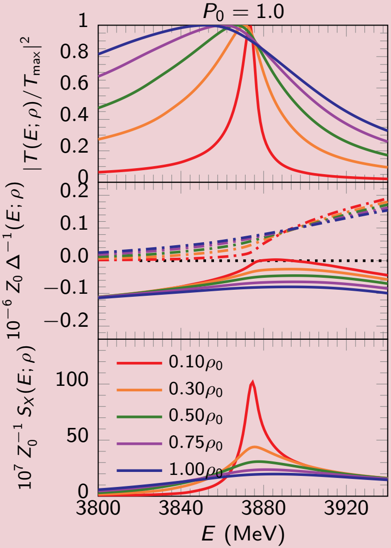
Loop functions $\Sigma(s;\rho)$



- **Threshold effect** washed out as ρ increases. $D^{(*)}$, $\bar{D}^{(*)}$ acquire in-medium widths.
- **Repulsion?** $\mathrm{Re}[\Sigma(E;\rho)]$ is smaller in magnitude as ρ increases. Does this imply repulsion?
- Not so clear:

$$|\mathrm{Im}\Sigma(E;\rho)| \gtrsim |\mathrm{Re}\,(\Sigma(E;\rho) - \Sigma_0(E))|$$

Amplitudes (high P_0)



- For P_0 high ($\gtrsim 0.7$) almost no difference between V_A and V_B
- Very large broadening.
- Quasi-particle peak: $\mathrm{Re}[\Delta^{-1}(E_{\mathrm{qp}};\rho)] = 0$
- $P_0 = 1$:
  - $|T|^2$ peak shifted to the left
  - No E_{qp}
- $P_0 = 0.8$:
  - $|T|^2$ peak shifted to the right
  - E_{qp}, but. . .

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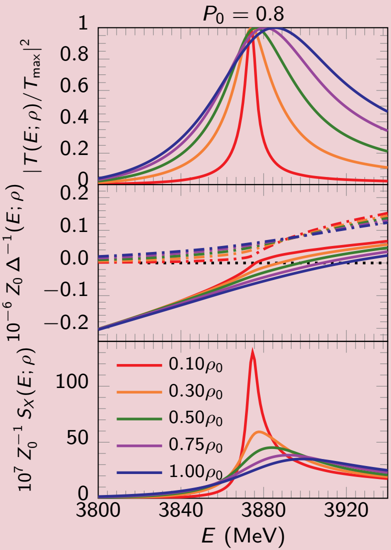

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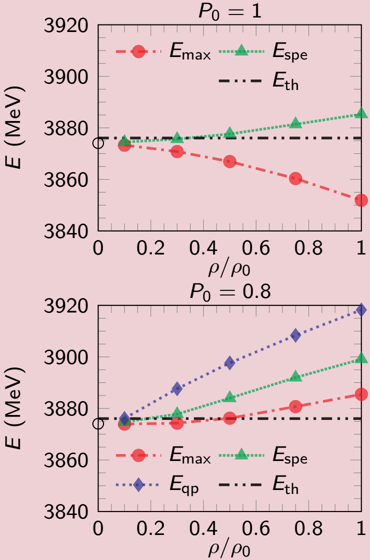

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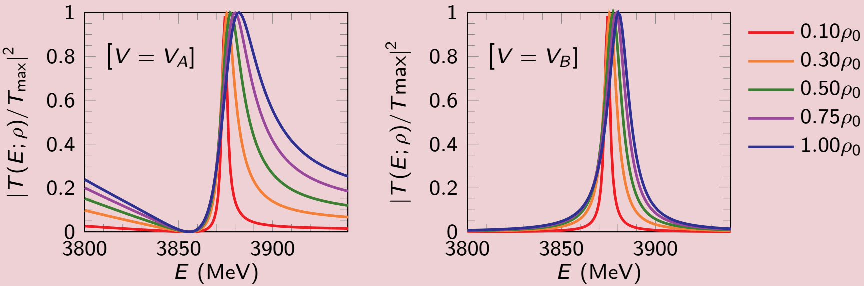
Amplitudes (low P_0)

$P_0 = 0.4$

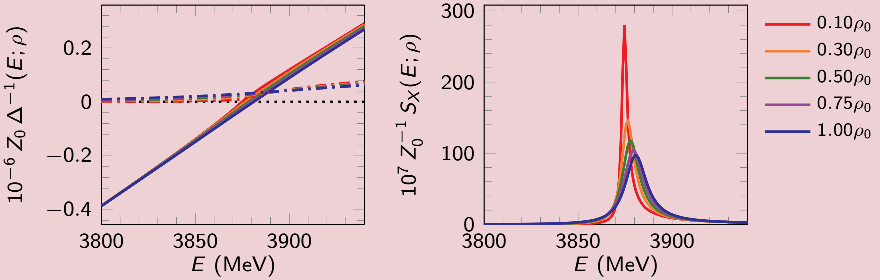


- For low P_0 $V_A(s)$ and $V_B(s)$ tend to give **different results** (as expected).
- Zero in $V_A(s)$ gets closer to m_0^2 for $P_0 \to 0$.
- Density effects are larger for V_A than for V_B outside the $X(3872)$ region.

Amplitudes (low P_0)

- In $S_X(s;\rho)$ or $\Delta^{-1}(s;\rho)$ **little variation** wrt vaccuum.
- Physically $P_0 \to 0$ little coupling $\to$ little medium effect.
- Always E_{qp} solution, very close to vaccuum mass m_0.

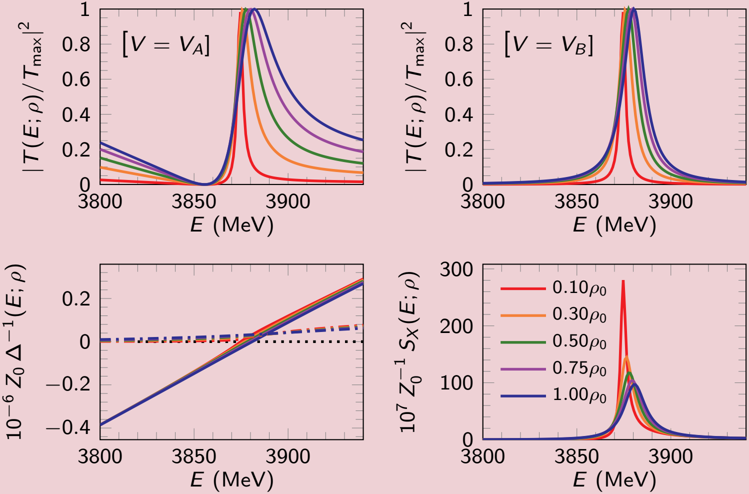
$$P_0 = 0.4$$



Amplitudes (low P_0)

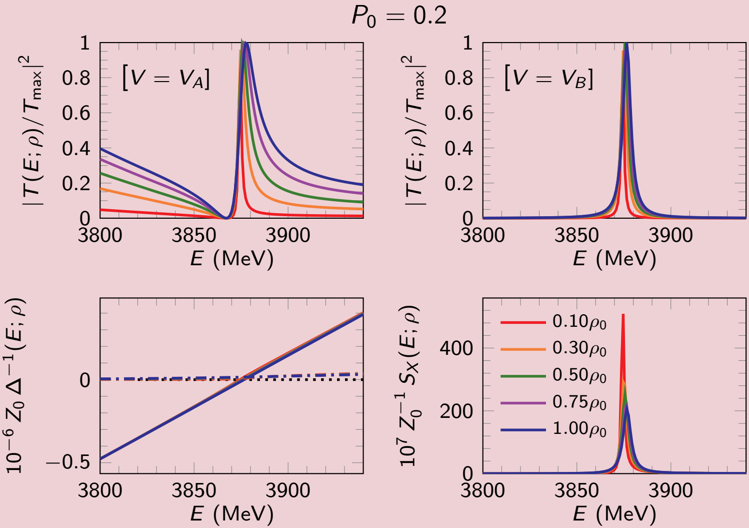
- These features more visible at $P_0 = 0.2$ $\boxed{P_0 = 0.4 \Longrightarrow P_0 = 0.2}$

$P_0 = 0.4$



Amplitudes (low P_0)

- These features more visible at $P_0 = 0.2$ $\boxed{P_0 = 0.4 \Longrightarrow P_0 = 0.2}$



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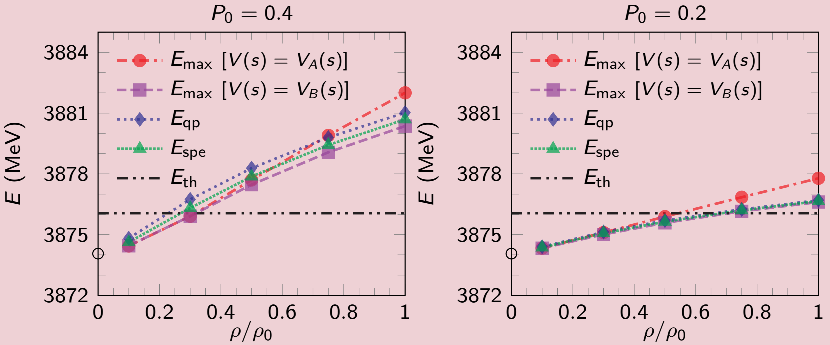
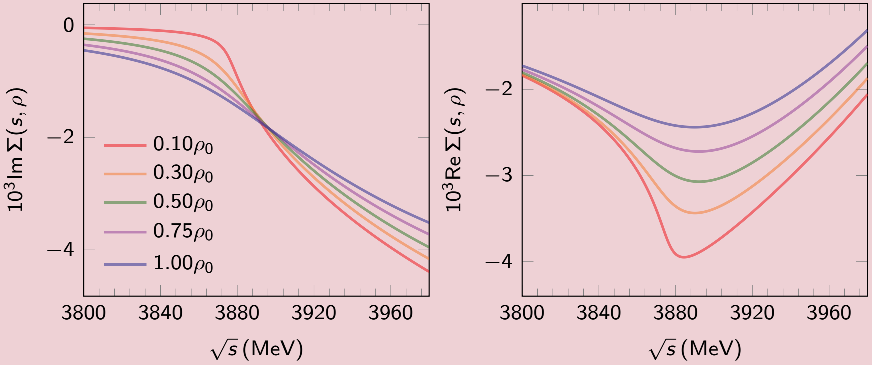


- For $P_0 = 0.2$, $E_{\text{qp}} \simeq E_{\text{spe}} \simeq E_{\text{max,A}}$, and $E_{\text{max,B}}$ still a bit off.
- For $P_0 = 0.4$, similar, but some more differences.

Effective Loop function



- Observation: All the structure of $S_{D^{(*)}}$ and $S_{\overline{D}^{(*)}}$ washes out in $\Sigma(s;\rho)$.
- Ansatz:

$$\Sigma(s;\rho) \simeq G^{(\mathrm{eff})}(s;\rho) \equiv G(s, m_D^{(\mathrm{eff})}(\rho), m_{D^*}^{(\mathrm{eff})}(\rho))$$

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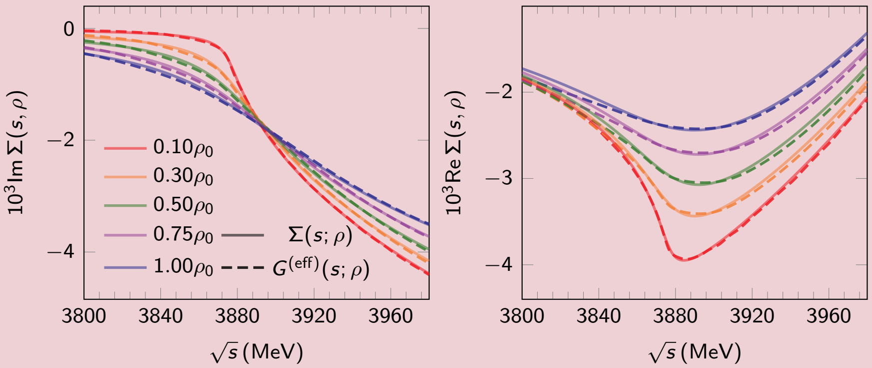

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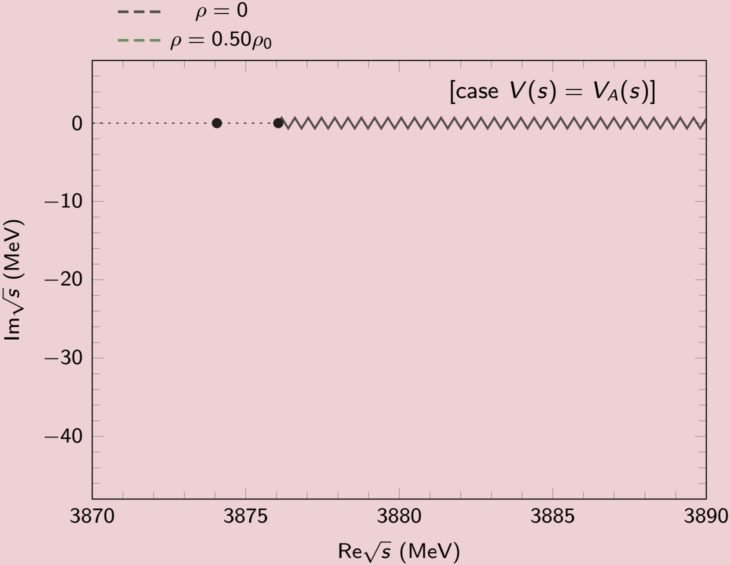
Results: Poles



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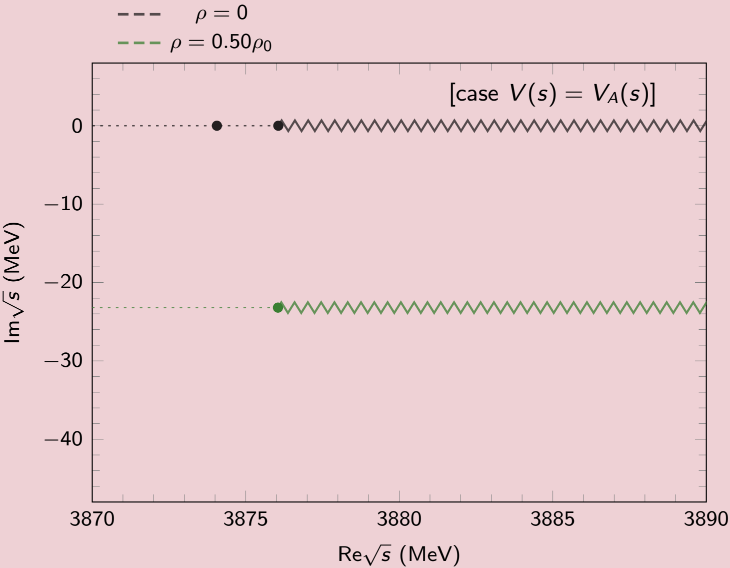

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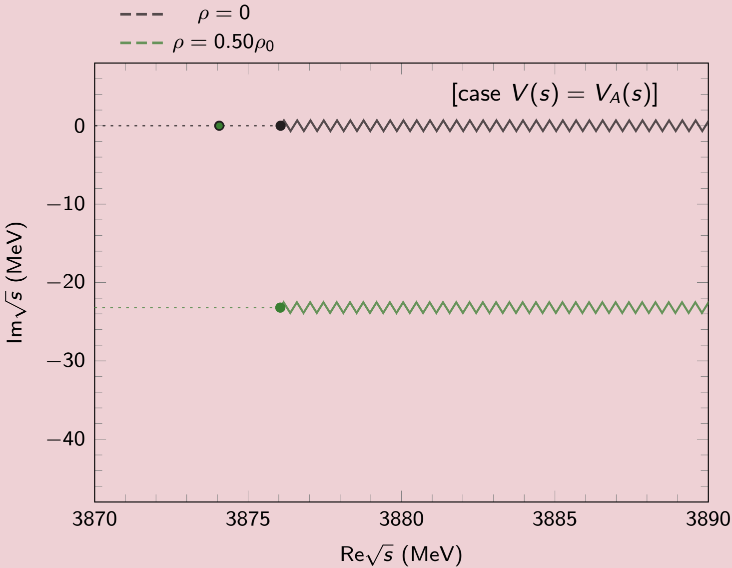

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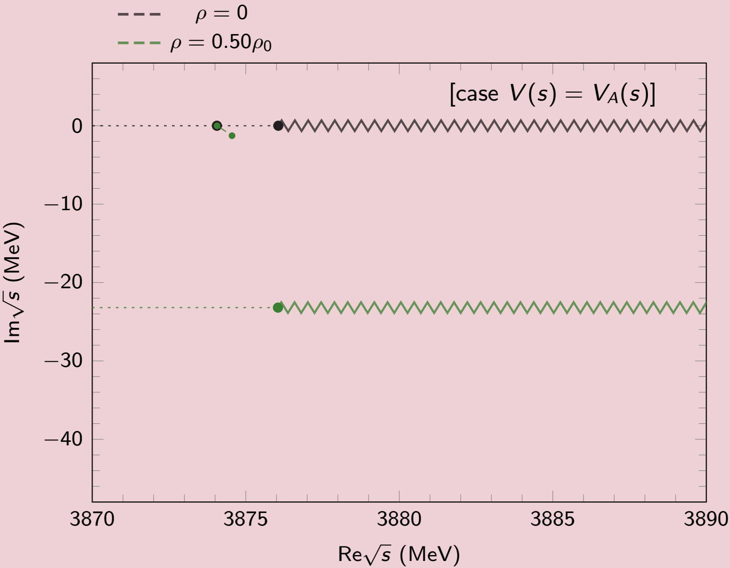

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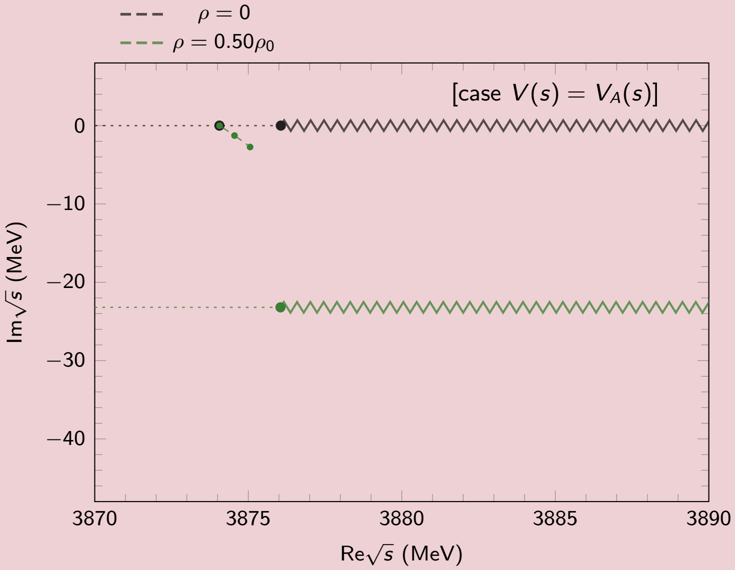

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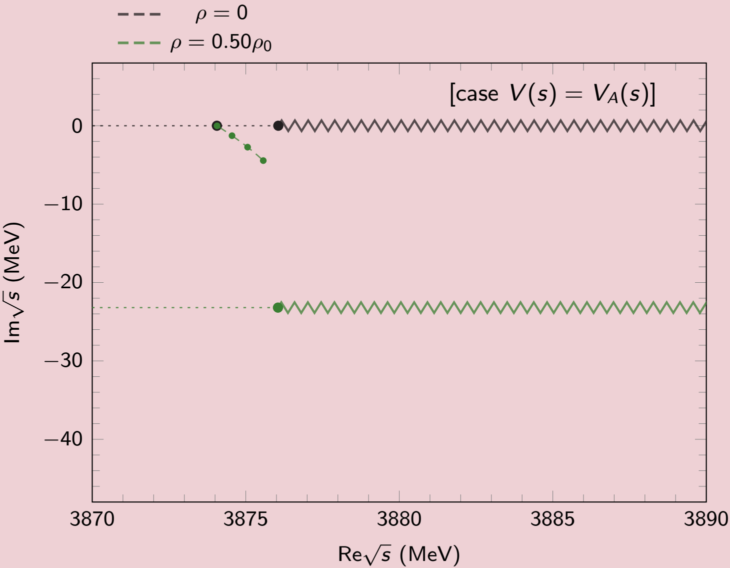

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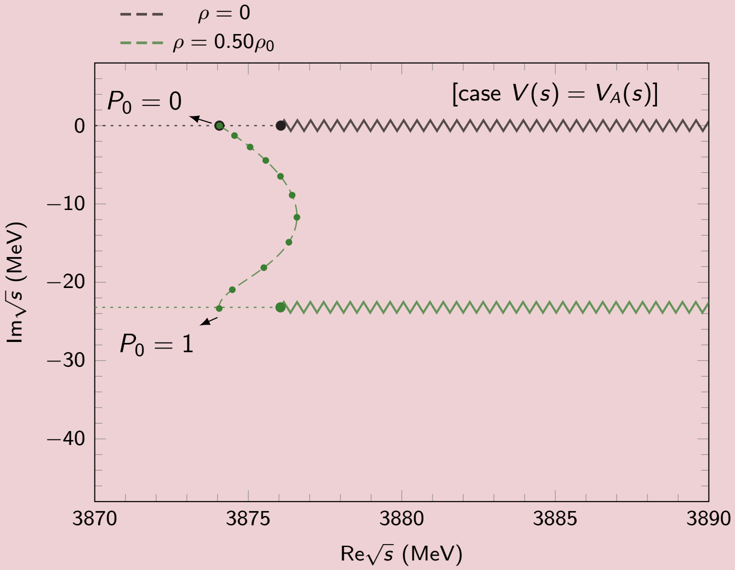

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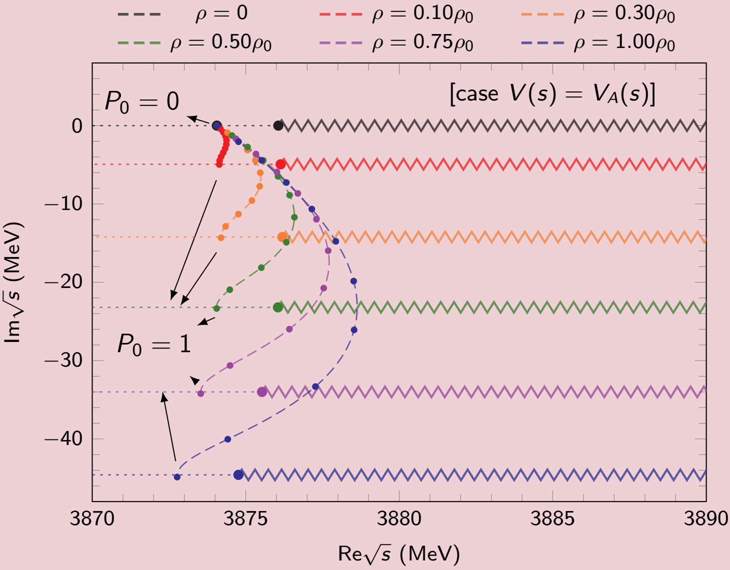
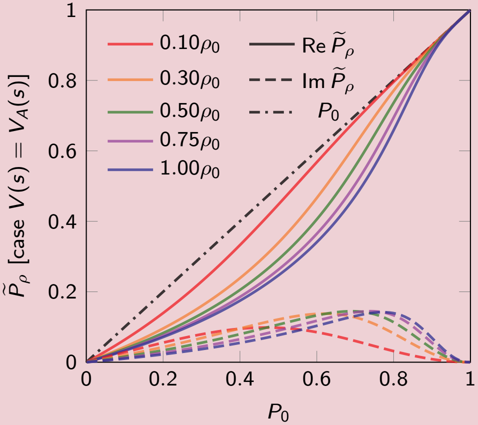


Results: "Probability"

$$\boxed{P_0 = -g_0^2 \Sigma_0'(m_0^2) \Longrightarrow \widetilde{P}_\rho = -g^2(\rho) \left. \frac{dG^{(\mathrm{eff})}(s;\rho)}{ds} \right|_{s=m^2(\rho)}}$$

- In-medium **generalization** of the formula for P_0.
- Complex masses → complex $\widetilde{P}_\rho$: **no interpretation** as probability.
- For $P_0 \to 0$ or 1, $\widetilde{P}_\rho \to P_0$.



Explaining poles

- $P_0 \to 0$: Coupling of X to $D\bar{D}^*$ tends to zero, so X ignores what happens to $D\bar{D}^*$ in the medium
- $P_0 \to 1$:
  - In this case $V_A(s) \simeq 1/\Sigma_0(m_0^2)$ (no energy dependence)
  - The pole must satisfy also $\operatorname{Im} G^{(\mathrm{eff})}(m(\rho)^2; \rho) = 0$
  - This happens only at the line to the left of the threshold
  - The pole is "dragged" by the threshold

Outline

Conclusions

- Formalism and results for the in-medium modifications of $D\bar{D}^*$ scattering in the $X(3872)$ channel has been presented.
- Studied with both the T-matrix and self-energy formalisms. **Understood** when both formalism give equivalent results
- E_{qp} and $E_{\mathbf{max}}$ do not generally coincide.
- A **novel way** to "hunt" poles with in-medium amplitudes.
- Measuring the modification of amplitudes in nuclear matter could help in understanding $X(3872)$ in vacuum.
- Question: how could these results be **experimentally tested?**: